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CHARACTERIZING FUEL USE AND EMISSIONS RATES OF HEAVY-DUTY DIESEL EQUIPMENT: A CASE STUDY FOR WHEEL LOADER

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ABSTRACT: Heavy duty diesel construction equipment consumes large quantities of fuel and subsequently emits significant quantities of air pollutants. This paper presents a methodology for characterizing fuel use and emissions rates of construction equipment in order to better estimate air pollution emission rates. The research is based on real-world data collected from the equipment as it performed construction activities in the field. This study examined five wheel loaders by estimating the weighted-average fuel use and emissions rates via an engine load modal analysis. For each wheel loader, the engine load data was classified into 10 modes, ranging from the minimum to the maximum engine load, and an average fuel use and emissions rates were determined for each mode. The overall weighted-average fuel use rate was determined by multiplying the modal average fuel use and emissions rates by the percentage of time spent in that particular engine mode and then summing the results for each of the 10 modes. Monte Carlo simulation was used to model the distributions of the weighted-average fuel use rate for each wheel loader by randomly selecting values (within specified ranges) for the percentage of time spent in each engine mode and the modal average fuel use rate. The results indicate that there is inter-vehicle variability in the weighted-average fuel use rates of the five wheel loaders. A sensitivity analysis was also performed in order to determine which variables have the greatest impact on the weighted-average fuel use and emissions rates.

KEYWORDS: *Heavy-duty diesel construction equipment, fuel use, emissions rates*

1. INTRODUCTION

Human health and environmental problems have been in serious concerns due to the effect of air pollution. Construction activities consume a substantial amount of fuel and contribute a significant amount of pollutants emitted to the environment. EPA (2005) mentioned that approximately more than two million items of construction and mining equipment in the United States spend about six billions gallons of diesel fuel annually. Furthermore, in most construction activities, heavy-duty diesel (HDD) construction equipment is the primary source of emissions. It was estimated that in 2005 HDD construction vehicles produced U.S. national annual totals of 657,000 tons of NO_x, 1,100,000 tons of CO, 63,000 tons of PM_{10} and 94,000 tons of SO_2 (EPA, 2005). HDD construction equipment is typically a larger contributor of PM and NOx accounting for 65% and 30%, respectively (EPA, 2006).

HDD plays a significant role in contributing emissions to the environment which also affect human health problems. Diesel exhaust (DE) emissions are comprised of many constituents of pollutants such as oxides of nitrogen (NO_x), oxides of sulfur (SO_x), particulate matter (PM), and carbon monoxide (CO), Hydrocarbons (HC) and carbon dioxide (CO_2). According to EPA (2002), DE exposure may cause both long term and short term effects. Long term or chronic exposure to DE is potentially to trigger a lung cancer and lung damage risk to human. Meanwhile, short term or acute exposure to DE may pose irritation of the eyes and throat,

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neurophysiological symptoms (lightheadedness, nausea) and respiratory symptoms (cough, phlegm).

In order to address the issue with respect to the significant influence of DE from HDD to environment and human health, there is a need to measure the level of emission productions and fuel consumptions from HDD construction equipment. However, there is lack of research related to estimating fuel use and emission rates for HDD construction equipment based on the real-world data. Therefore, a thorough and reliable study on fuel use and emission rates quantification based on real-world data is essentially required.

This paper presents a methodology for characterizing fuel use rates and emission rates of construction equipment in order to better estimate air pollution impact. It is based on real-world data collected from the equipment as it performed construction activities in the field. This case study examined five wheel loaders by estimating the weighted-average fuel use rate via an engine load modal analysis.

2. PREVIOUS WORKS

Some of the most prominent real-world emissions measurements from HDD construction equipment were completed by the researchers at North Carolina State University (Abolhasani *et al.*, 2008; Lewis, 2009; Rasdorf *et al.*, 2010; Frey *et al.*, 2008; Kim, 2007). Other researchers from West Virginia University and the University of California – Riverside also directed their studies on the use of on-board emission measurement for particular construction equipment.

Lewis *et al.* (2012) studied the influence of engine idling with respect to fuel use and emission rates of CO_2 for HDD construction equipment. Similar to the prior study, this study also investigated 34 items of construction equipment which comprised of 8 backhoes, 6 bulldozers, 3 excavators, 6 motor graders, 3 off-road trucks, 3 truck loaders, and 5 wheel loaders. Moreover, this study determined the operational efficiency of each item of equipment indicated by the ratio of nonidle time to total equipment use time. The results showed that nonidle fuel use and emission rates were significantly higher than those in idle condition. In addition, results also showed that as idle time increased, the fuel use and emissions rates of CO_2 increased significantly.

