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E3 – a User's Interface for Quantifying Total Cost, Diesel Consumption, and Emissions from Bulldozers and Its Comparison to Field Data

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Abstract. The use of bulldozer in construction projects determines a vast number of diesel consumption, emissions and the portion of total cost of the project. Construction equipment operators need a method that can be utilized to predict and quantify not only the cost, but also the diesel consumption and emissions of construction projects, particularly for bulldozer's activities. The main purpose of this paper is to propose an E3, the predicting tool for the economic, energy, and environmental impact of the use of bulldozer. The tool was developed by using the productivity rate model of bulldozer to the US EPA's NONROAD model. The results show that the bulldozer's productivity model can be used as the platform for predicting the total cost and diesel consumption that will be required and the total expected emissions for the project.

INTRODUCTION

Bulldozers are used intensively in constructing the roads, toll ways and other infrastructures. There are nearly more than half of million bulldozers used in roads construction and mining globally. The US Environmental Protection Agency (EPA) said that bulldozers can consume billions gallons of diesel diesel and emits thousands tons pollutants [1]; therefore, infrastructure projects have important impact on the environment, especially which relates to diesel consumption and air quality. Because some of worldwide environmental authorities were mandated responsibilities to minimize the emissions of pollutants, bulldozer owners and managers have to put their serious attention to the environmental effects of their work. A tool that can be used to the diesel consumption and emissions quantity of construction projects, particularly from equipment activities like bulldozers is needed. The purpose of this study is (1) to propose a model that can be used as user's interface to calculate and estimate the cost, diesel, and emissions quantity from a bulldozer, and (2) to compare the results from the model to actual field data to display the relationships between them.

PREVIOUS STUDIES

In estimating cost, diesel consumption, and emissions from bulldozers, productivity rate is a determinant factor. CO_2 emissions are dependent upon of diesel consumption, and diesel consumption is dependent upon productivity. Productivity is determined by the ratio of the quantity of soil to the duration of work [2]. For example, if a bulldozer hauls 1,000 bank cubic yards (bcy) of earth in ten hours (hr), the productivity rate is 100 bcy/hr. This ratio also shows that the duration of a bulldozer activity is inversed to productivity – when productivity rate is higher, the duration is lower. When the duration of bulldozer is high, it will lead to high costs, high diesel consumption rate, and high emissions rate. Therefore, it is important to estimate a bulldozer's productivity prior to estimate it's cost, diesel consumption, and emissions.

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Some techniques and approaches have been studied to quantify emissions by using models or simulations. Some studies used machine's attributes, or diesel types and characteristics, or type of construction equipment activities to estimate or quantify the emissions rates. Heidari et.al. [3] predicted emissions by using three different methods: NONROAD2008, OFFROAD2011, and a modal statistical model. The main differences among them were generated by lower diesel consumption rates than estimated. Emission factors during working in the field were different from each equipment and from those of other earthwork activities. The use of diesel is also related to equipment's productivity rate. There is also a relationship between energy use and overall factors of productivity by the use of technological efficiency enhancement [4 and 5]. In term of engine attributes, the manifold absolute pressure (MAP) also had the biggest influence on diesel consumption and emissions rate quantification [6]. Some research also reveal that it is a good opportunity to identify total equipment emissions based on project volume, working time, and total cost [7]. The use of information on the productivity rate and engine performances of selected construction equipment and the volume of soil to be dozed during earthwork activities is also crucial in quantifying emissions. It is later utilized as initial information for quantifying the energy use and carbon-dioxide emissions of the working equipment. The method will help estimators and operators to observe the energy and environmental information of earthmoving plans, and to choose proper equipment that will reduce these quantities [8]. The emissions estimate can also be produced by using Artificial Neural Network (ANN). Jassim, et.al. [9] used the CAT handbook's performance data, that covered operational configurations of more than twenty types of excavators. The ANN models were also applied to investigate which aspects from all the pre-work parameters have the most significant impact on energy and emissions, based on weighting approach. Moreover, some researchers also propose the method in reducing CO2 emissions. The proposed methods include identifying and comparing a set of realistic project alternatives, and conducting this at an early stage of the project planning process so that favorable alternatives can be implemented during construction [10]. To support this effort, Lewis and Rasdorf [11] use the method that is called taxonomy of diesel consumption and emissions rate. The taxonomy of diesel use gives an precise and practical platform to help equipment operators in quantifying diesel consumption and following pollutants. For practical level, it is also important to develop a mathematical model that could be a basis for managing emissions from earthwork construction with accurate methods and tools [12, 13, and 14].

