DEVELOPMENT OF A FUEL CONSUMPTION AND EMISSIONS TAXONOMY FOR NONROAD DIESEL EQUIPMENT

Phil Lewis, Ph.D., P.E.
Assistant Professor
School of Civil and Environmental Engineering
Oklahoma State University
Stillwater, OK 74078
Telephone 405-744-5207, Fax 405-744-7554
Email phil.lewis@okstate.edu

Heni Fitriani, Ph.D.
Faculty of Engineering
University of Sriwijaya, Indonesia
Jl. Raya Palembang - Prabumulih Km. 32 Indralaya, OI, Sumatera Selatan 30662
Telephone 0711-580739, 580740, Fax 0711-580741
Email heni.fitriani@okstate.edu

Yongwei Shan, Ph.D., P.E.
Assistant Professor
School of Civil and Environmental Engineering
Oklahoma State University
Stillwater, OK 74078
Telephone 405-744-5207, Fax 405-744-7554
Email yongwei.shan@okstate.edu

Submitted for Consideration for Presentation at the 95th Annual Meeting of the Transportation Research Board and Publication in the Transportation Research Record

Presented for Review by AHD 60 Maintenance Equipment Committee

Text words 5,100 plus 1,250 words for 4 Tables and 1 Figures = 6,350 Words

ABSTRACT

The purpose of this paper is to present a taxonomy of fuel consumption and pollutant emissions rates for nonroad equipment to assist equipment managers in estimating the energy and environmental impacts of their fleets. Diesel fuel is the primary energy source for nonroad diesel equipment. Without it, the equipment is inoperable and non-productive. Estimating fuel requirements can be extremely difficult due to high variability in published fuel consumption rates. Moreover, equipment publications provide no guidance for selecting pollutant emissions rates. The taxonomy is based on real world fuel consumption and emissions data collected from in-use equipment. An engine modal analysis was conducted on the data to categorize it by engine load. Weighted average fuel consumption and pollutant emissions rates were calculated based on the results of the engine modal analysis. The taxonomy presents the weighted average fuel consumption and emissions rates according to equipment type, Environmental Protection Agency engine tier technology type, and pollutant including nitrogen oxides, hydrocarbons, carbon monoxide, carbon dioxide, and particulate matter. The taxonomy provides an accurate and easy to use guide for equipment managers to use in estimating their fuel consumption and resulting pollutant emissions.

INTRODUCTION

Taxonomy is a term used in biology that refers to the science of categorizing and classifying organisms *(1)*. Just as living creatures eat food and eliminate waste, heavy equipment consumes fuel and exhausts harmful byproducts in the form of pollutant emissions; therefore, members of the nonroad diesel equipment kingdom need to be categorized and classified in order to properly evaluate their energy and environmental impacts. The purpose of this paper is to present a taxonomy of fuel consumption and pollutant emissions rates for nonroad diesel construction equipment based on real world data from in-use equipment.

Diesel fuel is the lifeblood of heavy equipment – without it the equipment is inoperable. Diesel fuel also has a significant economic impact on equipment operations due to its high cost. Volatility in fuel prices makes it difficult to estimate total fuel costs in the short term and especially in the long term. Although it is impossible to predict the rise and fall of future fuel prices, it is possible to accurately estimate required fuel quantities. This paper examines common procedures for estimating fuel consumption and builds upon that body of knowledge by adding metrics for estimating pollutant emissions resulting from diesel fuel usage.

Background

Fuel consumption is most accurately measured in the field; however, if no opportunity exists to do so, fuel consumption may be estimated if the equipment application is known. Application determines the engine load factor which has a significant impact on fuel consumption. Engine load factor refers to the instantaneous loading of the engine relative to its maximum capability. An engine continuously producing full rated horsepower is operating at a load factor of 100%. Heavy equipment may reach a 100% load factor intermittently, but it seldom operates at this level for extended periods of time. Periods spent at idle, travel in reverse, traveling empty, close maneuvering at partial throttle, and operating downhill are examples of conditions which reduce load factor *(2)*. Equation 1 summarizes the relationship between fuel consumption, rated horsepower, and engine load factor:

$$FC = FF \times HP \times LF \qquad (1)$$

where: FC = hourly fuel consumption rate (gal/h)
FF = fuel factor (gal/hp-h)
HP = engine rated horsepower (hp)
LF = engine load factor (%)

Although *HP* and *LF* are important variables in estimating *FC*, they primarily serve as scalars to adjust *FF*; thus, *FF* is the foundational variable in estimating *FC*. Help is available for selecting values for *FF*, including equipment manufacturer guides such as the Cat® Performance Handbook *(2)*. This handbook provides tables of hourly fuel consumption rates for various types of equipment. The problem with these tables is that they require the user to select from a wide range of values. For example, the user must first identify in the tables the specific equipment item of interest based on the appropriate rated horsepower. Then, the user must determine whether the equipment's application is low, medium, or high based on typical application descriptions. Finally, the user must select an engine load factor from a range of average values provided for each application category.