Abolhasani *et al.* (2008) mainly focused on measuring fuel use and emission rates of NO_x, CO, HC, CO_2 and PM for hydraulic excavators using real-world measurement. This study showed that nearly 90% of measurement was valid and approximately 50% of nitric oxides emissions were produced during 30% of the time of operation. Moreover, mass per time emission rates for nonidle activity modes were significantly higher; seven times compared to those of idle modes. Frey *et al.* (2008a) compared petroleum diesel and B20 emissions from backhoes, motor graders, and wheel loaders while performing typical duty-cycles. Furthermore, Frey *et al.* (2008b) highlighted the field activity, fuel use, and emissions of motor graders in terms of using petroleum diesel and B20 biodiesel.

3. METHODOLOGY

This paper presents a methodology for characterizing fuel use and emissions rates of heavy-duty diesel construction equipment specifically for five wheel loaders. However, only the calculations for fuel use rates are presented. Engine load was determined by measuring the MAP, which was used as a surrogate for engine load. Since most of the equipment has various ranges of MAP values, normalization of the MAP was conducted as explained by the following equation.

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$$MAP\ nor = \frac{\text{MAP}-\text{MAP min}}{\text{MAP max}-MAP\ min} \tag{1}$$

where:

MAP_{nor}	= Normalized MAP for a measured MAP for a specific item of equipment
MAP_{max}	= Maximum MAP for a specific item of equipment
MAP_{min}	= Minimum MAP for a specific item of equipment
MAP	= Measured MAP for a specific item of equipment

For each wheel loader, engine load data was classified into 10 modes, ranging from the minimum to the maximum engine load, and an average fuel use rate was determined for each mode. The overall weighted-average fuel use rate was determined by multiplying the modal average fuel use rate by the percentage of time spent in that particular engine mode and then summing the results for each of the 10 modes.

Monte Carlo simulation was used to model the distributions of the weighted-average fuel use rate for each wheel loader by randomly selecting values (within specified ranges) for the percentage of time spent in each engine mode and the modal average fuel use rate.

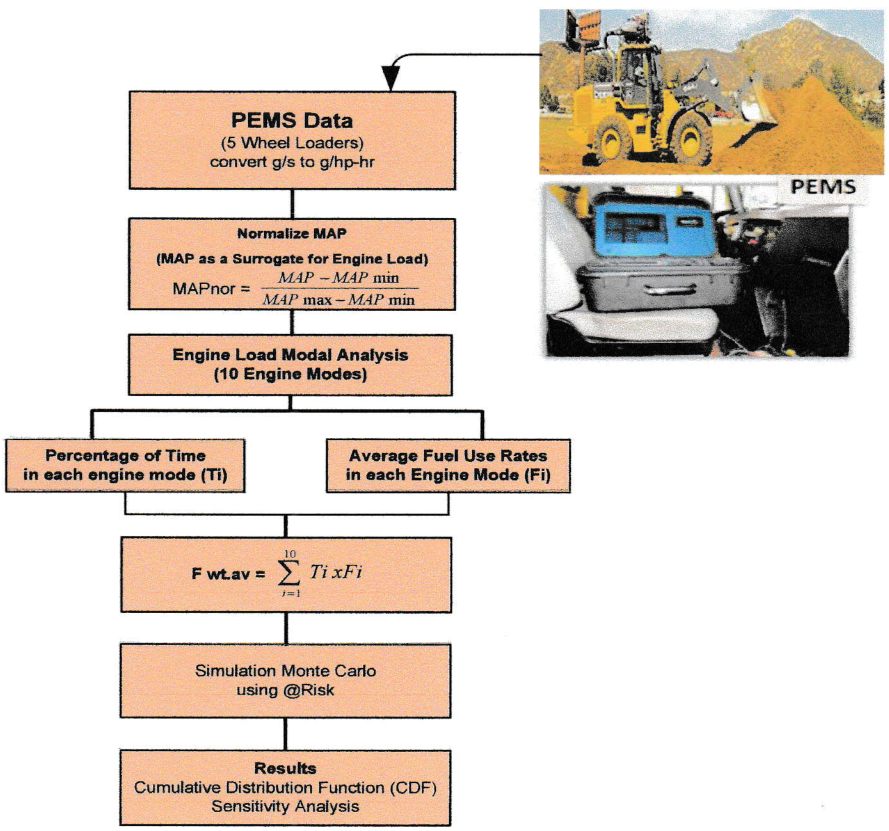

Figure 1. Procedure for Monte Carlo Simulation

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Two scenarios were developed for analysis:

- **Scenario 1**

Assume distribution % of time and fuel use rates for each mode in each wheel loader as lognormal function where the parameters are mean and standard deviation (10% of mean value).