METHOD

The proposed quantifying tool is developed by inserting the productivity rate model from an equipment's performance data source into the algorithm from the EPA's NONROAD model (Figure 1). In order to develop the models, earthwork activity using a bulldozer was retrieved. The information for this selected earthmoving work was collected from RSMeans Heavy Construction Data 2010. The RSMeans will help estimators and equipment operators to compare and investigate design alternatives, conduct cost analysis, and review change orders prepared by other parties in the project [15]. The data from RSMeans also covers information of the project according to the newest Construction Specification Institute (CSI) Master Format classification system, which has 48 divisions ranging from General Requirements to Electrical Power Generation.

Bulldozer activity is provided in 'Earthwork' section. Based on the data from RSMeans, the productivity rate and was developed by using multiple linear regression (MLR). The MLR model is written in the following form:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip} + \varepsilon_i \qquad (1)$$

where:

- y_i is the response, which is productivity rate at i-th observation
- $\beta_0, \beta_1, \beta_2, \ldots \beta_p$ are the coefficients in which the explanatory variables correspond to, while β_0 is the intercept.

The information of engine horsepower (HP) and engine model year is used to calculate the diesel consumption and the amount of emission. To estimate diesel consumption and total emissions, emission factors (EF) and brake-specific diesel consumption (BSFC) were needed. The EF and BSFC for this calculation were taken from the EPA's NONROAD Model [16]. For the emissions of NOx, HC, and CO, the calculation is as follows:

$$EF_{adj(NOx,\, HC,\, CO)} = EF_{ss}\ x\ TAF\ x\ DF \qquad (2)$$

where:

EF_{adj} = emission factor (g/hp-hr)
EF_{ss} = zero-hour emission factor (g/hp-hr)
TAF = transient adjustment factor (unitless)
DF = deterioration factor (unitless)

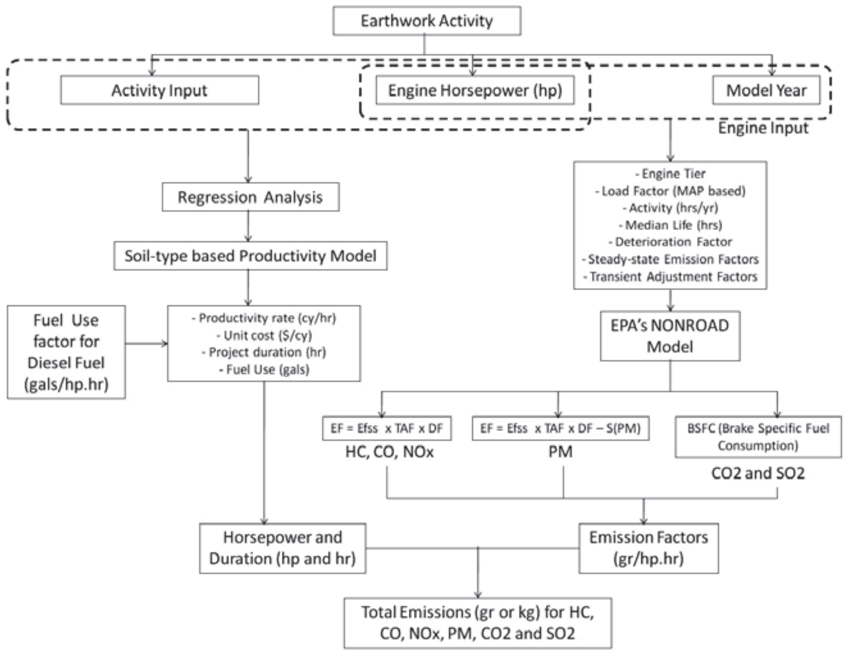

FIGURE 1. Development methodology of E3 quantifying tool

The TAF and DF used in the emission quantification were taken from EPA's *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition* [16]. The calculation for EF of PM is as follows:

$$EF_{adj(PM)} = EF_{ss} \ x \ TAF \ x \ DF - S_{PMadj.} \quad (3)$$

where:
S_{PMadj} = PM emission factor (g/hp-hr).

