BENCHMARKING FUEL USE AND EMISSION RATES FOR HEAVY DUTY DIESEL HIGHWAY MAINTENANCE EQUIPMENT

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ABSTRACT
Many public agencies rely on heavy duty diesel equipment to perform highway maintenance activities. This equipment consumes large quantities of diesel fuel and consequently emits substantial amounts of air pollution, thus posing a significant energy and environmental impact for the nation. In hopes of minimizing these impacts, some public fleet owners have turned to biodiesel as an alternative to traditional diesel fuel to reduce petroleum consumption as well as air pollutant emissions. The primary goal of this paper is to present real world HDD equipment fuel use rates and emission rates of nitrogen oxides, hydrocarbons, particulate matter, carbon monoxide, and carbon dioxide. These fuel use and emissions rates were based on second-by-second data collected by a portable emissions measurement system from five backhoes, six motor graders, and four wheel loaders as they performed real world activities. The primary output of this paper is a dataset of real world fuel use and emissions rates that are categorized by pollutant type, equipment type, EPA Engine Tier standards, and fuel type (including conventional petroleum diesel and B20 biodiesel). The intended purpose of this dataset is for public fleet owners to use it as a benchmark for comparison to their own equipment fuel use and emissions performance in order to make informed decisions regarding the energy and environmental impacts of their fleets.

INTRODUCTION

Infrastructure maintenance operations and management are major activities of public equipment fleet owners. Their fleets consist of numerous units of nonroad heavy-duty diesel (HDD) equipment. These fleets consume large quantities of diesel fuel and thus emit large quantities of pollutants and greenhouse gases; thus, the energy and environmental impacts of maintenance operations are significant.

In the past, most fleet managers seldom concerned themselves with the environmental impact of their equipment, specifically air pollutant emissions. As new environmental regulations appear on the horizon, fleet managers can no longer afford to disregard the energy and environmental impacts of their work. They must be able to quantify the fuel use and emissions of their equipment in order to manage them. Furthermore, some fleet owners are investigating using alternative fuels, such as biodiesel, to reduce their dependence on traditional diesel fuel.

The objective of this paper is to compare the pollutant emissions rates of biodiesel and petroleum diesel (referred to simply as diesel) for HDD equipment used for highway maintenance operations. The primary research question for this paper is: Does biodiesel offer reductions in emissions of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM) compared to conventional diesel fuel when used in the same equipment? Specific research questions that are addressed include:

- How do mass per time and mass per fuel used pollutant emissions rates compare for biodiesel versus diesel when categorized by equipment type?
- How do mass per time and mass per fuel used emissions rates compare for biodiesel versus diesel when categorized by engine tier classification?
- What is the percentage change (increase or decrease) in pollutant emissions rates for biodiesel versus diesel?

Background

According to the United States Environmental Protection Agency (EPA), there are approximately two million items of nonroad HDD construction and mining equipment in the United States *(1)*. This equipment consumes about six billion gallons of diesel fuel annually. EPA also estimates that in 2005, HDD construction equipment emitted approximately 657,000 tons of nitrogen oxides (NO_x), 1,100,000 tons of carbon monoxide (CO), and 63,000 tons of particulate matter (PM). Each of these pollutants is a criteria pollutant as designated by the EPA National Ambient Air Quality Standards (NAAQS) *(2)*. Other pollutants found in diesel exhaust include hydrocarbons (HC), which is a precursor to ground level ozone (another NAAQS criteria pollutant). Although not a regulated pollutant, carbon dioxide (CO_2) is perhaps the most recognized emission from HDD equipment because of its notoriety as a greenhouse gas and its potential global warming effect.

Diesel emissions have numerous impacts on human health and the environment. Diesel exhaust may lead to serious health conditions, including asthma and allergies, and can worsen heart and lung disease, especially in vulnerable populations like children and the elderly. PM and NO_x emissions lead to the formation of smog and acid rain which damage plants, animals, crops, and water resources. CO_2 is a major GHG emission that leads to climate change, which affects air quality, weather patterns, sea level, ecosystems, and agriculture. Reducing GHG emissions from diesel engines through improved fuel economy and idle reduction strategies can help address climate change, improve the nation's energy security, and strengthen the economy.