To illustrate the variability in this process, consider a Cat® 420F backhoe loader with a 100 hp, Tier 2 engine. If the equipment application is assumed to be low, values for hourly fuel consumption range from 0.7-3.1 gal/h and values for load factor range from 20-40%. Hence, the hourly fuel consumption rate is estimated to be between 0.14-1.24 gal/h – an astounding 785% difference. Although the true value of the average hourly fuel consumption rate is likely within this range, such extreme variability in the possible values clearly confound the ability to accurately estimate fuel and costs for this item of equipment.

Another approach to estimating hourly fuel consumption is to use a typical value for *FF*. Many equipment textbooks *(3-5)* use a common value of 0.04 gal/hp-h for all nonroad diesel equipment. Unlike the variability issues faced with using fuel consumption tables, the problem with using a common value for *FF* is that it may be too rigid and consistently over- or under-estimate hourly fuel consumption for a specific type of equipment. Furthermore, neither the hourly fuel consumption tables nor the common value approach provide any values for pollutant emissions that result from fuel consumption. A real-world approach is needed to quantify and characterize the energy and environmental impacts of nonroad diesel equipment.

Objectives

The major goal is to present a taxonomy of fuel use and emissions data for nonroad diesel equipment. In order to accomplish this goal, the following objectives were achieved:

1. Evaluate the efficacy of *FF = 0.04 gal/hp-h* using real world, in-use equipment data;
2. Conduct an engine modal analysis of the equipment data to determine the distribution of time, fuel consumption, and emissions over the full range of equipment engine loads;
3. Compute weighted average fuel consumption and emissions rates based on the amount of time spent in each engine mode; and
4. Develop a taxonomy of fuel consumption and emissions rates based on equipment type and Environmental Protection Agency (EPA) engine tier technology type.

The primary output is a matrix of fuel consumption and emissions rates for nonroad diesel equipment categorized by equipment type, engine tier, and pollutant. The major outcome is that equipment managers are better equipped to quantify and assess the energy and environmental impacts of their fleets.

Scope

The scope of the analysis was limited to data collected from a case study fleet of nonroad diesel equipment including backhoes, bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders. The equipment ranged in engine rated horsepower from 70 – 306 hp and in model year from 1988 – 2007. EPA engine tier technology type included Tier 0, Tier 1, and Tier 2. Tier 3 and Tier 4 engines were not available for the original research. Pollutants included nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM). Equipment engine variables included intake air temperature (IAT), manifold absolute pressure (MAP), and revolutions per minute (RPM).

RELATED WORK

The analysis was based on a prominent and well-documented dataset that included real-world fuel consumption and emissions measurements for nonroad diesel equipment. This dataset was developed by researchers at North Carolina State University (NC State) from 2005 through 2008. The NC State research team used a portable emissions measurement system (PEMS) to collect, analyze, and characterize real-world engine, fuel consumption, and emissions data from 31 items of nonroad diesel equipment. The equipment types included backhoes, bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders.

Numerous papers were published by the NC State research team. Lewis *et al. (6)* outlined requirements and incentives for reducing air pollutant emissions from construction equipment. They also compared sources of emissions from various types of equipment. Based on those concepts, Lewis *et al. (7)* developed a fuel use and emissions inventory for a publicly-owned fleet of nonroad diesel 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 technology type. The impact on the inventory of different emissions reduction strategies were compared. Frey *et al. (8)* presented the results of a comprehensive field study that characterized real-world emission rates of NO_x, HC, CO, and PM from nonroad diesel equipment. Average emissions rates were developed for each equipment type and were presented on a mass per time and mass per fuel consumed basis for both petroleum diesel and B20 biodiesel. Frey *et al. (9)* 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 emissions rates for the different EPA engine tier standards of the equipment.

Lewis *et al. (10-12)* published three papers on the impacts of idling on equipment fuel consumption and emissions rates. These papers characterized the change in total activity fuel consumption and emissions based on the change in the ratio of idle time to non-idle time. The major finding was that total fuel consumption and emissions for an activity increases as equipment idle time increases. Ahn *et al. (13)* used the dataset and previous studies to develop an integrated framework for estimating, benchmarking, and monitoring pollutant emissions from construction activities. Hajji and Lewis *(14)* 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. (15)*. Frey *et al. (16, 17)* also outlined the methods and procedures for collecting and analyzing data for nonroad diesel equipment activity, fuel consumption, and emissions; thus, the methodology may be easily replicated by those with the necessary expertise and instrumentation.