For BSFC, DF is not applied, so the algorithm is as follows:

$$EF_{adj(BSFC)} = EF_{ss} \ x \ TAF \quad (4)$$

NONROAD model estimates CO_2 emissions from operational BSFC; so

$$EF_{adj(CO2)} = (BSFC \ x \ 453.6 - HC) \ x \ 0.87 \ x \ (44/12) \quad (5)$$

where:
BSFC = operational brake specific fuel consumption (lbs/hp-hr)
453.6 = conversion from pounds to gram
HC = operational hydrocarbon emission (g/hp-hr)
0.87 = carbon mass fraction
44/12 = ratio of CO_2 mass to carbon mass

The individual diesel consumption and emissions estimates for bulldozer were quantified by using EPA's *Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling* [17].

To compare the calculation results from E3 model with the on-field diesel consumption and emissions, the field data were measured by using portable emissions measurement system (PEMS). The PEMS was set on the working bulldozers and inserting cords to the body of engine. Previous research by Rasdorf et al. [18] have demonstrated the techniques and methods of acquiring operational emissions by using of PEMS.

RESULTS AND DISCUSSION

Productivity and Cost Models

To have a robust model for quantifying the productivity and total cost, the data are separated into two sets: model developing data set and model validating data set. Since the data have the evidence of unequal variance, the final MLR model of productivity and cost have to be transformed. The transformed models for bulldozer's productivity and total cost are shown in Table 1 and Table 2

TABLE 1. Productivity models for bulldozer

Soil Type	Productivity Model
Sand-gravel	$Y = (1.8786 + 0.0035X_1 - 0.0024X_2 + 0.23656)^5$
Sandy clay-loam	$Y = (1.8786 + 0.0035X_1 - 0.0024X_2 + 0.21667)^5$
Common earth	$Y = (1.8786 + 0.0035X_1 - 0.0024X_2 + 0.16644)^5$
Clay	$Y = (1.8786 + 0.0035X_1 - 0.0024X_2)^5$

where:
Y = bulldozer productivity (bcy/hr)
X_1 = engine horsepower (hp)
X_2 = dozing distance (feet)

TABLE 2. Cost models for bulldozer

Soil Type	Cost Model
Sand-gravel	$Y = 10^{(1.565 - 0.00398X1 + 0.0058X2 - 0.574)}$
Sandy clay-loam	$Y = 10^{(1.565 - 0.00398X1 + 0.0058X2 - 0.539)}$
Common earth	$Y = 10^{(1.565 - 0.00398X1 + 0.0058X2 - 0.430)}$
Clay	$Y = 10^{(1.565 - 0.00398X1 + 0.0058X2)}$

where:
Y = unit cost ($/bcy)
X_1 = engine horsepower (hp)
X_2 = dozing distance (feet)

A plot in Figure 2 shows both the productivity and cost models were accurate, precise, and had no bias. It can be decided that the MLR models for bulldozer appropriately indication have the good predictive ability.

E3 – Economic, Energy, Environmental Models

The 'economic' refers to cost models, the 'energy' refers to total amount of diesel consumption, and the 'environmental' refers to total emission. The cost is calculated in dollars per cubic yard ($/cy), the soil quantity in cubic yard (cy), and the total cost in dollars ($).

The estimation formula for obtaining the total diesel consumption and emissions are formulated by inserting the productivity model to EPA's NONROAD model. To estimate the total emissions and diesel consumption from an earthwork performed by a bulldozer, the time duration of work is required. The time duration is acquired by dividing the soil volume with the productivity rate. Because the time duration acquired and engine's HP is given, the estimated emission will be calculated by multiplying the EF or BSFC with engine's horsepower (hp) and time duration (hr).