- **Scenario 2**

Assume distribution % of time as lognormal function where the parameters are mean and standard deviation (10% of mean value) and fuel use rates for each mode in each wheel loader using fitted distribution.

4. RESULTS

This section presents the results of the weighted average of fuel use and emissions rates for five wheel loaders. The weighted-average fuel use as a function of percentage of time and fuel use rate is explained. Data from wheel loader 1 is provided as a baseline for analyzing further results.

Table 1 presents the summary of average percentage of time for each engine mode in 5 wheel loaders including the total average of all wheel loaders. Meanwhile, Figure 2 shows the distribution of engine modes and average percentage of time for 5 wheel loaders.

As seen in the table, it was found that the higher the engine load (shown by the minimum to maximum orders of engine modes), the lower the percentage of time spent in each engine mode. As indicated from the Table 1 and Figure 2, approximately 40% of time was spent in engine mode 1, 20% in engine mode 2, and 13% in engine mode 3, and less than 2% of time in engine mode 10. The average percentages of time are used to calculate the weighted average fuel use and emission rates.

Table 1. Percentage of Time in each Engine Mode

Modes	WL1	WL2	WL3	WL4	WL5	Average
1	46.99%	20.73%	48.44%	28.99%	54.71%	39.97%
2	18.98%	18.07%	17.22%	23.09%	22.49%	19.97%
3	9.83%	19.52%	8.74%	17.99%	5.84%	12.38%
4	6.78%	15.49%	6.96%	7.51%	4.61%	8.27%
5	4.85%	11.83%	4.65%	3.54%	2.80%	5.53%
6	3.89%	6.53%	3.94%	3.69%	2.26%	4.06%
7	2.37%	4.04%	3.27%	4.82%	1.55%	3.21%
8	2.36%	2.10%	2.83%	6.21%	1.72%	3.04%
9	2.33%	0.94%	2.31%	3.74%	2.09%	2.28%
10	1.63%	0.75%	1.64%	0.42%	1.93%	1.27%
Total						**100.00%**

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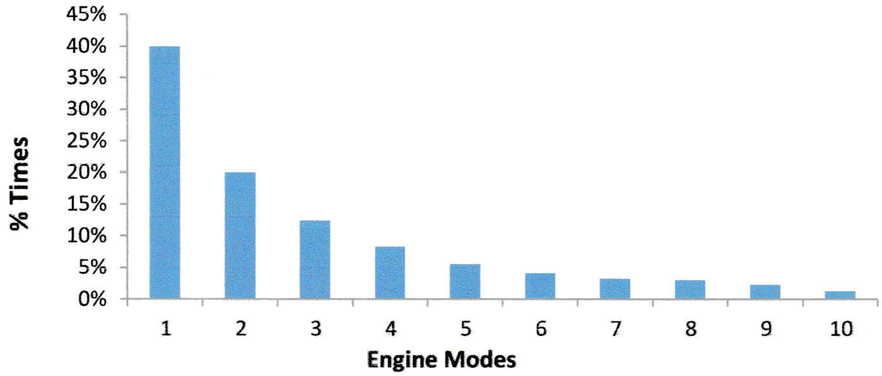

Figure 2. Average Engine Mode Distribution

Table 3 presents summary statistics and distribution graphs of weighted average fuel use rates for each wheel loader using Scenario 1 and 2. The graphs indicate there is variability in each wheel loader.