Another concern with diesel emissions is environmental justice. It is possible that many minority and disadvantaged populations may receive disproportionate impacts from diesel emissions *(3)*.

Fleet owners are increasingly considering alternative fuels such as biodiesel to reduce their dependence on foreign oil and to mitigate the environmental impacts associated with traditional diesel fuel. In order to quantify and characterize both biodiesel and diesel emissions, real-world data are needed; however, most fuel use and emissions estimates are based on engine dynamometer data. Although engine dynamometer testing is a reliable source of data, it is performed in a laboratory setting and does not accurately represent the episodic nature of real-world equipment activity. The data presented in this paper are based on real-world data collected from in use HDD equipment by an on-board portable emissions measurement system (PEMS).

Scope

The equipment of interest in this paper includes backhoes, motor graders, and wheel loaders. These types of equipment were selected because they are often used for many highway maintenance operations and are frequently the most represented units in a highway maintenance fleet. The case study equipment fleet was owned by the North Carolina Department of Transportation (NCDOT). The fleet was observed performing activities such as light grading, fine grading, excavating, and hauling materials for highway maintenance operations. Real-world fuel use and emissions data were collected for this equipment for both B20 biodiesel and diesel fuels.

RELATED WORK

The most prominent and well-documented dataset of real-world fuel use and emissions measurements from off-road HDD equipment was developed by researchers at North Carolina State University (NC State) from 2005 through 2008. This dataset is widely considered to be the largest publicly-available source of real-world fuel use and emissions data for nonroad construction equipment. The research team utilized PEMS testing to collect, analyze, and characterize real-world engine, fuel use, and emissions data from over thirty items of HDD equipment. The equipment types included backhoes, bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders. For 15 items of equipment, the team made comparisons of pollutant emissions for petroleum diesel versus B20 biodiesel.

Numerous papers were published based on the aforementioned dataset. Lewis *et al. (4)* outlined requirements and incentives for reducing air pollutant emissions from construction equipment. The authors also compared sources of emissions from various types of equipment. Based on those concepts, Lewis *et al. (5)* developed a fuel use and emissions inventory for a publicly-owned fleet of nonroad diesel construction equipment. This emissions inventory quantified emissions of NO_x, HC, CO, and PM for the fleet for both petroleum diesel and B20 biodiesel. The results were categorized by equipment type and EPA engine tier standards. The impact on the inventory of different emissions reduction strategies were compared. Frey *et al. (6)* followed up on this work by presenting the results of a comprehensive field study that characterized and quantified real-world emission rates of NO_x, HC, CO, and PM from nonroad diesel construction equipment. Average emission rates were developed for each equipment type and were presented on a mass per time and mass per fuel used basis for both petroleum diesel and B20 biodiesel. Frey *et al*. *(7)* conducted a comparison of B20 versus petroleum diesel emissions for backhoes, motor graders, and wheel loaders working under real-world conditions.

This paper also compared emission rates for the different EPA engine tier standards of the equipment.

Lewis *et al. (8-10)* published a series of papers on the impacts of idling on equipment fuel use and emission rates. These papers quantified the change in total activity fuel use and emissions as the ratio of idle time to non-idle time changes. The major finding was that total fuel use and emissions for an activity increases as equipment idle time increases. Ahn *et al. (11)* used the dataset and previous studies to develop an integrated framework for estimating, benchmarking, and monitoring pollutant emissions from construction activities. Hajji and Lewis *(12)* developed a productivity-based estimating tool for fuel use and air pollutant emissions for nonroad construction equipment performing earthwork activities. The methodology for the field data collection in these studies using a PEMS is well-documented by Rasdorf *et al. (13)*. Frey *et al. (14-15)* also outlined the methods and procedures for collecting and analyzing data for construction equipment activity, fuel use, and emissions; thus, the methodology may be easily duplicated by those with the necessary expertise and implementation.

