CHARACTERIZATION OF REAL-WORLD ACTIVITY, FUEL USE, AND EMISSIONS FOR SELECTED MOTOR GRADERS FUELED WITH PETROLEUM DIESEL AND B20 BIODIESEL

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ABSTRACT

Motor graders are a common type of nonroad vehicle used in many road construction and maintenance applications. In-use activity, fuel use, and emissions were measured for six selected motor graders using a portable emission measurement system (PEMS). Each motor grader was tested on petroleum diesel and B20 biodiesel. Duty cycles were quantified in terms of the empirical cumulative distribution function (ECDF) of manifold absolute pressure (MAP), which is an indicator of engine load. The motor graders were operated under normal duty cycles for road maintenance and repair at various locations in Wake and Nash Counties, NC. Approximately 3 hours of quality assured second-by-second data were obtained during each test. An empirical modal-based model of vehicle fuel use and emissions was developed, based on stratifying the data with respect to ranges of normalized MAP, in order to enable comparisons between duty cycles, motor graders, and fuels. Time-based emission factors were found to increase monotonically with MAP. Fuel-based emission factors were mainly sensitive to differences between idle and non-idle engine operation. Cycle average emission factors were estimated for road ‘resurfacing,’ ‘roading,’ and ‘shouldering’ activities. On average, the use of B20 instead of petroleum diesel leads to a negligible decrease of 1.6 percent in nitric oxide (NO) emission rate, and decreases of 19 to 22 percent in emission rates of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). Emission rates decrease significantly when comparing newer engine tier vehicles to older ones. Significant reductions in tail-pipe emissions accrue especially from the use of B20 and adoption of newer vehicles.

IMPLICATIONS

Field measurements of selected nonroad vehicles provide insight into the real world emissions implications of alternative fuels, engine technology, and duty cycles. 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. Furthermore, such data provides insight regarding the potential effect of changes in operational strategies such as idle reduction, on fuel use and emissions. These data will become necessary for meeting both regulatory and owner imposed requirements for some projects and for green fleet certification programs.

Key Word)
Real-World, Motor Grader, B20 Biodiesel, Petroleum Diesel, Emissions, Duty Cycle

INTRODUCTION

Heavy duty diesel vehicles, including both onroad and nonroad vehicles, emit significant amounts of NO_x, which is a precursor to ozone formation, and particulate matter (PM). Unlike emissions trends for on-road vehicles, emissions of CO, NO_x, and PM from nonroad engines and vehicles increased steadily from 44 percent to 110 percent, depending on the pollutant, from 1970 to 2006.[1] 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 sulfur dioxide (SO_2) (EPA, 2005).[2]

In the U.S., there are an estimated 29,697 motor graders based on data used for the NONROAD 2005 model, which is approximately 2 percent of all construction vehicles (EPA, 2005).[2] A motor grader is a rubber tire tractor with an undercarriage blade used for scraping and spreading material. Typical models have three axles, with the engine and cab situated above the rear two axles. There is a third axle at the front of the vehicle, with the blade in between front and rear axles. Typical transportation uses include fine grading for road beds or haul paths, excavating for small ditches, and snow and ice removal from roadways. A typical construction use includes the preparation of the foundations for parking lots.

Biodiesel

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).[3] Biodiesel can be blended with petroleum diesel fuel at any ratio. A common blend rate, referred as B20, is 20 percent renewable source and 80 percent petroleum diesel (EPA, 2002).[3]

Based on the properties of B20 biodiesel versus petroleum diesel, an average increase in mass-based fuel use rate of 2.2 percent is expected in order to supply the same amount of chemical energy to the engine (EPA, 2002).[3] Based on engine dynamometer tests, the use of B20 biodiesel is expected to reduce emissions of PM and CO by approximately 10 percent, and emissions of HC by 20 percent, but to increase NO_x emissions by 2 percent (EPA, 2002).[3] However, engine dynamometer tests are not representative of real-world duty cycles, and actual fuel properties may affect the results for NO_x emissions. For example, Frey and Kim (2006)[4] conducted Portable Emission Measurement Systems (PEMS) measurement of 12 dump trucks and found that B20 leads to reductions in emission rates of 10 percent for NO, CO, and PM, and of 20 percent for HC. Furthermore, fuel quality has been shown to be important with respect to NO_x emissions in diesel engines.[5] There is variation in NO_x emissions depending on whether a test fuel uses a B100 blend stock that is compliant with the American Society for Testing and Materials (ASTM) standard D6751.[5, 6] Therefore, there is a need to further evaluate the differences in emissions for B20 biodiesel versus petroleum diesel under real-world conditions for construction equipment, using an ASTM compliant blend stock.

Engine Tiers

Over time, increasingly stringent regulations have been implemented to reduce tailpipe emissions of NO_x and PM from diesel vehicles. 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. These standards are phased in depending on engine size, with Tier 3 engines becoming available in 2007. 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 percent and 90 percent, respectively, compared to Tier 3.[7, 8] However, the existing vehicle fleet will emit pollutants at higher rates than Tier 3 and Tier 4 for years to come because of the longevity of older vehicles and their resulting continued presence in the U.S. construction fleet.

Measurements of Construction Vehicles

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 various construction vehicles.[9-12] However, not all of these data are quality assured or publicly available. Many of these studies focus on average emission rates without specifically relating emissions to duty cycles, fuels, or engine tiers. None of these studies specifically included or focused on motor graders. Thus, there is a need for data for motor graders to enable comparison of duty cycles, fuels, and engine tiers.

On-board emissions measurement enables data collection under representative real-world conditions in the operating environment.[13-15] PEMS are designed for measuring in-use emissions rates during real-world operations under various ambient conditions, site conditions, and operational/duty cycles.[16, 17] Initially, PEMS had the capability to measure HC, NO, CO, and CO_2 emissions using repair-grade gas analyzers.[18] More recently, PM measurement capabilities have been added to some PEMS.[19] The connections of the portable system to the vehicle are reversible and no engine or vehicle modifications are necessary.

RESEARCH OBJECTIVES

The primary objectives of this study are to:

- Measure real-world, in-use duty cycles for a motor grader;
- Simultaneously measure real-world, in-use emissions;
- Develop recommended duty cycles and emissions factors; and
- Compare duty cycles, tiers, and fuels.

METHODOLOGY

Vehicle, Fuel, and Site Selection

The test vehicles were selected from the North Carolina Department of Transportation (NCDOT) equipment inventory. The PEMS was installed by North Carolina State University (NCSU). During data collection, the vehicles were operated during their normal duty cycles by NCDOT operators. Six motor graders were selected, including 2 Tier 0, 2 Tier 1, 1 Tier 2, and 1 Tier 3 vehicles.

Each vehicle was tested on one day using ultra-low sulfur diesel and on a separate day using soy-based B20 biodiesel. The biodiesel was blended with the same ultra low sulfur petroleum diesel. The B100 blend stock that was used for blending conformed to the applicable ASTM standard.

Data collection occurred at field sites where the instrumented vehicles conducted normal road maintenance tasks. Motor graders were used for resurfacing unpaved roads or for grading of road shoulders.

Instrumentation

The PEMS used in this study was the "Montana" system manufactured by Clean Air Technologies International Inc.[19] The Montana system collects emissions data, using a sample probe inserted into the tailpipe, for NO, HC, CO, and CO_2, which are detected in two parallel five-gas analyzers.[12, 17, 20] HC, CO, and CO_2 are measured using non-dispersive infrared (NDIR). Measurements of CO and CO_2 are accurate to within 10 percent when compared to measurement of average emission rates for a test cycle in a dynamometer lab.[21] The accuracy of the HC measurement depends on type of fuel used.[22] NO is measured using an electrochemical cell in the PEMS, whereas total NO_x was measured in the dynamometer lab using chemiluminescence. The slope of parity plots of the dynamometer versus PEMS cycle average measurements ranged from 0.92 and 1.03, indicating that the PEMS measurements of NO (reported as equivalent NO_2) were accurate to well within plus or minus 10 percent of the dynamometer measurements of total NO_x (reported as equivalent NO_2).[21]

Typically, 95 volume percent of the NO_x emitted from diesel vehicles without post-combustion control is NO for both petroleum diesel and biodiesel.[6] Thus, measurement of NO emission rate is a useful indicator of NO_x emissions. All NO emission factors are reported as NO_2 mass equivalent. To determine PM, a light scattering method is used. This method is analogous to opacity and is used to make relative comparisons of PM emissions, but not to characterize the absolute magnitude of such emissions. The two parallel five-gas analyzers are calibrated periodically in the laboratory based on a certified cylinder gas and they also self-calibrate periodically in the field using ambient air as a reference.[20, 23]

The Montana system uses a sensor array to obtain engine data for estimating exhaust flow, including manifold absolute pressure (MAP), intake air temperature (IAT), and engine RPM.[20] The on-board computer in the Montana system synchronizes the incoming second-by-second emissions and engine data, as well as GPS data.