Table 2. Results using Deterministic Approach for Wheel Loader 1 (Baseline)

Modes	Times (%)	Fuel Use (g/hp-hr)	Wt. average Fuel use (g/hp-hr)
1	46.99%	0.00674	0.00317
2	18.98%	0.01102	0.00209
3	9.83%	0.01432	0.00141
4	6.78%	0.01806	0.00122
5	4.85%	0.02078	0.00101
6	3.89%	0.02355	0.00092
7	2.37%	0.02635	0.00062
8	2.36%	0.03007	0.00071
9	2.33%	0.03397	0.00079
10	1.63%	0.04117	0.00067
Total			**0.01261**

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Table 3. Summary Statistics and Distribution Graphs for 5 Wheel Loaders Using Scenario 1 and 2

Scenario	WL	Weighted Average Fuel Use Rate (g/hp-hr) Min	Mean	Max	5%	95%	Graph
1	WL 1	0.0101	0.0126	0.0155	0.0115	0.0137	
	WL 2	0.0133	0.0166	0.0203	0.0152	0.0180	
	WL 3	0.0067	0.0082	0.0101	0.0076	0.0089	
	WL 4	0.0077	0.0093	0.0111	0.0085	0.0100	
	WL 5	0.0075	0.0094	0.0118	0.0086	0.0103	
2	WL 1	0.0070	0.0126	0.0196	0.0101	0.0155	
	WL 2	0.0118	0.0166	0.0272	0.0146	0.0187	
	WL 3	0.0053	0.0083	0.0133	0.0069	0.0100	
	WL 4	0.0065	0.0093	0.0209	0.0078	0.0110	
	WL 5	0.0066	0.0095	0.0132	0.0082	0.0109	

Figure 3 and 4 illustrate detail comparison of CDF for weighted average fuel use rates of wheel loader 1 using scenario 1 and 2.

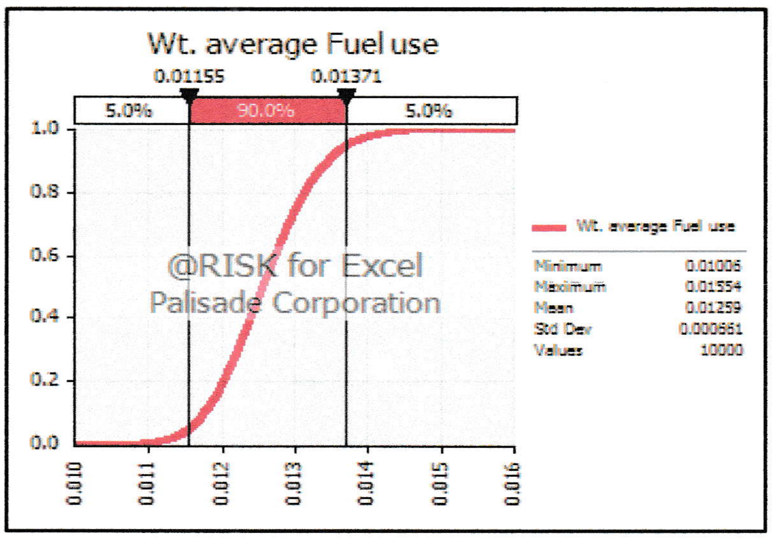

Figure 3. CDF for Weighted Average of Fuel Use Rate of Wheel Loader 1 using Scenario 1

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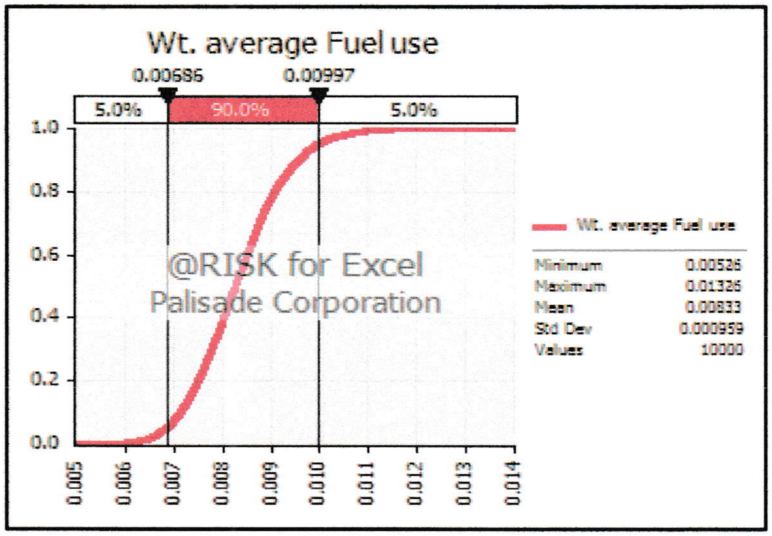

Figure 4. CDF for Weighted Average of Fuel Use Rate of Wheel Loader 1 using Scenario 2

A sensitivity analysis was also performed in order to determine which variables have the greatest impact on the weighted-average fuel use factors. Table 3 shows higher variability in Scenario 2 compared to Scenario 1; thus, a sensitivity analysis was completed for Scenario 2 as shown in Figure 5. Datasets illustrate that fuel use rate in mode 1 has the highest impact to the total weighted average fuel use rate. This is followed by mode 2 as the second most important variable.