METHODOLOGY

This section addresses the research approach that was used to develop the dataset of fuel use and emissions rates of HDD maintenance equipment. Fifteen units of equipment including five backhoes, six motor graders, and four wheel loaders were tested under real-world conditions as they performed highway maintenance operations. Each unit of equipment was tested once with diesel fuel and once with B20 biodiesel; thus, a one-to-one comparison of the two fuel types under similar conditions was possible. The field data collection procedures are described. A discussion of the equipment engine attributes for the case study fleet is provided. The analysis methods for developing the fuel use and emissions rates are presented.

Field Data Collection

The basis of the field data collection efforts was an on-board portable emissions measurment system (PEMS) that was used to gather engine, fuel use, and emissions data directly from in-use HDD equipment. The PEMS was secured to the body of the equipment and sensors were connected to the engine to collect engine performance data related to engine speed, intake air temperature, and engine load. Exhaust sample probes were inserted into the tailpipe of the equipment to collect emissions data for NO_x, HC, CO, and PM. All of these data were collected on a second-by-second basis, thus providing a high resolution timeline of engine performance, fuel use, and emissions data. A minimum of three hours of second-by-second data were targeted for collection from each item of equipment that was tested.

When the original field data (referred to as "raw data") had been collected, it underwent a rigorous quality assurance process to determine whether any errors or problems existed, such as unusual engine performance values or negative emissions values. If any errors were found, they were corrected when possible. If the errors could not be corrected, then the data were deemed invalid and removed from the dataset. The purpose of the quality assurance process was to produce a valid set of data (referred to as "processed data") for analyzing engine performance, fuel use, and emissions for each item of equipment.

Engine Attributes

There are many attributes of HDD equipment that affects its performance, fuel use, and emissions, particularly, the engine size, engine age, and engine tier. Typically, larger engines consume more fuel and thus produce more emissions. Engine size was represented by the engine's rated horsepower and the engine displacement. This information was collected in the field from the engine itself and was verified with the engine manufacturer's specifications.

As engines increase in age, their performance may deteriorate and they may use more fuel at a partial load than they would have previously at full load *(16)*. Consequently, engines may produce more emissions as they get older. Engine age was represented by the engine model year, which is the year that the engine was manufactured. Engine hours of operation are another attribute that can be used to measure engine age; however, insufficient data was collected for engine hours and therefore is not reported.

Engine tier is a hybrid attribute based on engine size and engine age. Tier classifications are based on the horsepower rating and the model year of the equipment's engine. Engine tiers are emissions standards adopted by the EPA in 1994 for all new nonroad diesel engines *(17)*. Diesel engines manufactured after a specified date must meet the performance levels specified in the standards. The EPA engine tier classifications include successive Tier 1, Tier 2, Tier 3, Tier 4 Transitional, and Tier 4 Final, which are effective in reducing emissions in a phased sequence from 1996 to 2013.

Engine performance affects the fuel use and emissions rates of construction equipment. The PEMS collected second-by-second engine data through a sensor array that was connected to the equipment's engine. The variables that were monitored included engine speed measured in revolutions per minute (RPM), engine intake air temperature (IAT) measured in Celsius degrees (°C), and pressure-based engine load measured by manifold absolute pressure (MAP) in units of kilopascals (kPa).

Average Emissions Rates

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

The mass per time and mass per fuel used emissions rates were categorized according to equipment type and also according to engine tier. Emissions rates categorized by equipment type are useful because they are based on similar duty cycles. Emissions rates based on engine tier are useful because they are based on engine manufacturing specifications aimed at reducing emissions. The percentage change in average emissions rates for B20 biodiesel versus diesel were computed for each of the 15 items of equipment on both a mass per time and mass per fuel used basis.

RESULTS

This section provides the results of the field data collection for the equipment that was tested. These results include engine attributes, mass per time and mass per fuel used average emissions rates, and a comparison of B20 biodiesel versus diesel fuel. Analyses of trends in the data are also discussed.

Field Data Collection

Overall, almost 45 hours of data were collected for the case study equipment fueled with diesel. This included approximately 12 hours for backhoes (BH), 17 hours for motor graders (MG), and 16 hours for wheel loaders (WL). Approximately 48 hours of data were collected from the same items of equipment fueled with B20 biodiesel including about 16 hours for each of the three equipment types. These values represent approximately 90% of the total raw data that remained after the quality assurance process.