To protect the Montana system from damage in the extreme environment in which the tests are conducted, a sturdy metal safety cage was developed. The safety cage securely holds the Montana system during data collection. The safety cage includes several layers of foam padding between the main unit of the PEMS and the bottom of the safety cage, and between the safety cage and surface of the vehicle. A dust cover is placed over the safety cage. Thus, the safety cage protects the Montana system from such hazards as overhanging tree branches, vibration, and dust.

Data Collection Procedure

The data collection procedure includes 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 the safety cage, engine sensors, external power batteries, global positioning system (GPS), and exhaust gas sampling hoses.

Installation is performed two hours prior to data collection and includes: placement of the PEMS into the safety cage; connection of the power cable, GPS receiver, and exhaust gas hoses; and setup of an auxiliary laptop and a video camera. An auxiliary laptop and a video camera are used to record modes of vehicle activity and test site conditions. Decommissioning includes reversing the pre-installation and 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.

Data Screening and Quality Assurance

Data screening and quality assurance (QA) 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, removing invalid data if errors or problems cannot be corrected, and properly synchronizing emissions, engine, and GPS data. A number of possible errors have been identified such as problems associated with the gas analyzers, sensor array, and air leakage into the sampling system based on the assessment of the air-to-fuel ratio (AFR).[23] A standardized procedure for data screening and evaluation has been developed and is consistently applied to all field data using Visual Basic macros in Excel™. The output of the QA procedure includes valid data, a report on the frequency with which invalid data were excluded, and the causes for such exclusion.

Exploratory Analysis of Data

The raw data were analyzed, in part, to determine the effect of engine activity on fuel use and emissions rates. There was a need to develop standard procedures to estimate modal emission rates based upon engine variables, such as MAP, engine RPM, IAT, and 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.

Determination of Representative Duty Cycles

A duty cycle is defined as the sum of tasks that a specific vehicle can perform at a work site to complete an activity, such as grading a road. For example, the duty cycle for a motor grader performing road resurfacing activity includes the tasks of moving, blade, and idle. *Moving* refers to forward or reverse movement between locations under engine power, but while not performing work because the blade is not in use. *Blade* refers to situations in which the blade is in contact with material on the ground and the vehicle is moving under power, such as to push or spread material. *Idle* refers to when the engine is on but the vehicle is not moving and is not performing work; hence, the engine is not under load.

Three types of duty cycles were observed: resurfacing, shouldering, and roading. *Resurfacing* refers to the use of most or all of the blade length to re-shape and repair ruts in the surface of an unpaved road. *Shouldering* refers to the use of a portion of the blade length to scrape and grade the shoulders and ditches beside a paved road. *Roading* refers to transport of a motor grader from one work location to another. Resurfacing typically has a higher engine load compared to shouldering or roading because a large portion of the blade is in contact with the ground.

Modal Analysis

Fuel use and emission rates were estimated for “engine-based” and “task-oriented” modes.

Engine-Based Modes
Based on the exploratory analysis of data, MAP has been consistently identified as the engine variable most highly correlated with variations in fuel use and emission rates.[23] To enable comparison between duty cycles, normalized MAP is defined as:

$$MAP_i^o = \frac{MAP_i - MAP_{\min}}{MAP_{\max} - MAP_{\min}}$$

Where,

MAP_i^o = Normalized MAP for one second of data for a specific vehicle
$MAP_{\max}$ = Maximum observed MAP for a specific vehicle
$MAP_{\min}$ = Minimum observed MAP for a specific vehicle
MAP_i = Measured MAP for one second of data for a specific vehicle

The normalized MAP is bounded by 0 and 1 and is divided into 10 equal width bins for the purposes of modal analysis. The emission rates in mass per time and mass per gallon of fuel consumed were estimated for each normalized MAP bin. Fuel use and CO_2 emission rates are reported on a time basis. However, fuel-based results are not shown for fuel use since the mass of fuel consumed per gallon of fuel is a constant. Since CO_2 emissions are highly correlated with fuel consumption, CO_2 emissions on a per gallon basis are approximately constant and, therefore, are also not shown.

Task-Oriented Modes
During field data collection, a notation regarding the tasks being performed was made using a laptop computer.[23] The average fuel use and emission rates by task-oriented mode were estimated, both on a mass per time and mass per gallon basis. The purpose of observing tasks was to determine if there are varying level of emissions rates based on the tasks.

Benchmarking Observed Fuel Use Rates with Owner Records

Fuel consumption rates estimated from the PEMS data were compared to historical fuel usage data, where such data were available. The purpose of this comparison was to assess the concordance of the magnitude of fuel consumption rates. However, because the owner records are based on annual averages whereas the field data are from only a few hours of operation, exact agreement is not expected. However, since emission rates can be estimated from the 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.

Benchmarking Measured Emission Rates Based on the NONROAD Model

Fuel-based emission factors from the 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. Theses estimates are not correlated with the real world duty cycles observed in the field. Therefore, differences are expected in the absolute values of the emission factors when comparing these differing approaches. However, the purpose of the comparison is to determine whether the magnitudes of the emission factors are similar.

Another benchmarking consideration is that the emission factors reported by the NONROAD model are in units of grams per brake horsepower-hour. However, the PEMS data are in terms of grams per second or grams per gallon of fuel consumed.[12] Thus, in order to enable comparisons with the PEMS data, the emission factors in the NONROAD model were converted to units of grams per gallon of fuel using a brake-specific fuel consumption rate (BSFC).[24]

RESULTS

Table 1 summarizes the engine and chassis information for all six tested motor graders and the site conditions during the tests. In addition, ambient conditions on each day of data collection are shown.

Challenges Encountered During Data Collection

The Montana system is a sensitive electro-mechanical instrument that was designed for use in a controlled and moderate environment such as the interior of a vehicle cab; it is not a "ruggedized" instrument. Thus, its use on the exterior of a motor grader at construction sites posed significant challenges, particularly with regard to temperature, moisture, dust, and equipment vibration. These problems and their solutions are briefly described.

Data collection cannot occur during a rain or snow event when the PEMS is installed on the exterior of the vehicle. Additionally, if the temperature drops below freezing (32ºF), data collection cannot occur because moisture in the sample line freezes. On the other hand, when the ambient temperature exceeds 90 ºF, the Montana system is susceptible to overheating and will shut down. Therefore, data were collected only on non-precipitation days and only when the ambient temperature was between 32 ºF and 90 ºF.

The Montana system is sensitive to vibration imposed on it by the construction vehicle as well as to dust or small particles that are typically found in abundance on construction sites. To minimize the effects of vibration, three layers of one inch polyurethane foam were placed under the Montana system. To prevent dust from entering the Montana system, a dust cover was fabricated using a fine mesh material that was used to cover the safety cage enclosing the instrument. The cover acted as a filter that prevented dust from entering the Montana system but allowed adequate air to flow to it for cooling. In addition, the Montana system was checked at approximately 30 minute intervals during the data collection process to ensure that it was functioning properly.

Quality Assurance

The data quality assurance process resulted in a processed data set that contained approximately 93.2 percent of the total initial raw data. Table 2 summarizes the quality assured results for each day of data collection. On average, the total error rate leading to loss of data is approximately 6.8 percent.

The error rate for an individual test varied from 2.5 to 15 percent. The leading attributed causes of lost data are inter-analyzer discrepancies, analyzer freezing, and air leakage (which leads to very low pollutant concentrations). Data were excluded if the parallel gas analyzer concentration measurements differed by threshold values for each pollutant, if the gas analyzer failed to update on a second-by-second basis, or if oxygen levels were beyond a wide normal range leading to concentration values below detection limits for most pollutants. These three sources of errors (combined) affected approximately 6.3 percent of the raw data, thus accounting for most of the data omitted for quality assurance reasons.

Exploratory Analysis

Fuel flow rate had a rank correlation of 93 percent with MAP. The rank correlation of emission rates with MAP ranged from 44 to 93 percent, depending on the pollutant. These correlations for fuel use and emission rates were higher than for either engine RPM or IAT. Thus, MAP was found to be the most useful explanatory variable for variability in fuel use and emission rates.