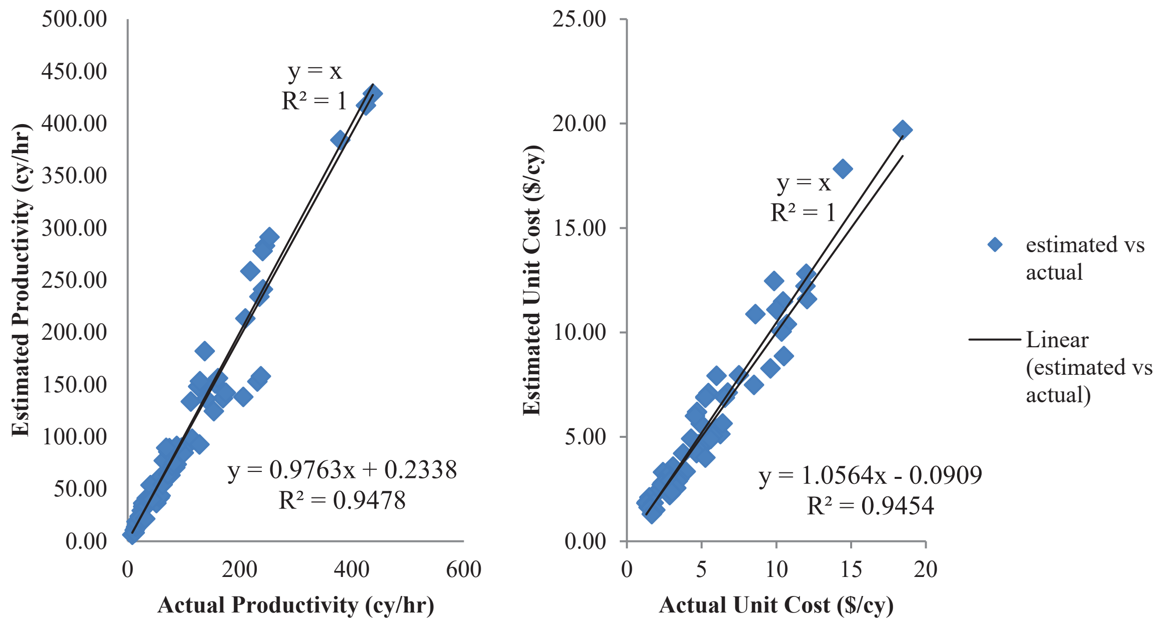

FIGURE 2. Predicted versus actual productivity rate and unit cost

$$E\ (gr) = Duration\ (hr) * engine\ horsepower\ (hp) * Emission\ factor\ (\frac{gr}{hp.hr}) \quad (6)$$

$$E\ (gr) = \frac{Soil\ Quantity\ (cy)}{Productivity\ Rate\ (\frac{cy}{hr})} * engine\ horsepower\ (hp) * Emission\ factor\ (\frac{gr}{hp.hr}) \quad (7)$$

$$F\ (gal) = \frac{Soil\ Quantity\ (cy)}{Productivity\ Rate\ (\frac{cy}{hr})} * engine\ horsepower\ (hp) * BSFC\ (\frac{gal}{hp.hr}) \quad (8)$$

The final calculation algorithm for quantifying each emission and diesel consumption are as follows:

For HC, CO, and NO_x:

$$E = \frac{Q}{(1.879+0.0035HP-0.0024D+fs)} * HP * EFss * TAF * DF \quad (9)$$

For PM:

$$E = \frac{Q}{(1.879+0.0035HP-0.0024D+fs)} * HP * ((EFss * TAF * DF) - S_{PM}) \quad (10)$$

For CO_2

$$E = \frac{Q}{(1.879+0.0035HP-0.0024D+fs)} * HP * ((BSFC * 453.6 - HC) * 0.87 * \left(\frac{44}{12}\right)) \quad (11)$$

For Diesel consumption:

$$F = \frac{Q}{(1.879+0.0035HP-0.0024D+fs)} * HP * (BSFC) * TAF \quad (12)$$

where,

E = emission (gr)
F = diesel consumption (gal)
Q = quantity of soil dozed/moved (cy)
fs = soil type factor (common earth: 0.166; sandy clay-loam: 0.2167; sand-gravel: 0.2366; clay: 0)
HP = engine horsepower (hp)
D = distance (feet)
EFss = steady state emission factor (gr/hp.hr)
TAF = transient adjustment factor (unitless)

DF = deterioration factor (unitless)
S_{PM} = diesel sulfur content for PM (gr/hp.hr)
EF(BSFC) = emission factor for brake-specific-diesel-consumption (gal/hp.hr)

Comparison with Field Data

Comparing the PEMS measurement data with E3 calculation results is conducted to observe if both quantities have similarities. In the field, PEMS had been installed in six different bulldozers with different engine's HP, different model year, and categorized in different engine tiers. The data of observed bulldozers are displayed in Table 3.