The PEMS measured accurate emissions for NO_x, CO, and CO_2. The emissions rates of these pollutants are of the same magnitude of those found in other data sources, such as the EPA NONROAD model *(1)*. The HC data tend to be biased low and the reported emissions rates may be low by a factor of two. The PM detection method for the PEMS is analogous to opacity. The field measurements are useful for relative comparisons of PM emissions rates for different fuels, equipment types, or engine tier but not for characterization of the absolute magnitude of PM emissions. The PM data reported here could be low by an order of magnitude according to previous comparisons of the opacity-based measurements to other PM data. Batelle *(18)* provides a detailed evaluation of the reporting accuracy of the PEMS used for this data collection effort.

Engine Attributes

Table 1 summarizes the HDD equipment specifications and the quantity of data that was collected for each item of equipment. Engine tier refers to the EPA regulation imposed on engine manufacturers aimed at reducing emission rates of NO_x, HC, CO, and PM. There were three Tier 0 units, seven Tier 2 units (almost half of the case study fleet), four Tier 2 units, and only one Tier 3 unit (MG 6). The horsepower rating and displacement values were quantitatively similar for all items in a particular equipment type. For example, all backhoes were in the 90-100 hp range, all motor graders were in the 160-200 hp range, and all wheel loaders were in the 125-130 hp range. The model years ranged from 1990 (MG 4) to 2007 (MG 6).

Average Emissions Rates

Table 2 summarizes the mass per time average emissions rates by equipment type for both diesel and B20 biodiesel. For both fuel types, motor graders had the highest average emissions of all pollutants. The only exception was that backhoes had the highest average emissions rate of CO when fueled with B20 biodiesel. In most cases, the average emissions rates for backhoes and wheel loaders were quantitatively similar. It should also be noted that motor graders had the highest average horsepower rating (185 hp), displacement (7.9 liters), and fuel use (3.0 gal/h) of the three equipment types. This finding indicates that equipment with larger engines consume more fuel and emit more pollutants over a specified timescale and it holds true for both diesel and B20 biodiesel.

Table 3 summarizes the mass per fuel used emissions rates by equipment type for both diesel and B20 biodiesel. The results are quantitatively similar for each pollutant regardless of equipment type, engine tier, or fuel type. The range (maximum minus minimum) of average values for mass per fuel used emissions rates are smaller than those for mass per time emissions rates. This finding indicates that mass per fuel used emissions rates are more consistent than mass per time rates, which are influenced more by engine horsepower rating and engine displacement. Likewise, mass per fuel used emissions rates are less likely to be impacted by duty cycles that may impose episodic or unstable engine loads on the equipment. Although not shown specifically in Table 3, the average mass per fuel used emissions rate for CO_2 for diesel was approximately 9,900 g/gal (+/- 2%) and approximately 9,700 g/gal (+/- 5%) for B20 biodiesel.

Perhaps a better way to categorize and compare emissions rates for different equipment types is by engine tier. Categorizing by engine tier allows comparison of equipment with engines that have the same EPA emissions standards. Tables 4 and 5 summarize the mass per time and mass per fuel used emissions rates by engine tier, respectively. For most pollutants, the average emissions rate for each pollutant decreases as the engine tier increases on both a mass per time and a mass per fuel used basis for both diesel and B20 biodiesel. This finding implies that the EPA engine tier standards have been effective in reducing emissions from nonroad HDD equipment; however, there are some interesting deviations in this finding. In Table 4 (mass per time), there is no change in B20 biodiesel average emissions of HC from Tier 0 to Tier 1. There is also a slight increase in B20 biodiesel average emissions of PM from Tier 0 to Tier 1. Notice that the Tier 3 emissions of all pollutants for both diesel and B20 biodiesel are higher than the average Tier 2 emissions; however, the Tier 3 emissions rates are based on only one item of equipment (MG 6). Similar findings are recognized in Table 5 (mass per fuel used). For both diesel and B20 biodiesel, there is an increase in average NO_x emissions from Tier 1 to Tier 2. Likewise, there is very little change in PM emissions among tiers for both fuel types.