Lewis *et al. (18)* published a recent paper on a variable impact analysis of nonroad diesel equipment. This study examined the relationships between engine performance variables (IAT, MAP, and RPM) and fuel consumption and pollutant emissions rates (NO_x, HC, CO, and PM). The paper concluded that MAP has the greatest impact on fuel consumption and emissions rates for nonroad diesel equipment. This conclusion is foundational for the engine modal analysis and the weighted average fuel consumption and emissions rates presented in this paper.

METHODOLOGY

This section describes the methodology used to accomplish the objectives. The primary steps of the analysis included: 1) Collect real world fuel consumption and emissions data from equipment being used in the field; 2) Conduct an engine modal analysis to categorize the fuel consumption and emissions data according to engine load; 3) Calculate weighted average fuel consumption and emissions rates based on the results of the engine modal analysis; and 4) Develop a taxonomy of fuel consumption and emissions rates based on the weighted averages.

Data Collection

The central component to the fuel use and emissions data collection effort was a portable emissions measurement system (PEMS). The PEMS was placed onboard the equipment and sample probes drew exhaust samples from the tailpipe. The PEMS collected and recorded second-by-second mass per time emissions data in grams per second (g/s) for NO_x, HC, CO, CO_2, and PM. The PEMS computed mass per time fuel consumption rates (g/s) via a proprietary carbon balance algorithm based on the CO_2 measurements. The PEMS gathered corresponding engine performance data including manifold absolute pressure (MAP), revolutions per minute (RPM), and intake air temperature (IAT). Other equipment data were collected including engine rated horsepower, engine displacement, equipment model year, and EPA engine tier.

A minimum of three hours of data were collected from each item of equipment. The field data underwent a thorough quality assurance process in order to identify missing or invalid values. The purpose of the quality assurance process was to ensure the availability of a robust dataset for statistical analysis. Mass per time fuel consumption and emissions rates were converted to gallons per hour (gal/h) and grams per hour (g/h), respectively, for consistency in reporting with common industry units. Mass per fuel consumed emissions rates in grams per gallon (g/gal) were computed for each pollutant by dividing the mass per time emission rate (g/h) by the corresponding mass per time fuel consumption rate (gal/h).

Engine Modal Analysis

Because of its high correlation with fuel consumption and emissions rates, MAP was used as a surrogate for engine load to conduct an engine modal analysis of the fuel consumption and emissions data *(18)*. The MAP field data were collected in units of kilopascals. In order to make the MAP data more analogous to engine load percentages, the field MAP data for each item of equipment were normalized according to Equation 2:

$$MAP_{norm} = \frac{MAP - Min\ MAP}{Max\ MAP - Min\ MAP}\ x\ 100 \qquad (2)$$

where: MAP_{norm} = normalized MAP value (%)
MAP = instantaneous MAP measurement from PEMS (kilopascals)
$Min\ MAP$ = minimum MAP measurement from PEMS (kilopascals)
$Max\ MAP$ = maximum MAP measurement from PEMS (kilopascals)

The normalized MAP values were ranked in ascending order along with their corresponding fuel consumption and emissions data. The data were categorized and classified in increasing engine modes such that normalized MAP values between 0 – 10% were Mode 1, and 90 – 100% were Mode 10; thus, Mode 1 data corresponded to the lowest equipment engine loads and Mode 10 to the highest. The average fuel consumption and emissions rate for each pollutant were computed for each engine mode. Likewise, the percentage of time spent in each engine mode was computed by dividing the number of seconds of data in each engine mode by the total number of seconds collected for that item of equipment. In order to visually examine the relationships of the modal time and modal average fuel consumption, these values were plotted on the same graph and a line-of-best-fit was added to each set of values.

In order to evaluate the efficacy of $FF = 0.04\ gal/hp\text{-}h$, the mass per time (gal/h) fuel consumption data were normalized by dividing it by the equipment's rated horsepower to yield units of gallons per horsepower-hour (gal/hp-h). Since $FF = 0.04\ gal/hp\text{-}h$ represents the maximum hourly fuel consumption rate at maximum engine load, the evaluation of *FF* used the overall average fuel use rate for Mode 10 from all 31 items of equipment (μ). A one sample *t*-test was used to test the statistical significance of the following hypothesis:

$$Ho\text{: } \mu = 0.04\ gal/hp\text{-}h \qquad Ha\text{: } \mu \neq 0.04\ gal/hp\text{-}h \qquad (3)$$

Weighted Average Fuel Consumption and Emissions Rates

Equipment application has a major influence on equipment engine load. Consequently, the equipment spends varying amounts of time in each engine mode and each engine mode has its own average fuel consumption and emissions rates. The modal average fuel consumption and emissions rates must be weighted by the amount of time spent in each mode and then summed in order to obtain realistic average fuel consumption and emissions rates for nonroad diesel equipment. Equations 4 and 5 show the formulas for calculating weighted average fuel consumption rates and weighted average emissions rates, respectively.