Time series plots of engine data, fuel use rate, and emission rates were used to visualize the association between these rates and engine data as illustrated in Figure 1. Typically, a peak in MAP is associated with a corresponding peak in fuel use and emission rates.

Modal Emission Rates

Engine-based modal emission rates were estimated for each motor grader and separately for petroleum diesel and B20 biodiesel based on ranges of normalized MAP. An example is shown in Figure 2 on a time basis (middle graph) and on a fuel consumed basis (lower graph), for both petroleum diesel and B20 biodiesel for NO.

Typically, average fuel use and time-based emissions rates of CO_2, NO, HC, CO, and opacity increase monotonically with an increase in MAP. This is borne out in Figure 2. An increase in MAP generally indicates an increase in engine load. The lowest normalized MAP range included idling of the engine. CO_2 emissions are highly correlated with fuel use because the majority of carbon in the fuel is emitted as CO_2.

For NO, the emission rates on a per gallon basis generally decrease as MAP increases. The fuel-based NO emission rate is highest for the lowest MAP range (idling). For the eight highest MAP ranges, the fuel-based NO emission rates are approximately similar to each other. At the higher values of MAP, the fuel-based NO emission rate is approximately two-thirds of the fuel-based emission rate at idle. Of course, the rate of fuel consumption at high values of MAP is much higher than at low MAP values. Thus, the mass emission rate per unit time for NO increases with MAP because fuel flow increases significantly.

A comparison of the two fuels with respect to fuel use and emission rates for the task-oriented modal analysis is given in Figures 3 on a time and fuel basis. The idle mode is 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 NO, as well as CO_2, HC, CO, and opacity-based PM, were approximately the same for the moving and blade modes. Thus, there was little difference in fuel use and emission rates among the two non-idle modes, but there were substantial differences in emission rates and fuel use for idle versus non-idle. The task-oriented modal analysis (Figure 3) does not explain as much of the variability in fuel use and emission rates as the engine-based data (Figure 2).

In some cases, HC and CO concentrations were 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. Mean values of a data set are often robust if the mean of the data is larger than the detection limit.[25] Based on Frey et al. 2008, the detection limits for HC and CO are approximately 13 ppm and 0.012 volume-percent, respectively.[23] If the mean modal average concentration in an MAP mode is below these detection limits, there is less confidence in the stability of the mean value. The influence of non-detects is indicated in subsequent result tables.

Representative Duty Cycles

In order to compare fuel use and emission rates, cycle-average emission rates are estimated based on selected duty cycles. In Figure 4, three representative duty cycles for a motor grader are characterized by frequency distributions of normalized MAP. The resurfacing cycle has a higher average engine load than the shouldering and roading cycles, as described earlier.

The average emission rates for each of these duty cycles were estimated for each motor grader and each fuel by weighting the time-based engine-based modes using the MAP distributions. The highest five MAP modes contribute 64 percent of time and 84 percent of fuel use for the resurfacing cycle. These modes contribute somewhat less to the roading cycle, at 46 percent of time and 63 percent of fuel consumption. For the lower engine load resurfacing cycle, these modes contributed only 13 percent of time and 28 percent of fuel consumption

Average Duty Cycle Emission Factors by Fuel and Tier

Duty cycle average emission rates were estimated for each motor grader for the three duty cycles and for both tested fuels. The time-based cycle average fuel use and emission rates are given in Table 3. The fuel-based emission rates are given in Table 4.

The time-based fuel usage rates of Table 3 are sensitive to duty cycles. On average, for all six motor graders and for both fuels, there is a 85 percent larger fuel consumption rate for the high engine load resurfacing cycle compared to the low engine load resurfacing cycle. The resurfacing cycle consumes an average of 53 percent more fuel than the intermediate engine load roading cycle. The difference in the time-based CO_2 emission rates is very similar, since most of the carbon in the fuel is emitted as CO_2. The Tier 3 motor grader appears to be significantly more fuel efficient than the Tier 2 motor grader, and both are more fuel efficient than the older Tier 0 and Tier 1 motor graders. For Tier 0 and Tier 1, there is very little difference in the fuel usage rates among the four motor graders tested, for a given cycle or fuel.

For the time-based emission factors of Table 3, there are significant differences in average emission rates when comparing the duty cycles with the largest and the smallest average emission rates, which are the resurfacing and shouldering cycles, respectively. For example, the cycle average NO emission rate for the resurfacing cycle is 67 percent higher, on average, than for the shouldering cycle. The two newer motor graders, however, appear to be less sensitive to differences in duty cycles; their NO emission rates differ by only 46 percent, versus 78 percent for the four older motor graders. For opacity (or particulate matter), the average difference is 87 percent, with no consistent trend as a function of tier. For HC and CO, the average difference between the two selected cycles is 36 percent.

The inter-vehicle variability in fuel use and emission rates is estimated based on the average coefficient of variation (CV), taking into account both fuels and all three duty cycles. The CV is the standard deviation of each individual rate divided by the mean rate. For fuel use and CO_2 emission rates, the CVs are 0.26 and 0.27. For NO, the CV is 0.22. For PM, CO, and HC, the CVs are 0.31, 0.19, and 0.21, respectively. Thus, there is relatively little inter-vehicle variability in fuel use and CO_2 emission rates, moderate variability in NO and opacity based PM emission rates, and larger relative variability in the CO and HC emission rates. These results are consistent with those for specific combinations of individual duty cycles and fuels.

The inter-vehicle variability can be attributed in large part to differences in emission rates for vehicles of different engine certification tiers. These differences are shown in Table 5, which provides pairwise comparisons of engine Tiers. For example, based on comparisons to Tier 0 vehicles, the average time-based NO emission rates for the three duty cycles and both fuels are 21 percent lower for Tier 1, 32 percent lower for Tier 2, and 67 percent lower for Tier 3. For the Tier 1 and 2 vehicles, the average differences are more pronounced for the higher engine load resurfacing cycle compared to the roading and shouldering cycles (shown in Figure 5). For opacity-based PM emission rates, the percent reductions in emission rate are similar to those for NO, ranging from 12 to 60 percent for Tier 1 and Tier 3, respectively, compared to Tier 0. For HC and CO, the Tier 3 vehicle had an average emission rate that was 76 and 81 percent, respectively, lower than for Tier 0. Thus, the higher Tier vehicles have substantially lower emission rates on a time basis than the Tier 0 vehicles.

For the fuel-based emission factors shown in Table 4, there is less relative variability between the rates for the three duty cycles than for the time-based emission factors. For example, whereas the time-based emission factors for NO differ on average by 67 percent between the resurfacing and the shouldering cycles, the fuel-based NO emission factors differ by only 8.5 percent for these two cycles. Theses two cycles represent the largest difference in engine load among the three duty cycles that were observed. The opacity-based emission factors for PM differ by less than 2 percent on a fuel basis, compared to 87 percent on a time basis. For CO and HC, the fuel-based emission factors differ by 25 percent rather than 36 percent as for the time-based emission factors. Thus, the modal fuel-based emission factors are less sensitive to engine load than are the time-based modal emission factors.

There is slightly less inter-vehicle variability for the fuel-based emission factors. For example, for NO, the average CV when comparing emissions of the six tested vehicles based on the three duty cycles and both fuels is 0.07 on a fuel basis versus 0.22 on a time-basis.

The fuel-based emission factors for the higher tier engines are significantly different from those of the lower tier engines; however, Table 5 shows that the relative differences are smaller than for the time-based results. For example, comparing Tier 3 vs. Tier 0, the difference for NO is 49 percent on a fuel basis versus 67 percent on a time basis.

For the comparisons between B20 and petroleum diesel shown in Table 6, the differences in rates for fuel use and CO_2 emissions were not significant, as expected. For four of the motor graders, there was a small decrease in the NO emission rate averaged over both cycles, whereas there was a small increase for the other two motor graders. The overall average difference of only -1.6 percent is not considered to be significant. However, the small decrease observed here is consistent with expectations of lower real world NO_x emissions associated with B20 from a B100 blend stock compliant with the ASTM standard.[5, 6] For the CO, HC, and opacity-based PM emission factors, average decreases were observed for all vehicles, with an overall average reduction of 22 percent in PM and 20 percent in HC, and 19 percent in CO. These reductions are approximately as expected.

Benchmark Comparison of Fuel Consumption Rates

The results of benchmark comparisons of fuel consumption rates from the PEMS data versus owner records are summarized in Table 7. The Tier 3 motor grader was acquired by the fleet owner in April 2007 and was tested as soon as it was placed in service. Thus, this vehicle does not have historical fuel use data.