Tables 6 and 7 compare average emissions rates of B20 biodiesel to diesel on a mass per time and mass per fuel used basis, respectively. The results are categorized by engine tier. For these tables, a positive number indicates the percentage increase in the emissions rate of B20 biodiesel relative to the diesel emissions rate; a negative number represents the percentage decrease in the B20 biodiesel emissions rate relative to the diesel emissions rate. In Table 6 (mass per time), B20 biodiesel for Tier 0 has reduced emissions on average for all pollutants compared to diesel. This is not the case, however, for Tiers 1-3. For Tier 1, B20 biodiesel has reduced emissions for HC, CO_2, and PM but an increase in emissions of NO_x and CO. For Tier 2, B20 biodiesel has reduced emissions for HC only but increased emissions for the other pollutants. In Table 7 (mass per fuel used), B20 biodiesel has reduced emissions on average for all pollutants except PM, which shows no change compared to the diesel emissions rate. For Tier 1, B20 biodiesel shows reduced emissions on average for NO_x and HC but increased emissions for CO and PM. For Tier 2, B20 biodiesel shows reduced emissions for HC and CO but increased emissions for NO_x and PM. In both Tables 6 and 7, B20 biodiesel shows increased emissions on average for all Tier 3 pollutants except for PM; however, this is based on one item of equipment.

CONCLUSIONS AND RECOMMENDATIONS

The primary research question for this paper was: Does B20 biodiesel offer reductions in emissions of NO_x, HC, CO, CO_2, and PM compared to conventional diesel when used in the same equipment? In order to address this question, real-world data were collected from a case study fleet of nonroad HDD equipment including backhoes, motor graders, and wheel loaders. Two sets of field tests were conducted: one test to measure emissions when the equipment was fueled with conventional diesel and a second test on the same items of equipment when it was fueled with B20 biodiesel. The data were quality assured and then analyzed to determine the average mass per time and mass per fuel used emissions rates. The resulting emissions rates were categorized by equipment type, EPA engine tier standards, and fuel type.

The primary conclusion of this paper is that B20 biodiesel does offer a reduction in pollutant emissions rates compared to diesel in some cases. For the 15 items of equipment that were tested, B20 biodiesel resulted in either a reduction or no change in the mass per fuel used emissions rate of NO_x for eight equipment units. For HC, a reduction occurred in 10 equipment units. For CO, a reduction occurred in seven units. For PM, a reduction or no change occurred in 10 units. In general, B20 biodiesel showed emissions reductions in about half of the equipment that was tested; thus, B20 biodiesel does have potential to reduce the environmental impact of highway maintenance equipment fleets.

The work presented here provides a solid foundation for developing a benchmarking dataset of fuel use and emissions information for HDD maintenance equipment; however, more research needs to be done. The research that produced these results must be continued to observe more equipment of the same type in order to refine the current data and also gather data from other non-represented equipment types. The equipment that was observed represents a range of engine attributes related to engine size, engine age, and engine tier; however, large populations of equipment exist outside of these ranges. Additional data must be collected from equipment outside of these ranges to represent more of the total maintenance equipment population. As this data is collected, the benchmarking dataset will grow and provide a useful tool for fleet managers to use to make informed decisions regarding the energy and environmental impacts of their fleets.

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LIST OF TABLES

TABLE 1 Summary of Equipment Attributes

Equipment	Horsepower (HP)	Displacement (Liters)	Model Year	Engine Tier
Backhoe 1	97	3.9	2004	2
Backhoe 2	90	4.2	1997	0
Backhoe 3	90	4.2	2001	1
Backhoe 4	99	4.5	1999	1
Backhoe 5	97	4.5	2004	2
Motor Grader 1	195	8.3	2001	1
Motor Grader 2	195	7.1	2004	2
Motor Grader 3	195	8.3	2001	1
Motor Grader 4	167	8.3	1990	0
Motor Grader 5	160	8.3	1993	0
Motor Grader 6	198	7.2	2007	3
Wheel Loader 1	130	5.9	2002	1
Wheel Loader 2	130	5.9	2002	1
Wheel Loader 3	126	5.9	2002	1
Wheel Loader 4	133	6.0	2005	2