$$FC = \sum_{i=1}^{10} Ti \; x \; Fi \qquad (4)$$

where: *FC* = weighted average fuel consumption rate (gal/hp-h)
Ti = time spent in mode *i* (%)
Fi = fuel consumption rate in mode *i* (gal/hp-h)

$$ERj = \sum_{i=1}^{10} Ti \; x \; Eij \qquad (5)$$

where: *ERj* = weighted average emission rate for pollutant *j* (g/hp-h)
Ti = time spent in mode *i* (%)
Eij = emission rate in mode *i* for pollutant *j* (g/hp-h)

The time spent in each mode (*Ti*) is primarily influenced by the equipment's application. Given that each equipment type has its own specific applications, the average time in each mode was calculated for each equipment type. An average *Ti* for each mode was calculated for each of the seven equipment types. Fuel use (*Fi*) and emissions (*Eij*) rates are primarily influenced by EPA engine tier technology type; thus, the equipment were categorized according to engine tier and then the average fuel consumption and emissions rates were computed for each mode. This approach allows the most appropriate modal fuel consumption and emissions rates to be weighted by the most appropriate modal time.

Many fleet managers maintain detailed fuel records and may find it easier to use mass per fuel used emissions rates (grams per gallon) to estimate total emissions. Equation 6 provides a formula for converting the weighted average mass per time emissions rates to weighted average mass per fuel used emissions rates.

$$ER'j = \frac{ERj}{FC} \qquad (6)$$

where: *ER'j* = mass per fuel used weighted average emission rate for pollutant *j* (g/gal)

Taxonomy of Fuel Consumption and Emissions Rates

The weighted average fuel consumption and emissions rates were categorized by equipment type and engine tier technology type to create a taxonomy based on real world data. Since these values are based on in-use data collected from the equipment, it is important to note that the fuel use and emissions rates in the taxonomy do not need to be adjusted for engine load factor. Engine load factor is already accounted for in the modal fuel use and emissions rates.

The taxonomy includes both mass per time and mass per fuel consumed emissions rates. The mass per time fuel consumption and emissions rates are based on rated horsepower in order to provide more flexibility in their use. The user simply needs to multiply the weighted average fuel use or emissions rate by the rated horsepower of the equipment to calculate the hourly fuel use or emissions rate. Furthermore, if total fuel consumed or total pollutants emitted is desired, the hourly rate is multiplied by the estimated hours of use. Also, total emissions are estimated by multiplying the mass per fuel consumed emission rate by the gallons of fuel consumed.

RESULTS

This section briefly summarizes the key findings of the analysis. This includes a summary of the engine attributes of the equipment in the case study fleet; engine modal fuel consumption rates and engine modal emissions rates; a figure showing the relationship between modal fuel consumption and modal emissions; and a taxonomy of fuel consumption and emissions rates categorized by equipment type and EPA engine tier.

Data Collection

Field data were collected from 31 units representing six types of nonroad diesel equipment. Table 1 summarizes the key attributes for this equipment. The units ranged from 70-306 hp for Track Loader 2 and Off Road Truck 1, respectively. The oldest item of equipment was Bulldozer 1, which was manufactured in 1988. Of the 31 units tested, five were Tier 0, 16 were Tier 1, and 10 were Tier 2. A minimum of three hours of data were collected from each unit.

Engine Modal Analysis

Table 2 presents the average modal fuel consumption rates (*Fi*). For each type of equipment, the average fuel consumption rate has a positive relationship with engine mode. In other words, the fuel consumption rate increases as engine load increases. Mode 10 average values ranged from 0.030 gal/hp-h for backhoes to 0.063 gal/hp-h for track loaders, with an overall average of 0.043 gal/hp-h for all types of equipment (based on the 31 tested units). This overall average value is very close to the typical fuel factor, *FF = 0.04 gal/hp-h*, found in equipment textbooks. In fact, the results of the one sample *t*-test indicated that there is no statistically significant difference in the two values so the null hypothesis $\mu = 0.04$ *gal/hp-h* cannot be rejected; thus, it was concluded that *FF= 0.04 gal/hp-h* is valid for nonroad diesel equipment.

Table 2 also shows the average modal time (*Ti*) for each equipment type. Conversely to the average fuel use rates, the modal time has a negative relationship with engine mode. In other words, the time spent in each mode decreases as engine mode increases. Figure 1 illustrates this inverse relationship between modal time and modal fuel use. Modal fuel use is a linearly increasing monotonic function whereas modal time is an exponentially decreasing monotonic function. The line-of-best-fit for each function accounted for over 95% ($R^2 > 0.95$) of the variability in the data. For modal fuel consumption, the slope component of the trend line ($m = 0.004$) further supported the claim that *FF = 0.04 gal/hp-h* is valid; when multiplied by 10 (for Mode 10), the average fuel use rate for Mode 10 is 0.04 gal/hp-h. The primary finding from Table 2 and Figure 1 was that nonroad diesel equipment typically spends most of its time working at its lowest fuel consumption rates and the least amount of its time working at its highest fuel consumption rates; therefore, it was imperative to develop weighted average fuel consumption and emissions rates.