The annual average fuel use rates range from 1.6 to 5.7 gallons per hour based on owner records. The variability is most likely because of differences in the engine model year and duty cycles. However, the duty cycles performed by each vehicle are not recorded in owner records.

The observed average fuel consumption rate based on one day of testing using the PEMS ranges from 1.9 to 4.8 gallons per hour. Thus, there is substantial overlap in the two fuel consumption data sets. For the five tested motor graders for which owner records are available, the average fuel consumption rates from the PEMS agreed to within approximately plus-or-minus 20 percent per vehicle and the average fuel consumption rate among all 5 vehicles agrees exactly. Given that this comparison involves annual average versus short term average values for the owner records and field data, respectively, the similarity of the results is remarkable.

MG 0a was found to have systematically lower fuel consumption than the others based on both the fleet records and the PEMS data. This motor grader is the oldest among the six tested. It has one of the lower horsepower ratings among the vehicles tested and operated with a relatively low range of MAP during the field tests compared to the other motor graders. The newest Tier 3 motor grader appears to be more fuel efficient than the Tier 1 and 2 motor graders.

Benchmark of Measured Emission Rates versus the NONROAD Model

The ranges of the fuel-based emissions from the field data were compared with similar estimates based on the data used in the NONROAD model, as summarized in Table 8. The NONROAD estimates are based on the same model year and engine size range as the measured motor graders. The ranges of data are influenced by variability between engine tiers. For example, the PEMS NO emission factor of 133 g/gallon is for a Tier 0 motor grader (MG 0b), whereas the 65 g/gallon emission factor is for the Tier 3 motor grader (MG3). As engine tier increases, the emission factors decrease, as shown in Figure 6.

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; however, they are much lower in magnitude for PM. 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.

The PEMS and NONROAD–based emission factors have a consistent trend for a given pollutant with respect to engine tier. For example for the NO_x emission rate, the highest values are observed for Tier 0, the lowest values are observed for Tier 3, and there is a monotonic decrease as Tier increases. The same trend is observed for PM and CO. For HC, there is little difference between Tier 0 and Tier 1 for the PEMS results, but the PEMS emission factors decrease monotonically for Tier 2 and Tier 3. The observed CO emission rates in the field are significantly lower than those predicted using NONROAD.

CONCLUSIONS

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 inter-vehicle variability and duty cycles 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 PM, HC, and CO. These results are approximately as expected. Therefore, the use of B20 is expected to lead to real world reductions in emission rates for PM, HC, and CO, and no significant change in NO_x emission rates. Other biodiesel blends, such as B30 or B40, which may offer even larger tailpipe emission reductions, should be assessed and compared.

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, a fleet owner can claim tailpipe emissions benefits by using B20 fuel, or replacing older vehicles with newer ones, or both.

There is relatively little inter-vehicle variability in fuel use and CO_2 emission rates, moderate variability in NO and opacity, and larger relative variability in the CO and HC emission rates. The inter-vehicle variability can be attributed in large part to differences in emission rates for vehicles of different engine certification tiers. The higher Tier vehicles have substantially lower emission rates on a time basis than the Tier 0 vehicles.

The fuel-based 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. The trends in emission factors versus engine tiers based on the PEMS data are qualitatively consistent with expectations based on the NONROAD model. Time-based emission factors are highly sensitive to duty cycles and inter-vehicles variability.

The study approach can be extended to other commonly used nonroad vehicles and equipment, such as bulldozers, front-end loaders, backhoes, excavators, compactor rollers, generator sets, skid-steer loaders, cement mixers, compressors, and tractors. Emissions and vehicle activity results from these additional types of vehicles will help to develop real-world duty cycles and emission factors for nonroad vehicles. Real-world fuel-based emission factors offer a more robust basis for emission inventory development than g/bhp-hr emission factors currently used in the NONROAD model. Thus, as the new MOVES model is developed for nonroad vehicles, consideration should be given to a fuel-based approach.

Finally, the results here demonstrate that real-world PEMS data can be used in accountability assessments to verify the real-world effectiveness of fuels and technologies intended to reduce emissions. For example, these results verify that more stringent engine certification tier standards are leading to substantial real world reductions in emissions, thereby providing independent confirmation of the impact of these standards. Therefore, the use of the real-world PEMS data collection and analysis methodology demonstrated here is recommended for use by government agencies, fleet owners, and other stakeholders as an independent check on regulatory effectiveness, as well as to assess compliance with “green” requirements imposed contractually for some projects or by independent certification organizations.

DISCLAIMER

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

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Table 1. Vehicle Information and Test Conditions for the Tested Motor Graders

<table>
<tr><th rowspan="2"></th><th rowspan="2">Description</th><th colspan="12">Motor Graders</th></tr>
<tr><th colspan="2">MG 0a</th><th colspan="2">MG 0b</th><th colspan="2">MG 1a</th><th colspan="2">MG 1b</th><th colspan="2">MG 2</th><th colspan="2">MG 3</th></tr>
<tr><td rowspan="5">Chassis</td><td>Manufacturer</td><td colspan="2">Dresser</td><td colspan="2">Champion</td><td colspan="2">Volvo</td><td colspan="2">Volvo</td><td colspan="2">Volvo</td><td colspan="2">Volvo</td></tr>
<tr><td>Model</td><td colspan="2">850</td><td colspan="2">G720</td><td colspan="2">G720VHP</td><td colspan="2">G720VHP</td><td colspan="2">G720B</td><td colspan="2">G930</td></tr>
<tr><td>Year</td><td colspan="2">1990</td><td colspan="2">1993</td><td colspan="2">2001</td><td colspan="2">2001</td><td colspan="2">2004</td><td colspan="2">2007</td></tr>
<tr><td>GVW (lbs)</td><td colspan="2">37,000</td><td colspan="2">37,000</td><td colspan="2">37,000</td><td colspan="2">37,000</td><td colspan="2">37,000</td><td colspan="2">37,000</td></tr>
<tr><td>Blade Length (yd)</td><td colspan="2">4</td><td colspan="2">4</td><td colspan="2">4</td><td colspan="2">4</td><td colspan="2">4</td><td colspan="2">4</td></tr>
<tr><td rowspan="10">Engine</td><td>Manufacturer</td><td colspan="2">Dresser</td><td colspan="2">Cummins</td><td colspan="2">Cummins</td><td colspan="2">Cummins</td><td colspan="2">Volvo</td><td colspan="2">Volvo</td></tr>
<tr><td>Model</td><td colspan="2">D505T</td><td colspan="2">6C8.3</td><td colspan="2">6C8.3</td><td colspan="2">6C8.3</td><td colspan="2">D7DGBE2</td><td colspan="2">D7</td></tr>
<tr><td>Year</td><td colspan="2">1990</td><td colspan="2">1993</td><td colspan="2">2001</td><td colspan="2">2001</td><td colspan="2">2004</td><td colspan="2">2007</td></tr>
<tr><td>Engine Tier</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td></tr>
<tr><td>Aspiration</td><td colspan="2">Turbocharged</td><td colspan="2">Turbocharged</td><td colspan="2">Turbocharged</td><td colspan="2">Turbocharged</td><td colspan="2">Turbocharged</td><td colspan="2">Turbocharged</td></tr>
<tr><td>Displacement</td><td colspan="2">8.27</td><td colspan="2">8.27</td><td colspan="2">8.27</td><td colspan="2">8.27</td><td colspan="2">7.1</td><td colspan="2">7.2</td></tr>
<tr><td>Cylinders</td><td colspan="2">6</td><td colspan="2">6</td><td colspan="2">6</td><td colspan="2">6</td><td colspan="2">6</td><td colspan="2">6</td></tr>
<tr><td>Horsepower</td><td colspan="2">167</td><td colspan="2">160</td><td colspan="2">195</td><td colspan="2">195</td><td colspan="2">195</td><td colspan="2">198</td></tr>
<tr><td>Rated RPM</td><td colspan="2">2,500</td><td colspan="2">2,200</td><td colspan="2">2,200</td><td colspan="2">2,200</td><td colspan="2">2,200</td><td colspan="2">2,100</td></tr>
<tr><td>Accumulated Hours</td><td colspan="2">440</td><td colspan="2">4,554</td><td colspan="2">4,367</td><td colspan="2">3,044</td><td colspan="2">841</td><td colspan="2">3</td></tr>
<tr><td rowspan="4">Test Condition</td><td>Test Fuel [a]</td><td>PD</td><td>B20</td><td>PD</td><td>B20</td><td>PD</td><td>B20</td><td>PD</td><td>B20</td><td>PD</td><td>B20</td><td>PD</td><td>B20</td></tr>
<tr><td>Temperature (°F)</td><td>73</td><td>45</td><td>35</td><td>60</td><td>48</td><td>48</td><td>75</td><td>87</td><td>47</td><td>64</td><td>83</td><td>86</td></tr>
<tr><td>Humidity (%)</td><td>44</td><td>37</td><td>39</td><td>72</td><td>43</td><td>38</td><td>54</td><td>63</td><td>42</td><td>44</td><td>42</td><td>56</td></tr>
<tr><td>Duty Cycle [b]</td><td>RS</td><td>SH</td><td>SH</td><td>SH</td><td>RS</td><td>RS</td><td>SH</td><td>SH</td><td>SH</td><td>SH</td><td>RS</td><td>RS</td></tr>
</table>