TABLE 2 Mass per Time Emissions Rates by Equipment Type

	Equipment	Tier	Fuel Use (gal/h)	NO_x (g/h)	HC (g/h)	CO (g/h)	CO_2 (g/h)	PM (g/h)
Diesel	BH 1	2	0.5	64	6.0	5.0	4,611	0.3
	BH 2	0	1.8	206	27	154	18,175	2.1
	BH 3	1	2.1	222	24	73	20,795	2.2
	BH 4	1	0.8	112	7.0	52	8,035	0.7
	BH 5	2	0.5	69	6.0	10	4,764	0.4
		Average	*1.1*	*135*	*14*	*59*	*11,276*	*1.1*
	MG 1	1	5.5	643	53	67	54,615	4.9
	MG 2	2	1.7	192	50	48	16,956	1.0
	MG 3	1	2.5	275	152	29	25,085	2.8
	MG 4	0	2.9	596	95	141	28,845	2.3
	MG 5	0	2.6	423	26	134	26,013	1.9
	MG 6	3	2.5	163	21	17	24,893	1.8
		Average	*3.0*	*382*	*66*	*73*	*29,401*	*2.5*
	WL 1	1	1.6	195	33	38	15,534	1.5
	WL 2	1	0.9	131	8.0	18	9,250	0.4
	WL 3	1	1.2	156	15	12	11,691	1.1
	WL 4	2	0.8	78	8.0	23	7,819	0.5
		Average	*1.1*	*140*	*16*	*23*	*11,074*	*0.9*
B20 Biodiesel	BH 1	2	0.6	77	9.0	6.0	5,994	0.3
	BH 2	0	1.8	213	25	125	18,290	2.0
	BH 3	1	2.0	178	19	64	19,575	2.1
	BH 4	1	1.2	111	42	105	11,388	1.6
	BH 5	2	0.4	69	2.0	6.0	4,346	0.3
		Average	*1.2*	*130*	*19*	*61*	*11,919*	*1.3*
	MG 1	1	5.1	561	62	64	49,997	4.2
	MG 2	2	1.7	233	16	34	17,102	0.5
	MG 3	1	3.8	364	47	53	36,710	2.1
	MG 4	0	1.3	201	36	NA	12,658	0.0
	MG 5	0	3.4	600	47	92	33,443	1.9
	MG 6	3	2.7	166	55	28	26,869	1.4
		Average	*3.0*	*354*	*44*	*54*	*29,463*	*1.7*
	WL 1	1	1.0	126	8.0	28	9,637	0.7
	WL 2	1	1.2	166	22	16	11,735	0.6
	WL 3	1	2.2	253	30	38	21,130	1.6
	WL 4	2	1.5	137	8.0	37	14,495	1.0
		Average	*1.5*	*171*	*17*	*30*	*14,249*	*1.0*

TABLE 3 Mass per Fuel Used Emissions Rates by Equipment Type

	Equipment	Tier	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	PM (g/gal))
Diesel	BH 1	2	172	14	11	0.8
	BH 2	0	111	15	80	1.1
	BH 3	1	106	12	35	1.1
	BH 4	1	164	13	61	0.8
	BH 5	2	168	17	27	0.9
		Average	*144*	*14*	*43*	*0.9*
	MG 1	1	129	16	17	1.0
	MG 2	2	148	43	29	0.5
	MG 3	1	131	77	20	1.1
	MG 4	0	215	43	72	0.7
	MG 5	0	179	15	113	0.7
	MG 6	3	86	10	7.0	0.7
		Average	*148*	*34*	*43*	*0.8*
	WL 1	1	132	30	42	0.9
	WL 2	1	179	14	38	0.6
	WL 3	1	145	22	13	1.0
	WL 4	2	104	13	36	0.6
		Average	*140*	*20*	*32*	*0.8*
B20 Biodiesel	BH 1	2	181	56	NA	1.8
	BH 2	0	114	14	66	1.1
	BH 3	1	91	10	33	1.1
	BH 4	1	139	33	73	1.2
	BH 5	2	202	3	16	0.5
		Average	*145*	*23*	*47*	*1.1*
	MG 1	1	129	15	22	0.9
	MG 2	2	173	13	24	0.3
	MG 3	1	122	18	22	0.4
	MG 4	0	131	32	NA	0.8
	MG 5	0	195	24	57	0.6
	MG 6	3	100	34	12	0.5
		Average	*142*	*23*	*27*	*0.6*
	WL 1	1	151	19	53	1.8
	WL 2	1	170	27	22	0.6
	WL 3	1	132	21	29	0.7
	WL 4	2	103	8.0	33	0.6
		Average	*139*	*19*	*34*	*0.9*