TABLE 1 Summary of Equipment Attributes

Equipment	Horsepower (HP)	Displacement (L)	Model Year	Engine Tier
Backhoe 1	88	4.0	2004	2
Backhoe 2	88	4.2	1999	1
Backhoe 3	88	4.2	2000	1
Backhoe 4	97	3.9	2004	2
Backhoe 5	99	4.5	1999	1
Backhoe 6	97	4.5	2004	2
Bulldozer 1	89	5.0	1988	0
Bulldozer 2	95	3.9	2002	1
Bulldozer 3	90	5.0	2003	1
Bulldozer 4	175	10.5	1998	1
Bulldozer 5	285	14.2	1995	0
Bulldozer 6	99	4.2	2005	2
Excavator 1	254	8.3	2001	1
Excavator 2	138	6.4	2003	2
Excavator 3	93	3.9	1998	1
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
Off-Road Truck 1	306	9.6	2005	2
Off-Road Truck 2	285	10.3	1998	1
Off-Road Truck 3	285	10.3	1998	1
Track Loader 1	121	7.2	1998	1
Track Loader 2	70	4.5	1997	0
Track Loader 3	127	7.2	2006	2
Wheel Loader 1	149	5.9	2004	2
Wheel Loader 2	130	5.9	2002	1
Wheel Loader 3	130	5.9	2002	1
Wheel Loader 4	126	5.9	2002	1
Wheel Loader 5	133	6.0	2005	2

TABLE 2 Modal Fuel Consumption Rates and Modal Time

Modal Fuel Consumption Rates, *Fi* (gal/hp-h)								
Mode	**BH**	**BD**	**EX**	**MG**	**OT**	**TL**	**WL**	***Average***
1	0.004	0.006	0.010	0.003	0.004	0.010	0.005	*0.006*
2	0.008	0.013	0.013	0.009	0.012	0.013	0.009	*0.011*
3	0.011	0.019	0.015	0.013	0.017	0.017	0.012	*0.015*
4	0.014	0.024	0.018	0.016	0.021	0.028	0.016	*0.019*
5	0.016	0.028	0.021	0.020	0.025	0.032	0.018	*0.023*
6	0.019	0.032	0.023	0.024	0.029	0.035	0.021	*0.026*
7	0.021	0.037	0.026	0.028	0.032	0.040	0.024	*0.030*
8	0.024	0.042	0.028	0.032	0.035	0.048	0.028	*0.034*
9	0.027	0.047	0.031	0.037	0.040	0.056	0.032	*0.039*
10	0.030	0.050	0.033	0.042	0.043	0.063	0.039	*0.043*
Modal Time, *Ti* (%)								
Mode	**BH**	**BD**	**EX**	**MG**	**OT**	**TL**	**WL**	***Average***
1	29%	25%	31%	24%	72%	27%	40%	*35%*
2	26%	15%	5%	7%	10%	5%	20%	*13%*
3	24%	16%	8%	10%	5%	4%	12%	*11%*
4	10%	9%	8%	11%	3%	4%	8%	*8%*
5	3%	7%	10%	10%	2%	8%	6%	*6%*
6	2%	7%	11%	12%	2%	13%	4%	*7%*
7	1%	5%	10%	12%	2%	9%	3%	*6%*
8	2%	4%	9%	6%	2%	8%	3%	*5%*
9	2%	7%	6%	5%	1%	9%	2%	*5%*
10	1%	6%	2%	4%	1%	14%	1%	*4%*

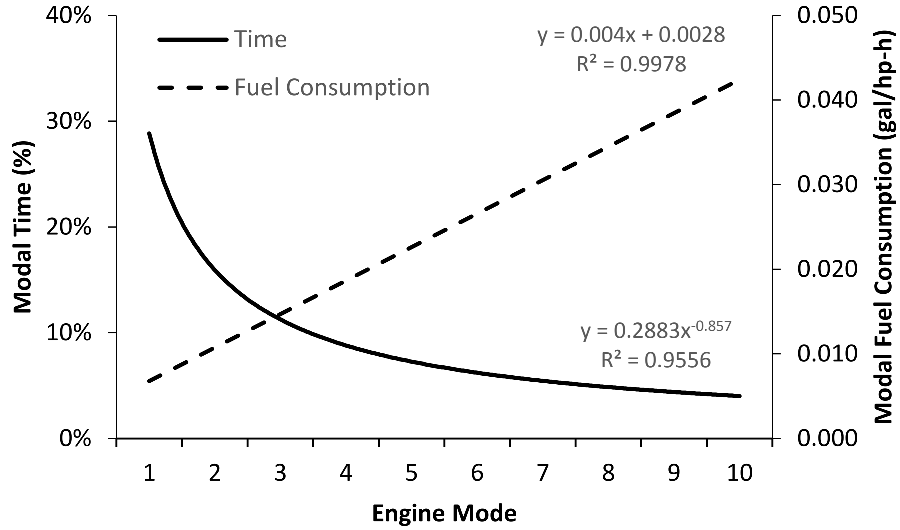

FIGURE 1 Relationship between modal fuel consumption and modal time.