[a] PD = Petroleum Diesel; B20 = B20 Biodiesel

[b] RS= Resurfacing Cycle; SH = Shouldering Cycle

Table 2. Rate of Loss of Data Because of Data Quality Errors

ID	Fuel	Raw [a] (sec)	Amount of Data Lost for a Specific Type of Error (sec) [b]							Error [c] (%)	QA Data [d] (sec)
			1	2	3	4	5	6	7		
MG 0a	PD	11,500	0	60	641	469	238	52	0	13	10,040
	B20	14,304	0	48	541	418	156	0	3	8.2	13,138
MG 0b	PD	10,602	20	16	404	349	24	0	0	7.7	9,789
	B20	14,606	0	22	283	106	38	0	9	3.1	14,148
MG 1a	PD	16,348	10	83	166	284	78	0	0	3.8	15,727
	B20	19,532	0	92	397	126	317	153	0	5.6	18,447
MG 1b	PD	7,860	0	37	42	64	54	0	0	2.5	7,663
	B20	13,415	0	35	229	389	19	8	2	5.1	12,733
MG 2	PD	12,205	0	52	150	201	92	0	6	4.1	11,704
	B20	17,713	13	11	493	2,135	62	0	0	15	14,999
MG 3	PD	9,262	0	0	293	188	94	0	0	6.2	8,687
	B20	9,500	0	0	203	167	38	0	0	4.3	9,092
Overall											
Total Seconds		156,847	43	456	3,842	4,896	1,210	213	20	-	146,167
Percentage of raw data (%)			0.03	0.29	2.4	3.1	0.77	0.14	0.01	6.8	93.2

[a] Total Initial Raw Data

[b] Definition of Errors

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

[c] Average Error Rate

[d] Quality Assured Data

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

Fuel Use and Emissions	Engine Type	Test ID	B20 Biodiesel			Petroleum Diesel		
			RS [a]	**RD** [b]	**SH** [c]	**RS** [a]	**RD** [b]	**SH** [c]
Fuel Use (g/sec)	Tier 0	MG 0a	5.4	4.6	3.0	5.8	4.8	3.1
		MG 0b	5.5	4.5	2.9	5.6	4.7	3.0
		Average	**4.3**			**4.5**		
	Tier 1	MG 1a	5.3	4.4	2.9	5.3	4.4	3.1
		MG 1b	5.4	4.5	2.9	5.4	4.4	2.9
		Average	**4.2**			**4.3**		
	Tier 2	MG 2	5.0	4.4	2.9	5.0	4.3	2.9
		Average	**4.1**			**4.1**		
	Tier 3	MG 3	4.0	3.1	2.0	4.0	3.2	2.0
		Average	**3.0**			**3.1**		
CO_2 (g/sec)	Tier 0	MG 0a	17	14	9.2	18	15	9.7
		MG 0b	17	14	8.9	18	15	9.3
		Average	**13**			**14**		
	Tier 1	MG 1a	16	14	9.1	17	14	9.6
		MG 1b	17	14	9.1	17	14	8.9
		Average	**13**			**13**		
	Tier 2	MG 2	16	14	8.9	16	14	9.0
		Average	**13**			**13**		
	Tier 3	MG 3	12	9.6	6.1	13	10	6.3
		Average	**9.2**			**9.8**		
NO as NO_2 (mg/sec) [d]	Tier 0	MG 0a	209	176	112	242	192	125
		MG 0b	238	187	123	236	183	130
		Average	**174**			**185**		
	Tier 1	MG 1a	163	140	100	174	145	110
		MG 1b	185	155	103	175	140	103
		Average	**141**			**141**		
	Tier 2	MG 2	145	130	98	141	125	96
		Average	**124**			**121**		
	Tier 3	MG 3	68	60	49	72	58	48
		Average	**59**			**59**		
Opacity-based PM (mg/sec)	Tier 0	MG 0a	1.4	1.2	0.64	1.7	1.3	0.75
		MG 0b	1.4	1.2	0.78	1.8	1.6	1.0
		Average	**1.1**			**1.4**		
	Tier 1	MG 1a	1.2	1.0	0.71	1.7	1.2	0.75
		MG 1b	1.1	0.86	0.52	1.8	1.1	1.0
		Average	**0.90**			**1.3**		
	Tier 2	MG 2	0.70	0.64	0.50	0.97	0.86	0.59
		Average	**0.61**			**0.81**		
	Tier 3	MG 3	0.53	0.47	0.31	0.67	0.57	0.38
		Average	**0.44**			**0.54**		

(Continued on the next page)

Table 3. Continued

Fuel Use and Emissions	Engine Type	Test ID	B20 Biodiesel			Petroleum Diesel		
			RS [a]	**RD [b]**	**SH [c]**	**RS [a]**	**RD [b]**	**SH [c]**
HC (mg/sec)	Tier 0	MG 0a	22	20	16	28	25	21
		MG 0b	20	17	15	21	21	16
		Average	**18**			**22**		
	Tier 1	MG 1a	19	16	11	22	21	16
		MG 1b	20	19	15	28	25	17
		Average	**17**			**22**		
	Tier 2	MG 2 [d]	12	11	8.8	14	15	13
		Average	**11**			**14**		
	Tier 3	MG 3 [e]	4.7	4.6	3.6	5.5	6.1	4.8
		Average	**4.3**			**5.5**		
CO (mg/sec)	Tier 0	MG 0a	37	35	34	47	43	34
		MG 0b	28	28	27	42	44	42
		Average	**32**			**42**		
	Tier 1	MG 1a	20	17	14	20	18	15
		MG 1b	19	17	14	25	22	14
		Average	**17**			**19**		
	Tier 2	MG 2 [e]	13	14	12	13	15	14
		Average	**13**			**14**		
	Tier 3	MG 3 [f]	6.1	6.5	3.4	12	8.6	5.6
		Average	**5.3**			**8.7**		

[a] RS: Resurfacing Cycle
[b] SH: Shouldering Cycle
[c] RD: Roading Cycle
[d] NO emissions are corrected based on the ambient temperature and humidity given in Table 1.
[e, f] The average emission factor in shaded table cell is based on a high proportion of data below the gas analyzer detection limit.

Table 4. Average Measured Fuel-Based Emission Factors for Selected Motor Graders: Comparison of Tiers, Fuels, and Duty Cycles