TABLE 4 Mass per Time Emissions Rates by Engine Tier

	Equipment	Tier	Fuel Use (gal/h)	NO_x (g/h)	HC (g/h)	CO (g/h)	CO_2 (g/h)	PM (g/h)
Diesel	BH 2	0	1.8	206	27	154	18,175	2.1
	MG 4	0	2.9	596	95	141	28,845	2.3
	MG 5	0	2.6	423	26	134	26,013	1.9
		Average	*2.4*	*408*	*49*	*143*	*24,344*	*2.1*
	BH 3	1	2.1	222	24	73	20,795	2.2
	BH 4	1	0.8	112	7.0	52	8,035	0.7
	MG 1	1	5.5	643	53	67	54,615	4.9
	MG 3	1	2.5	275	152	29	25,085	2.8
	WL 1	1	1.6	195	33	38	15,534	1.5
	WL 2	1	0.9	131	8.0	18	9,250	0.4
	WL 3	1	1.2	156	15	12	11,691	1.1
		Average	*2.1*	*248*	*42*	*41*	*20,715*	*1.9*
	BH 1	2	0.5	64	6.0	5.0	4,611	0.3
	BH 5	2	0.5	69	6.0	10	4,764	0.4
	MG 2	2	1.7	192	50	48	16,956	1.0
	WL 4	2	0.8	78	8.0	23	7,819	0.5
		Average	*0.9*	*102*	*18*	*23*	*8,576*	*0.6*
	MG 6	3	2.5	163	21	17	24,893	1.8
		Average	*2.7*	*166*	*55*	*28*	*26,869*	*1.4*
B20 Biodiesel	BH 2	0	1.8	213	25	125	18,290	2.0
	MG 4	0	1.3	201	36	NA	12,658	0.0
	MG 5	0	3.4	600	47	92	33,443	1.9
		Average	*2.2*	*338*	*36*	*109*	*21,464*	*1.3*
	BH 3	1	2.0	178	19	64	19,575	2.1
	BH 4	1	1.2	111	42	105	11,388	1.6
	MG 1	1	5.1	561	62	64	49,997	4.2
	MG 3	1	3.8	364	47	53	36,710	2.1
	WL 1	1	1.0	126	8.0	28	9,637	0.7
	WL 2	1	1.2	166	22	16	11,735	0.6
	WL 3	1	2.2	253	30	38	21,130	1.6
		Average	*2.0*	*252*	*36*	*61*	*20,125*	*1.6*
	BH 1	2	0.6	77	9.0	6	5,994	0.3
	BH 5	2	0.4	69	2.0	6	4,346	0.3
	MG 2	2	1.7	233	16	34	17,102	0.5
	WL 4	2	1.5	137	8.0	37	14,495	0.6
		Average	*1.1*	*129*	*9.0*	*21*	*10,484*	*0.5*
	MG 6	3	2.7	166	55	28	26,869	1.4
		Average	*2.7*	*166*	*55*	*28*	*26,869*	*1.4*