Weighted Average Fuel Consumption and Emissions Rates

Table 3 shows sample calculations for Equations 4 and 5. These sample results are for the weighted average fuel consumption rate and weighted average NO_x emission rate for a Tier 0 backhoe loader. These calculations were carried out on all seven equipment types and Tier 0, 1, and 2 equipment to develop the taxonomy of fuel consumption and emissions rates.

As seen in Table 3, *Fi* and *Ei* increase monotonically over the range of engine modes. When weighted by *Ti*, which decreases monotonically over the range of engine modes, the weighted values of *Ti* × *Fi* and *Ti* × *Ei* is non-monotonic as they increase and decrease over the range of engine modes. For this particular example, Mode 3 contributed the most to the weighted average fuel consumption and emission rate. In fact, backhoe loaders spend about 90% of their time in Modes 1-4 which contributed about 70% of the weighted average fuel consumption rate and weighted average NO_x emission rate; thus, it was concluded that backhoe loaders consume most of its fuel and emit most its NO_x at engine loads less than or equal to 40%.

TABLE 3 Sample Calculations for Tier 0 Backhoe Fuel Consumption and NO_x Emissions

Mode	*Ti* (%)	*Fi* (gal/hp-h)	*Ti* × *Fi* (gal/hp-h)	*Ei* (g/hp-h)	*Ti* × *Ei* (g/hp-h)
1	29%	0.005	0.0015	1.1	0.3
2	26%	0.013	0.0034	2.4	0.6
3	24%	0.019	0.0045	3.3	0.8
4	10%	0.026	0.0026	4.4	0.4
5	3%	0.030	0.0010	4.9	0.2
6	2%	0.034	0.0007	5.3	0.1
7	1%	0.039	0.0006	5.9	0.1
8	2%	0.046	0.0009	7.6	0.1
9	2%	0.053	0.0008	9.3	0.1
10	1%	0.060	0.0007	10.9	0.1
Weighted Average			**0.017**		**2.9**

Taxonomy of Fuel Consumption and Emissions Rates

Table 4 presents the taxonomy of fuel consumption and emissions rates for seven types of nonroad diesel equipment with three different engine tiers. This matrix of values is based on real world data collected from in-use equipment in the field. For that reason, the values in Table 4 do not need to be adjusted for engine load because it was accounted for in the engine modal analysis. The mass per time rates were normalized by rated horsepower in order to provide more flexibility in their use; thus, these values are valid over the range of engine rated horsepower from 70-306 hp (the range of rated horsepower that was observed in the data).

The mass per time rates (fuel consumption and emissions) decrease monotonically as engine tier increases. This indicates that the EPA engine tier standards have been effective in reducing emissions rates of NO_x, HC, CO, and PM. Although engine tier standards do not exist for fuel consumption and CO_2 emissions rates, the values in Table 4 show that these rates also decreased as engine tier increased. With regard to the mass per fuel consumed emissions rates, engine tier did not have such a profound effect. As the engine tier increased, there was a monotonic decrease in the emissions rate of NO_x, a slight monotonic decrease for HC, and very little change for CO, CO_2, and PM with respect to engine tier. However, the mass per fuel consumed emissions rates were the lowest for Tier 2 equipment for each pollutant.

CONCLUSIONS AND RECOMMENDATIONS

The results of the analysis yielded many conclusions and recommendations. The first conclusion is that *FF = 0.04 gal/hp-h* is a valid fuel factor for nonroad diesel equipment. This assessment is based on an average of 31 items of equipment operating under real world conditions, using the average fuel consumption rate in its highest engine modal category. It was found that there was no statistically significant difference between the real world average fuel consumption rate and *FF = 0.04 gal/hp-h*; thus, in the absence of more detailed information, it is recommended that *FF = 0.04 gal/hp-h* continue to be used as an estimate for nonroad diesel fuel consumption. It must be remembered, however, that this is a maximum fuel consumption rate and it must be adjusted accordingly by an appropriate estimate of engine load, as well as multiplied by the engine rated horsepower in order to achieve an hourly fuel consumption rate.

The second conclusion is that modal time has an inverse relationship with modal fuel consumption. Specifically, the time spent in each mode decreases exponentially as engine mode increases from 1-10. Conversely, modal fuel consumption rates increase linearly as engine mode increases from 1-10. This means that the equipment spends most of its time operating at low engine loads that have low fuel consumption rates but spends little time operating at the highest engine loads with the highest fuel consumption rates. On average, nonroad diesel equipment typically spends about 60% of its application time operating at an engine load of 30% or less. It is recommended that equipment managers use Table 2 and Figure 1 as guides in evaluating usage of their equipment. These guides may prove helpful in other areas such as identifying proper maintenance schedules for their equipment.