Emissions	**Engine Type**	**Test ID**	**B20 Biodiesel**			**Petroleum Diesel**		
			RS [a]	**RD** [b]	**SH** [c]	**RS** [a]	**RD** [b]	**SH** [c]
NO as NO_2 (g/gallon) [c]	Tier 0	MG 0a	125	124	121	134	127	126
		MG 0b	140	133	136	136	123	139
		Average	**130**			**131**		
	Tier 1	MG 1a	99	101	109	104	105	113
		MG 1b	111	110	114	105	102	115
		Average	**107**			**107**		
	Tier 2	MG 2	94	95	110	90	92	106
		Average	**100**			**96**		
	Tier 3	MG 3	57	62	82	59	58	77
		Average	**67**			**65**		
Opacity-based PM (g/gallon)	Tier 0	MG 0a	0.81	0.86	0.69	0.93	0.86	0.77
		MG 0b	0.88	0.87	0.86	1.0	1.1	1.1
		Average	**0.83**			**0.96**		
	Tier 1	MG 1a	0.72	0.74	0.78	0.86	0.88	0.90
		MG 1b	0.66	0.61	0.56	0.80	0.80	0.80
		Average	**0.68**			**0.84**		
	Tier 2	MG 2	0.44	0.47	0.55	0.62	0.63	0.65
		Average	**0.49**			**0.63**		
	Tier 3	MG 3	0.43	0.48	0.52	0.53	0.56	0.61
		Average	**0.48**			**0.57**		
HC (g/gallon)	Tier 0	MG 0a	13	14	17	16	17	21
		MG 0b	12	12	17	12	14	17
		Average	**14**			**16**		
	Tier 1	MG 1a	12	11	11	13	15	17
		MG 1b	12	13	17	17	18	19
		Average	**13**			**17**		
	Tier 2	MG 2 [d]	7.6	8.4	9.7	9.2	11	15
		Average	**8.6**			**12**		
	Tier 3	MG 3 [e]	4.0	4.8	6.0	4.5	6.1	7.9
		Average	**4.9**			**6.2**		
CO (g/gallon)	Tier 0	MG 0a	23	25	33	27	28	34
		MG 0b	17	20	30	26	30	46
		Average	**25**			**32**		
	Tier 1	MG 1a	12	12	15	12	13	15
		MG 1b	12	12	16	15	16	16
		Average	**13**			**15**		
	Tier 2	MG 2 [d]	8.3	11	14	8.5	11	15
		Average	**11**			**12**		
	Tier 3	MG 3 [e]	4.9	6.7	5.8	9.3	8.5	8.7
		Average	**5.8**			**8.8**		

[a] RS: Resurfacing Cycle

[b] SH: Shouldering Cycle

[c] RD: Roading Cycle

[d] NO emissions are corrected based on ambient temperature and humidity given in Table 1.

[e, f] The average emission factor in shaded table cell is based on a high proportion of data below the gas analyzer detection limit.

Table 5. Percent Changes (%) in Time- and Fuel-Based Emission Factors between Engine Tiers for Selected Motor Graders

Engine Tiers	NO as NO_2		Opacity-based PM		HC		CO	
	Time [a]	Fuel [b]	Time [a]	Fuel [b]	Time [a]	Fuel [b]	Time [a]	Fuel [b]
Tier 1 vs Tier 0	-21	-18	-12	-15	-5.4	-3.8	-51	-51
Tier 2 vs Tier 0	-32	-25	-42	-37	-39	-33	-63	-60
Tier 3 vs Tier 0	-67	-49	-60	-42	-76	-63	-81	-74
Tier 2 vs Tier 1	-13	-8.9	-34	-26	-36	-30	-25	-18
Tier 3 vs Tier 1	-58	-39	-55	-31	-74	-62	-61	-47
Tier 3 vs Tier 2	-52	-33	-31	-6.8	-60	-45	-48	-35

[a] Time-Based Emission Factor, averages over three duty cycles and two fuels

[b] Fuel-Based Emission Factor, averages over three duty cycles and two fuels

Table 6. Percent Differences (%) in B20 Biodiesel vs. Petroleum Diesel Fuel Use Rates and Emission Factors for Each Motor Grader

Fuel Use and Emissions	Test ID	RS[a]	RD[b]	SH[c]	Avg[d]	Fuel Use and Emissions	Test ID	RS[a]	RD[b]	SH[c]	Avg[d]
Fuel Use	MG 0a	-6.9	-4.2	-3.2	-4.8	Opacity-based PM	MG 0a	-18	-7.7	-15	-13
	MG 0b	-1.8	-4.3	-3.3	-3.1		MG 0b	-22	-25	-22	-23
	MG 1a	0.0	0.0	-6.5	-2.2		MG 1a	-29	-17	-5.3	-17
	MG 1b	0.0	2.3	0.0	0.76		MG 1b	-39	-22	-48	-36
	MG 2	0.0	2.3	0.0	0.78		MG 2	-28	-26	-15	-23
	MG 3	0.0	-3.1	0.0	-1.0		MG 3	-21	-18	-18	-19
	Overall Average				**-1.6**		**Overall Average**				**-22**
CO_2	MG 0a	-5.6	-6.7	-5.2	-5.8	HC	MG 0a	-21	-20	-24	-22
	MG 0b	-5.6	-6.7	-4.3	-5.5		MG 0b	-4.8	-19	-6.3	-10
	MG 1a	-5.9	0.0	-5.2	-3.7		MG 1a	-14	-24	-31	-23
	MG 1b	0.0	0.0	2.2	0.75		MG 1b	-29	-24	-12	-21
	MG 2	0.0	0.0	-1.1	-0.37		MG 2	-14	-27	-32	-24
	MG 3	-7.7	-4.0	-3.2	-5.0		MG 3	-15	-25	-25	-21
	Overall Average				**-3.3**		**Overall Average**				**-20**
NO as NO_2	MG 0a	-14	-8.3	-10	-11	CO	MG 0a	-21	-19	0.0	-13
	MG 0b	0.85	2.2	-5.4	-0.78		MG 0b	-33	-36	-36	-35
	MG 1a	-6.3	-3.4	-9.1	-6.3		MG 1a	0.0	-5.6	-6.7	-4.1
	MG 1b	5.7	11	0.0	5.5		MG 1b	-24	-23	0.0	-16
	MG 2	2.8	4.0	2.1	3.0		MG 2	0.0	-6.7	-14	-7.0
	MG 3	-5.6	3.4	2.1	-0.01		MG 3	-49	-24	-39	-38
	Overall Average				**-1.6**		**Overall Average**				**-19**

[a] RS: Resurfacing Cycle

[b] SH: Shouldering Cycle

[c] RD: Roading Cycle

[d] Avg: Average

Table 7. Comparison of Measured Fuel Use Rates Versus Owner Records for Selected Motor Graders and Fuels

Vehicle ID [a]	Engine			Test Fuel	Fuel Consumption Rate (gal/hr)			MAP Range (kPa)
	Tier	Horsepower (*hp*)	Size (*l*)		Fleet Owner [b]	PEMS	Diff (%) [c]	
MG 0a	0	167	8.3	B20	1.6	1.9	19	96-188
MG 0b	0	160	8.3	PD	4.2	4.8	14	96-201
MG 1a	1	195	8.3	B20	4.6	4.6	0.0	102-243
MG 1b	1	195	8.3	B20	4.3	4.7	9.3	96-223
MG 2	2	198	7.1	PD	5.7	4.4	-23	101-246
MG 3	3	198	7.2	B20	N/A	3.3	N/A	97-290
Average of MG 0a to MG 2					4.1	4.1	0.0	

[a] All 6 motor graders are 37,000 lbs. GVW.

[b] These fuel consumption rates are averages over 3 years, including 2004, 2005, and 2006.

[c] Percent difference in observed fuel consumption rate versus the rate estimated based on the owner records.

Table 8. Comparison of Emission Rates from Selected Motor Graders Based on Real-World Tests and EPA's NONROAD Model Based on Petroleum Diesel

Vehicle ID	Engine Tier	NO_x (g/gallon) [a]		PM (g/gallon)		HC (g/gallon)		CO (g/gallon)	
		PEMS [b]	EPA [c]	PEMS [b]	EPA [c]	PEMS [b]	EPA [c]	PEMS [b]	EPA [c]
MG 0a	0	129	158	0.85	17	18	15	30	108
MG 0b	0	133	157	1.1	15	14	15	34	103
MG 1a	1	107	102	0.88	6.2	15	6.3	13	23
MG 1b	1	107	102	0.80	6.2	18	6.3	16	23
MG 2	2	96	72	0.63	2.4	12	6.2	12	22
MG 3	3	65	49	0.57	2.0	6.2	3.6	8.8	22
Overall		65–133	49–158	0.57–1.1	2.0–17	6.2–18	3.6–15	8.8–34	22–108

[a] NO_x emission rates were corrected for the ambient temperature and humidity based on U.S. EPA 2003 (40 CFR I Section 86.1342-90, 2003).[26]

[b] The PEMS field measurement data are based on petroleum diesel for the resurfacing duty cycle.