TABLE 5 Mass per Fuel Used Emissions Rates by Engine Tier

	Equipment	Tier	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	PM (g/gal)
Diesel	BH 2	0	111	15	80	1.1
	MG 4	0	215	43	72	0.7
	MG 5	0	179	15	113	0.7
		Average	*168*	*24*	*88*	*0.8*
	BH 3	1	106	12	35	1.1
	BH 4	1	164	13	61	0.8
	MG 1	1	129	16	17	1.0
	MG 3	1	131	77	20	1.1
	WL 1	1	132	30	42	0.9
	WL 2	1	179	14	38	0.6
	WL 3	1	145	22	13	1.0
		Average	*141*	*26*	*32*	*0.9*
	BH 1	2	172	14	11	0.8
	BH 5	2	168	17	27	0.9
	MG 2	2	148	43	29	0.5
	WL 4	2	104	13	36	0.6
		Average	*148*	*22*	*26*	*0.7*
	MG 6	3	86	10	7	0.7
		Average	*86*	*10*	*7*	*0.7*
B20 Biodiesel	BH 2	0	114	14	66	1.1
	MG 4	0	131	32	NA	0.8
	MG 5	0	195	24	57	0.6
		Average	*147*	*23*	*62*	*0.8*
	BH 3	1	91	10	33	1.1
	BH 4	1	139	33	73	1.2
	MG 1	1	129	15	22	0.9
	MG 3	1	122	18	22	0.4
	WL 1	1	151	19	53	1.8
	WL 2	1	170	27	22	0.6
	WL 3	1	132	21	29	0.7
		Average	*133*	*20*	*36*	*1.0*
	BH 1	2	181	56	NA	1.8
	BH 5	2	202	3	16	0.5
	MG 2	2	173	13	24	0.3
	WL 4	2	103	8	33	0.6
		Average	*165*	*20*	*24*	*0.8*
	MG 6	3	100	34	12	0.5
		Average	*100*	*34*	*12*	*0.5*

TABLE 6 B20 Biodiesel vs. Diesel: Change in Mass per Time Emissions Rates (Percentage Increase or Decrease)

Equipment	Tier	Fuel (%)	NO_x (%)	HC (%)	CO (%)	CO_2 (%)	PM (%)
BH 2	0	0	3	-7	-19	1	-5
MG 4	0	-55	-66	-62	NA	-56	-100
MG 5	0	31	42	81	-31	29	0
	Average	*-11*	*-17*	*-27*	*-24*	*-12*	*-38*
BH 3	1	-5	-20	-21	-12	-6	-5
BH 4	1	50	-1	500	102	42	129
MG 1	1	-7	-13	17	-4	-8	-14
MG 3	1	52	32	-69	83	46	-25
WL 1	1	-38	-35	-76	-26	-38	-53
WL 2	1	33	27	175	-11	27	50
WL 3	1	83	62	100	217	81	45
	Average	*-3*	*2*	*-17*	*46*	*-3*	*-17*
BH 1	2	20	20	50	20	30	0
BH 5	2	-20	0	-67	-40	-9	-25
MG 2	2	0	21	-68	-29	1	-50
WL 4	2	88	76	0	61	85	100
	Average	*22*	*29*	*-21*	*3*	*27*	*6*
MG 6	3	8	2	162	65	8	-22
	Average	*8*	*2*	*162*	*65*	*8*	*-22*

TABLE 7 B20 Biodiesel vs. Diesel: Change in Mass per Fuel Used Emissions Rates (Percentage Increase or Decrease)

Equipment	Tier	NO_x (%)	HC (%)	CO (%)	PM (%)
BH 2	0	3	-7	-18	0
MG 4	0	-39	-26	NA	14
MG 5	0	9	60	-50	-14
	Average	*-13*	*-4*	*-30*	*0*
BH 3	1	-14	-17	-6	0
BH 4	1	-15	154	20	50
MG 1	1	0	-6	29	-10
MG 3	1	-7	-77	10	-64
WL 1	1	14	-37	26	100
WL 2	1	-5	93	-42	0
WL 3	1	-9	-5	123	-30
	Average	*-5*	*-22*	*12*	*3*
BH 1	2	5	300	NA	125
BH 5	2	20	-82	-41	-44
MG 2	2	17	-70	-17	-40
WL 4	2	-1	-38	-8	0
	Average	*11*	*-8*	*-6*	*14*
MG 6	3	16	240	71	-29
	Average	*16*	*240*	*71*	*-29*