The third conclusion is that weighted average fuel consumption and emissions rates account for the variability in engine load in equipment application; thus, they do not need to be adjusted for engine load which may be difficult to approximate. Weighted average rates are based on observations of in-use equipment performing real world applications, which includes time spent in low, medium, and high engine loads. The weighted average rates are a single value whereas other guides, such as manufacturers' handbooks, require the user to select a base fuel use rate and adjust it by an estimated engine load based on an estimated application. Furthermore, these types of handbooks do not provide any guidance related to emissions. It is recommended that weighted average fuel use and emissions rates be used because of their simplicity in use.

Table 4 Taxonomy of Fuel Consumption and Emissions Rates

Variable	Tier	BH	BD	EX	MG	OT	TL	WL	*Average*
FC (gal/hp-h)	**Tier 0**	0.017	0.024	0.025	0.026	0.011	0.031	0.017	*0.022*
	Tier 1	0.013	0.018	0.019	0.020	0.009	0.023	0.013	*0.016*
	Tier 2	0.012	0.015	0.016	0.016	0.009	0.018	0.012	*0.014*
NO_x (g/hp-h)	**Tier 0**	2.9	4.1	4.2	4.3	1.9	5.2	2.9	*3.6*
	Tier 1	1.7	2.2	2.3	2.4	1.2	2.7	1.7	*2.0*
	Tier 2	1.2	1.5	1.5	1.5	1.0	1.7	1.2	*1.4*
HC (g/hp-h)	**Tier 0**	0.25	0.3	0.31	0.32	0.18	0.34	0.25	*0.28*
	Tier 1	0.17	0.2	0.21	0.22	0.13	0.23	0.17	*0.19*
	Tier 2	0.15	0.16	0.16	0.17	0.12	0.17	0.14	*0.15*
CO (g/hp-h)	**Tier 0**	0.68	0.71	0.69	0.73	0.49	0.72	0.64	*0.67*
	Tier 1	0.43	0.59	0.61	0.61	0.33	0.75	0.44	*0.54*
	Tier 2	0.39	0.44	0.44	0.46	0.29	0.49	0.38	*0.41*
CO_2 (g/hp-h)	**Tier 0**	175	251	264	275	116	325	178	*226*
	Tier 1	136	192	203	212	95	247	139	*175*
	Tier 2	127	162	167	172	99	195	128	*150*
PM (g/hp-h)	**Tier 0**	0.017	0.024	0.026	0.027	0.011	0.031	0.017	*0.022*
	Tier 1	0.014	0.020	0.021	0.022	0.010	0.027	0.014	*0.018*
	Tier 2	0.009	0.012	0.012	0.013	0.007	0.015	0.009	*0.011*
NO_x (g/gal)	**Tier 0**	171	171	168	165	173	168	171	*169*
	Tier 1	131	122	121	120	133	117	131	*125*
	Tier 2	100	100	94	94	111	94	100	*99*
HC (g/gal)	**Tier 0**	15	13	12	12	16	11	15	*13*
	Tier 1	13	11	11	11	14	10	13	*12*
	Tier 2	13	11	10	11	13	9	12	*11*
CO (g/gal)	**Tier 0**	40	30	28	28	45	23	38	*33*
	Tier 1	33	33	32	31	37	33	34	*33*
	Tier 2	33	29	28	29	32	27	32	*30*
CO_2 (g/gal)	**Tier 0**	10,300	10,500	10,600	10,600	10,500	10,500	10,500	*10,500*
	Tier 1	10,500	10,700	10,700	10,600	10,600	10,700	10,700	*10,600*
	Tier 2	10,600	10,800	10,400	10,700	11,000	10,800	10,700	*10,700*
PM (g/gal)	**Tier 0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	*1.0*
	Tier 1	1.1	1.1	1.1	1.1	1.1	1.2	1.1	*1.1*
	Tier 2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	*0.8*

The fourth conclusion is that the taxonomy of fuel consumption and emissions rates provides a valid and reliable source of information for evaluating the energy and environmental impacts of nonroad diesel equipment. The taxonomy permits the user to select a fuel consumption rate and emissions rate for a specific type of equipment for a specific EPA engine tier technology type. The user is able to estimate emissions on a mass per time or a mass per fuel consumed basis. The major advantage of the taxonomy is that the user does not have to guess a value for engine load based on a vague description of equipment activity because engine load is accounted for in the taxonomy. It is highly recommended that research continue to expand the taxonomy to include other equipment types as well as Tier 3 and Tier 4 equipment.