[c] Estimates based on EPA's NONROAD model based on petroleum diesel. These estimates were converted from g/bhp-hr to g/gallon using an estimate of brake specific fuel consumption (BSFC) of 0.37067 lb/bhp-hr.[2]

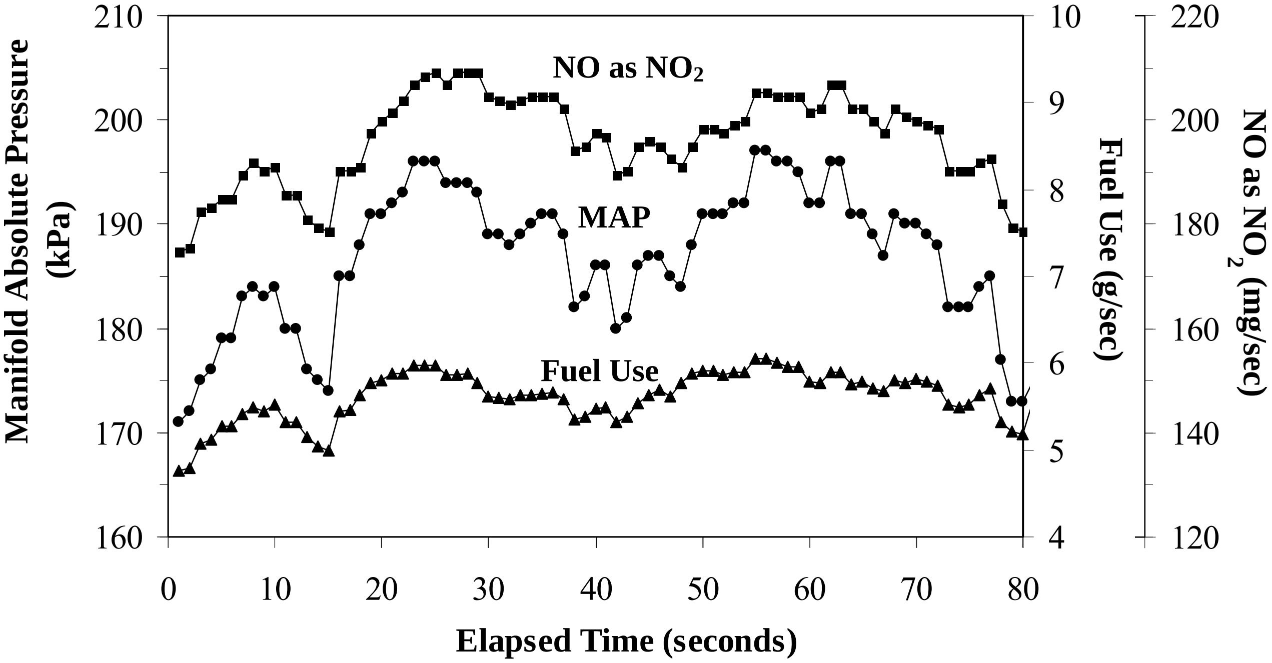
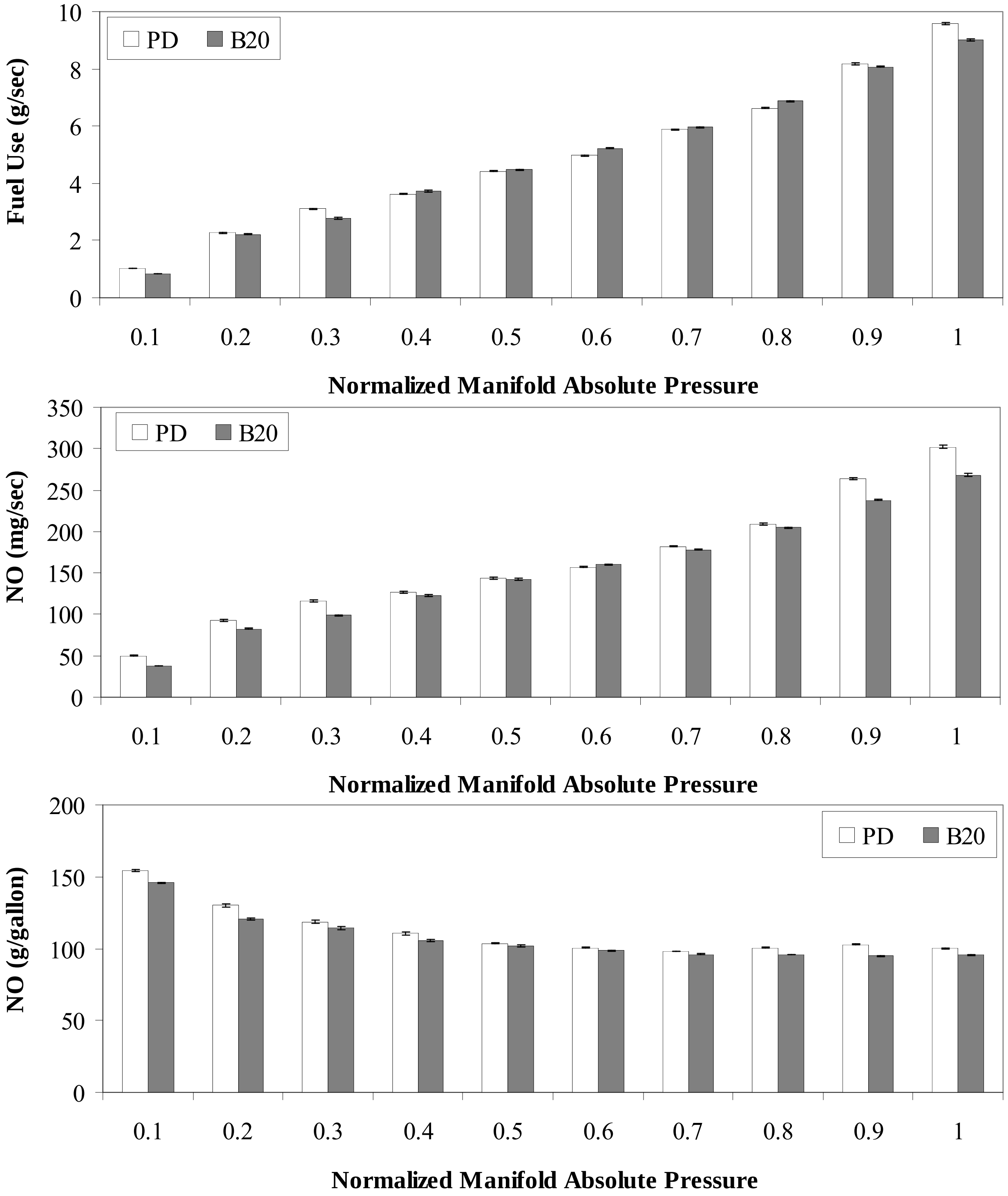
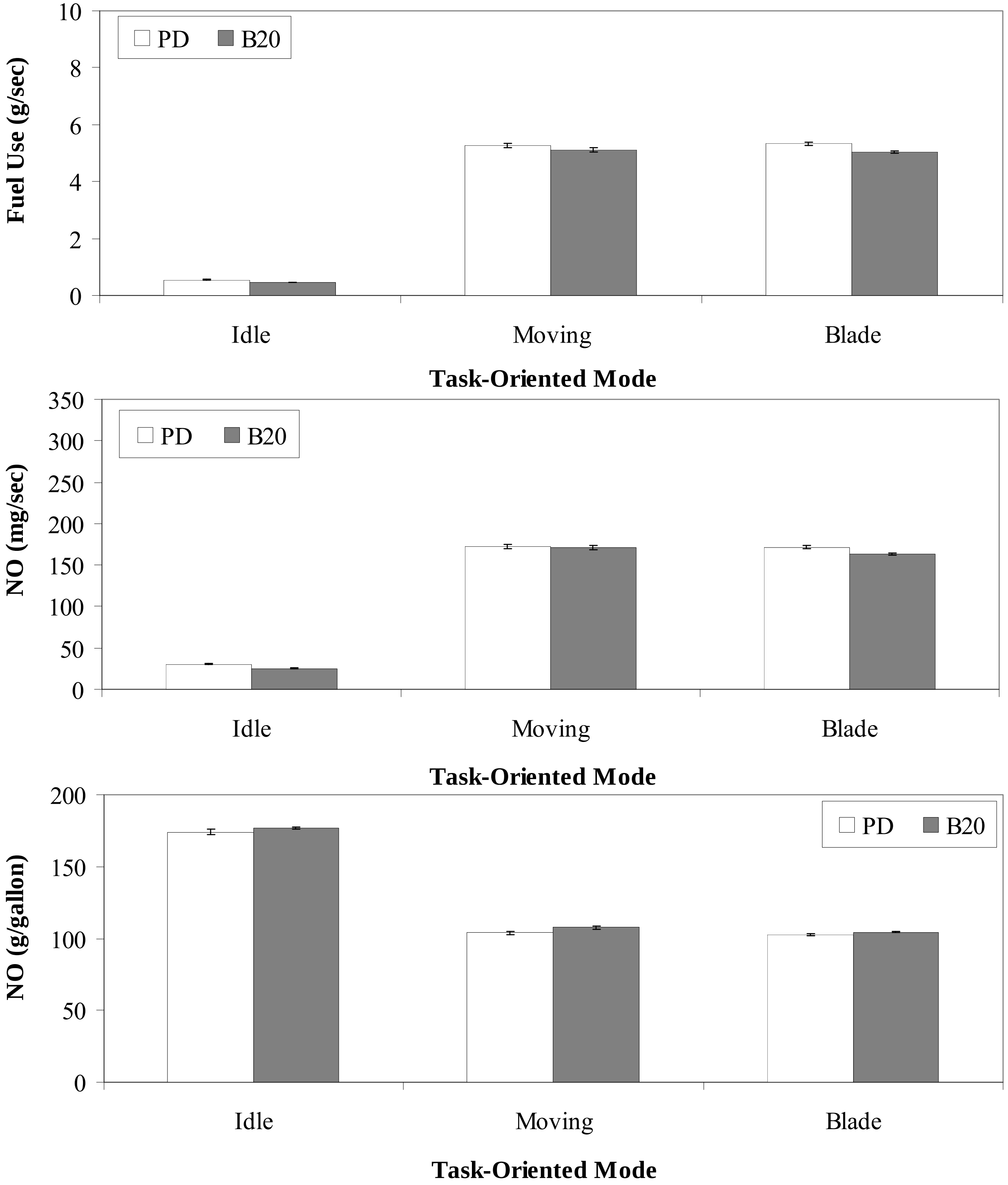