TABLE 3. Bulldozers used for PEMS field measurement

Equipment	Horsepower (HP)	Model Year	Engine Tier	Work Duration (hrs)
Bulldozer 1	89	1988	0	0.839
Bulldozer 2	95	2002	1	5.862
Bulldozer 3	90	2003	1	2.631
Bulldozer 4	175	1998	1	2.188
Bulldozer 5	285	1995	0	2.083
Bulldozer 6	99	2005	2	1.415

PEMS acquires total emissions of bulldozer based on the EF at its rated engine horsepower in terms of mass per time. Table 4 and Table 5 display the total diesel consumption and total emissions from both E3 model and PEMS results.

TABLE 4. Diesel consumption comparison between E3 model and PEMS measurement results

Equipment	Diesel consumption			
	Diesel consumption Factor (gal/hp-hr)		Total Diesel consumption (gal)	
	E3	PEMS	E3	PEMS
Bulldozer 1	0.049	0.062	3.69	4.62
Bulldozer 2	0.049	0.037	27.54	20.46
Bulldozer 3	0.049	0.072	11.71	17.01
Bulldozer 4	0.044	0.056	17.03	21.29
Bulldozer 5	0.044	0.061	26.40	36.31
Bulldozer 6	0.049	0.015	6.93	2.05

In general, the average total diesel consumption obtained from E3 is relatively similar to those from field PEMS measurement. The average total diesel consumption from six bulldozers estimated by E3 is 15.6 gallons, while that measured by PEMS is 16.9 gallons or 9% higher. For bulldozer 2 and 6, E3 estimates higher than PEMS results, while for bulldozer 1, 3, 4, and 5 E3 estimates lower than PEMS results. Bigger difference magnitude was found in comparison of total emissions from these two sources. In average, total HC emission estimated by E3 is 6% lower than by PEMS, while estimated total CO emission is 63% higher, total NO_x emission is 124% lower, total PM emission is 87% higher, and total CO_2 emission is 63% lower than those by PEMS. These big differences between those two results are due to the basic estimation of NONROAD model which is used in E3 estimating tool. In estimating diesel consumption and emissions, NONROAD uses approximate usage of transient adjustment factors (TAF) and engine load factors that estimate a fraction of the engine power.

TABLE 5. Total emission comparison between E3 model and PEMS measurement

Equipment	Total Emission									
	HC (gr)		CO (gr)		NO_x (gr)		PM (gr)		CO_2 (kg)	
	E3	PEMS	E3	PEMS	E3	PEMS	E3	PEMS	E3	PEMS
Bulldozer 1	50.2	26.0	324.2	116.7	302.9	585.9	75.9	7.7	26.1	48.9
Bulldozer 2	182.8	283.2	1243.7	249.6	1766.6	1671.2	224.5	28.4	195.3	216.3
Bulldozer 3	77.7	108.1	528.8	250.2	751.1	2398.8	95.5	48.3	83.1	180.3
Bulldozer 4	83.6	182.1	334.0	536.2	1246.4	3822.2	114.8	14.3	120.9	224.9
Bulldozer 5	267.4	92.5	1842.2	521.1	2887.0	7726.3	286.8	N/A	187.0	385.0
Bulldozer 6	32.4	43.5	312.9	39.1	370.5	167.8	27.7	9.8	49.2	21.6

CONCLUSION

The total diesel consumption and total emissions estimates from the output of E3 model can be used as a platform in observing the energy-economic-environmental impact of earthwork activities performed by bulldozers. Total diesel consumption estimates can help the bulldozer or other equipment operators in deciding the type and the engine size to be deployed in the field. Regarding the field and working conditions, such as soil type and hauling distance, total diesel consumption and emissions will be higher as the soil becomes more hard to doze or haul, or as the area or distance becomes larger or further. As for total emissions, generally, the total emissions will be lower when the horsepower of the engine is bigger. The equipment operators can now decide that by using more powerful engine, indicated by bigger blades or scoop, the productivity rate will be higher and the time duration of the activities will be shortened.

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