REFERENCES

1. Dictionary.com, "Taxonomy," http://dictionary.reference.com/browse/taxonomy, Information viewed on August 1, 2015.
2. CAT. *Caterpillar Performance Handbook, Edition 44*. Caterpillar, Peoria, IL, 2014.
3. Nichols, H. and Day, D. *Moving the Earth: The Workbook of Excavation, Fifth Edition*. McGraw-Hill, New York, NY, 2005.
4. Peurifoy, R. and Oberlender, G. *Estimating Construction Costs, Sixth Edition*. McGraw-Hill, New York, NY, 2014.
5. Peurifoy, R., Schexnayder, C., Shapira, A., and Schmitt, R. *Construction Planning, Equipment, and Methods, Eighth Edition*. McGraw-Hill, New York, NY, 2011.
6. Lewis, P., Rasdorf, W., Frey, H.C., Pang, S-H., and Kim, K., "Requirements and Incentives for Reducing Construction Vehicle Emissions and Comparison of Non-road Diesel Engine Emissions Sources," Journal of Construction Engineering and Management, American Society of Civil Engineers, 135 (5), 341-351, 2009.
7. Lewis, P., Frey, H.C., and Rasdorf, W., "Development and Use of Emissions Inventories for Construction Vehicles," Transportation Research Record: Journal of the Transportation Research Board, National Research Council, Washington, D.C., 2123, 46-53, 2009.
8. Frey, H.C., Rasdorf, W., and Lewis, P., "Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment," Transportation Research Record: Journal of the Transportation Research Board, National Research Council, Washington, DC, 2158, 69-76, 2010.
9. Frey, H.C., Rasdorf, W., Kim, K., Pang, S-H., and Lewis, P., "Comparison of Real World Emissions of Backhoes, Front-End Loaders, and Motor Graders for B20 Biodiesel vs. Petroleum Diesel and for Selected Engine Tiers," Transportation Research Record: Journal of the Transportation Research Board, National Research Council, Washington, DC, 2058, 33-42, 2008.
10. Lewis, P., Rasdorf, W., Frey, H.C., Leming, M., "Effects of Engine Idling on NAAQS Criteria Pollutant Emissions from Nonroad Diesel Construction Equipment," Transportation Research Record: Journal of the Transportation Research Board, National Research Council, Washington, DC, 2270, 67-75, 2012.
11. Lewis, P., Leming, M., and Rasdorf, W., "Impact of Idling on Fuel Use and CO_2 Emissions of Nonroad Diesel Construction Equipment," Journal of Management in Engineering *Special*

Issue: Engineering Management for Sustainable Development, American Society of Civil Engineers, 28(1), 31-38, 2012.

12. Lewis, P., Leming, M., Frey, H.C., and Rasdorf, W., "Assessing the Effects of Operational Efficiency on Pollutant Emissions of Nonroad Diesel Construction Equipment," Transportation Research Record: Journal of the Transportation Research Board, National Research Council, Washington, DC, 2233, 11-18, 2011.

13. Ahn, C., Lewis, P., Golparvar-Fard, M. and Lee, S., "Toward an Integrated Framework for Estimating, Benchmarking, and Monitoring the Pollutant Emissions of Construction Operations," Journal of Construction Engineering and Management *Special Issue: Sustainability in Construction*, American Society of Civil Engineers, 139(12) A4013003, 2013.

14. Hajji, A. and Lewis, P., "Development of productivity-based estimating tool for energy and air emissions from earthwork construction activities," Smart and Sustainable Built Environment, Emerald Group Publishing Limited, 2(1), 84-100, 2013.

15. Rasdorf, W., Frey, H.C., Lewis, P., Kim, K., Pang, S-H., and Abolhassani, S., "Field Procedures for Real-World Measurements of Emissions from Diesel Construction Vehicles," Journal of Infrastructure Systems, American Society of Civil Engineers, 16 (3), 216-225, 2010.

16. Frey, H. C., Rasdorf, W., Pang, S. H., Kim, K., Abolhasani, S., and Lewis, P., "Methodology for Activity, Fuel Use, and Emissions Data Collection and Analysis for Nonroad Construction Equipment," Proceedings of the Air and Waste Management Association Annual Conference, AWMA, Pittsburgh, PA, 2007.

17. Frey, H.C., Rasdorf, W., Pang, S., Kim, K., and Lewis, P., "Methods for Measurement and Analysis of In-Use Emissions of Nonroad Construction Equipment," Proceedings of the EPA Emissions Inventory Conference, Environmental Protection Agency, Raleigh, NC, 2007.

18. Lewis, P., Fitriani, H., and Arocho, I., "Engine Variable Impact Analysis of Fuel Use and Emissions for Heavy Duty Diesel Maintenance Equipment," Transportation Research Record: Journal of the Transportation Research Board, National Research Council, Washington, DC, In Press, 2015.