Figure 1. Example of a Time Series Plot of Manifold Absolute Pressure, Fuel Use, and NO (as NO_2) Emissions for Motor Grader 1a Fueled with B20 Biodiesel



NO emissions are corrected based on the ambient temperature and humidity given in Table 1.
Values shown in the figure are the upper end of each MAP range: e.g., “0.1” = 0 ≤ Normalized MAP < 0.1; “0.2” = 0.1 ≤ Normalized MAP < 0.2, and so on.

Figure 2. Example of Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and NO (as NO_2) Emission Rates on a Per Time and on a Gallon of Fuel Consumed Basis for Engine-Based Modes for Motor Grader 1a



NO emissions are corrected based on the ambient temperature and humidity given in Table 1.

Idle	: Engine on, but the vehicle is not working or moving
Moving	: Movement of the motor grader when the blade is not in contact with the ground (forward or backward)
Blade	: Movement of the motor grader when the blade is in contact with the ground.

Figure 3. Example of Comparison Between Petroleum Diesel and B20 Biodiesel of Average Fuel Use and NO (as NO_2) Emission Rates on a Per Time and on a Gallon of Fuel Consumed Basis for Task-Oriented Based Modes for Motor Grader 1a

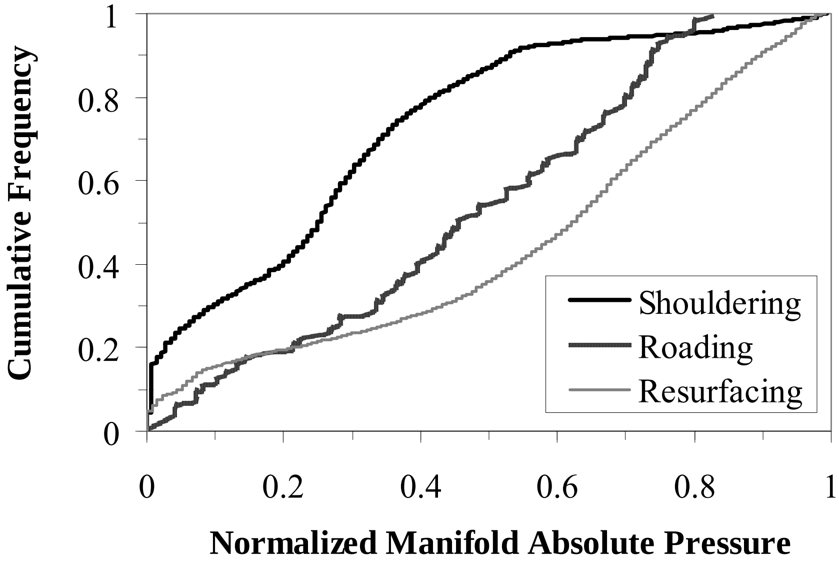


Figure 4. Cumulative Frequency Distribution of Normalized Manifold Absolute Pressure for Three Representative Duty Cycles for a Motor Grader

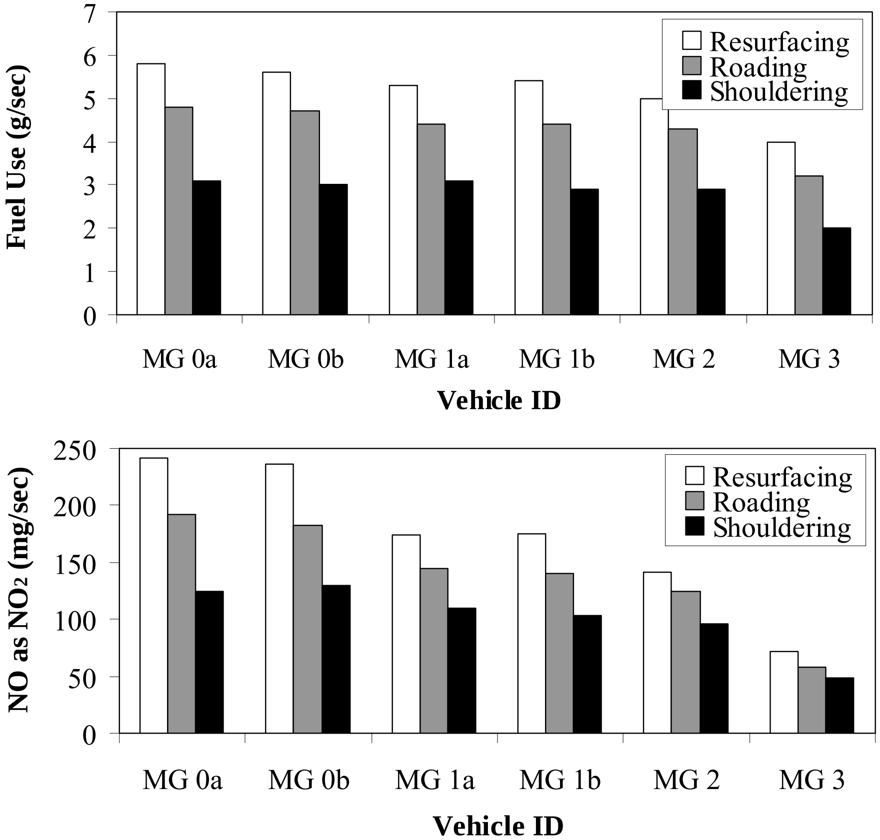


Figure 5. Example of Inter-Cycle and Inter-Vehicle Variability in Mass Per Time Rates for Fuel Use Rates and NO (as NO_2) Emission Factors

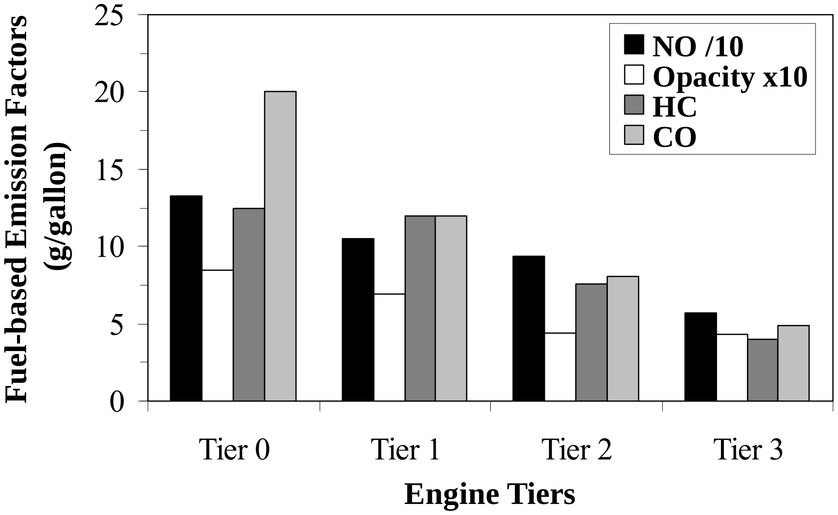


Figure 6. Fuel-Based Emission Factors Based on PEMS Data by Engine Tiers Fueled with B20 Biodiesel and Resurfacing Duty Cycle