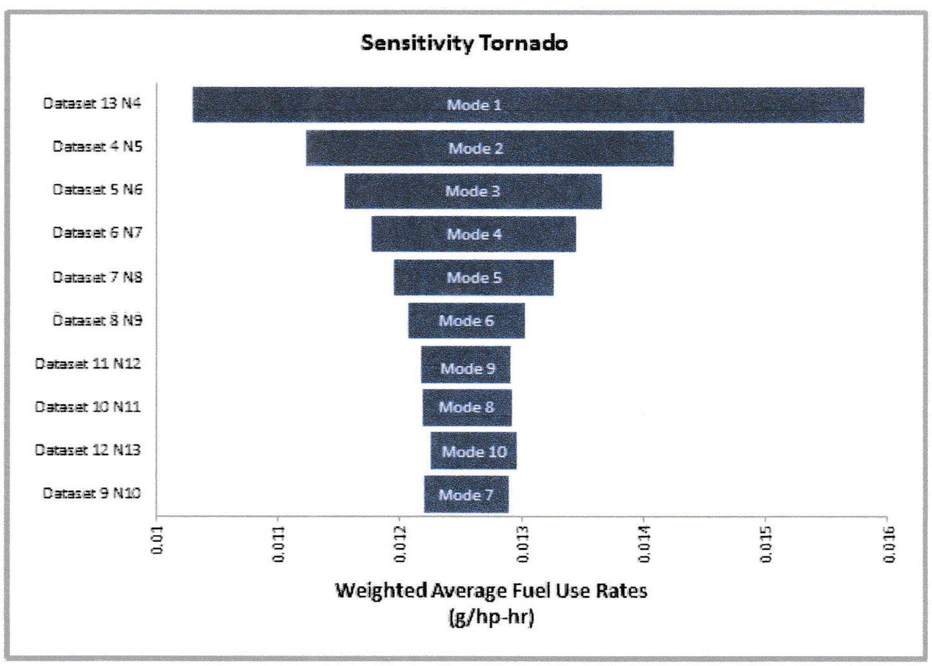

Figure 5. Sensitivity Analysis for Wheel Loader 1 in Scenario 2

5. CONCLUSIONS

The purpose of this paper was to demonstrate a methodology for characterizing fuel use rates and emission rates of construction equipment in order to better estimate air pollution impact. It is based on real-world data collected from the equipment as it performed construction activities in the field. This case study examined five wheel loaders by estimating the weighted-average fuel use rate via an engine load modal analysis.

It can be concluded that the fuel use rates increase as engine modes increase. The results for emissions rates for each pollutant actually followed the same results. It was found that fuel use and emission rates (g/hp-hr) increase significantly when engine modes reach to maximum values. This simply means that there are linear relationships between the fuel use and emission rates and engine modes. Therefore, the weighted average fuel use and emission rates were obtained by the multiplication of the average percentages of time and fuel use and emissions rates for each engine mode.

Monte Carlo simulation was used to model the distributions of the weighted-average fuel use rate for each wheel loader by randomly selecting values (within specified ranges) for the percentage of time spent in each engine mode and the modal average fuel use rate. The results indicate that there is inter-vehicle variability in the weighted-average fuel use rates of the five wheel loaders. The mean value for weighted average fuel use rates for scenario 1 and 2 are not significantly different. However, there is variability in the minimum and maximum values for weighted average fuel use rates including the values using 5% and 95% percentile.

Sensitivity analysis indicates that mode 1 has the highest impact to the total weighted average fuel use rate. This is then followed by mode 2 and mode 3 that gave the second and third highest impacts to the total weighted average fuel use rate.

Overall, the results of this study help quantify and characterize the air pollution problems from HDD equipment used in construction. The methodologies presented may certainly be used to develop fuel use and emissions prediction for other types of equipment.

6. ACKNOWLEDGEMENT

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