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Combining Off-the-Job Productivity Regression Model with EPA's NONROAD Model in Estimating CO_2 Emissions from Bulldozer

Hajji, A.M.[1*], Larasati, A.[2], and Lewis, M.P.[3]

Abstract: Heavy duty diesel (HDD) construction equipment which includes bulldozer is important in infrastructure development. This equipment consumes large amount of diesel fuel and emits high level of carbon dioxide (CO2). The total emissions are dependent upon the fuel use, and the fuel use is dependent upon the productivity of the equipment. This paper proposes a methodology and tool for estimating CO_2 emissions from bulldozer based on the productivity rate. The methodology is formulated by using the result of multiple linear regressions (MLR) of CAT's data for obtaining the productivity model and combined with the EPA's NONROAD model. The emission factors from NONROAD model were used to quantify the CO_2 emissions. To display the function of the model, a case study and sensitivity analysis for a bulldozer's activity is also presented. MLR results indicate that the productivity model generated from CAT's data can be used as the basis for quantifying the total CO_2 emissions for an earthwork activity.

Keywords: Bulldozer; CO_2 emissions; EPA's NONROAD model; productivity rate.

Introduction

The productivity of construction equipment has long been estimated and studied along with the project costs. Some models have been developed to accurately estimate economic impact of infrastructure projects [1]. However, these models typically do not address the environmental issues. It is important to lay the groundwork for a tool that can be used to estimate not only the productivity rate of heavy duty diesel (HDD) equipment, but also to use it as the basis for estimating fuel use and pollutant emissions. This paper proposes a method to develop an emission and energy estimation tool for bulldozer. This tool can be also used to quantify the impacts of various energy and environmental mitigation strategies. This tool can help fleet managers to quantify fuel consumption and emissions of GHG and air pollutants for each individual item of equipment.

CO_2 emissions are dependent upon 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]. 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 its cost, diesel consumption, and emissions.

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. A study has been performed to predict emissions by using three different methods: NONROAD2008, OFFROAD2011, and a modal statistical model [3]. 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 [4,5]. 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 earth-

[1] Civil Engineering Department, Universitas Negeri Malang, Malang, INDONESIA.
[2] Industrial Engineering Study Program, Universitas Negeri Malang, Malang, INDONESIA.
[3] School of Civil and Environmental Engineering, Oklahoma State University, USA.
* Corresponding author; Email: apif.miptahul.ft@um.ac.id

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work 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 earth-moving 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). Researchers have used the CAT handbook's performance data, that covered operational configurations of more than twenty types of excavators [9]. 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 CO_2 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 as cited in [11] use the method that is called taxonomy of diesel consumption and emissions rate. The taxonomy of diesel use gives a 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 [12-14].

Method

The study used CAT Performance Handbook, which provides various types of construction equipment's performance data. The data covers specifications and off-the-job projection of their productivity. For the purpose of this paper, bulldozer section was used. The productivity estimates in this handbook are based on several factors, such as engine and operational conditions. In this study, the estimates of productivity rate for bulldozer is projected by using productivity chart for universal type of blade (Figure 1). The chart is used with the data of bulldozer's specifications as activity inputs, such engine size, blade capacity, hauling distance, working efficiency, soil grade, and operator's skill. The information regarding the activity characteristics of bulldozer used in this study to obtain productivity model are shown in Table 1. The information will then be analyzed by using regression to formulate the productivity estimates for bulldozer.

The emissions of CO_2 correlates to the consumption of fuel. To estimate the total fuel use, it was required to have productivity rate and working time for the bulldozer. The working time (hr) was acquired by dividing the volume of soil to be hauled or dozed by the predicted hourly productivity rate. The working time (hr) was then multiplied by the engine size (horsepower or hp) and the fuel use rate for diesel engines (0.04 gal/hp-hr) [15] to have the fuel consumed for bulldozer's activity (gal).

The CO_2 emissions has a significant correlation with fuel use [3]. It is about 10.15 kilograms (kg) of CO_2 is released for one gallon consumption ofdiesel fuel [2]. To predict CO_2 emissions from bulldozer's activity, the total diesel fuel consumption (gal) was multiplied by 10.15 kg/gal and converted to pounds (lbs) based on 454 grams per pound.

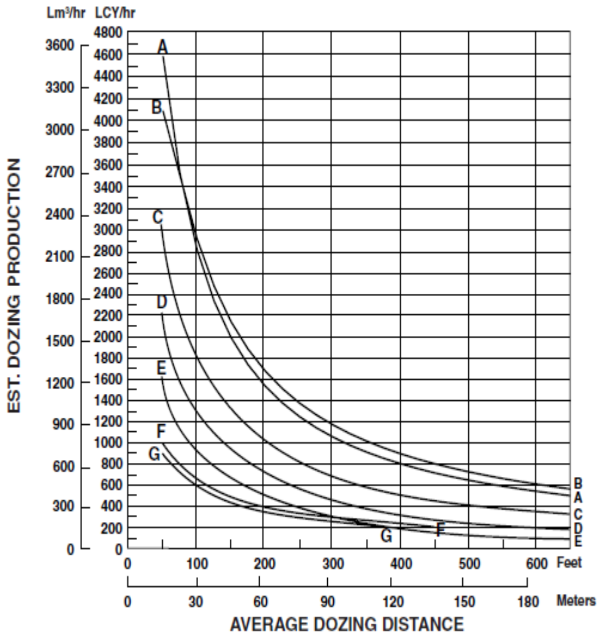

Figure 1. Productivity Chart for CAT Bulldozer with Universal Type of Blade

Table 1. Activity Inputs of Bulldozer.

Type of Equipment	Activity Input	Unit/type/range
Bulldozer	Engine size	Horsepower (HP)
	Capacity of Scoop or Blade	7.53-45 cy
	Dozing Distance	100-500 feet
	Operational Efficiency	67-83%
	Soil grade	0.2-1.8
	Skills of Operator	Excellent Average poor
	Soil type	Loose-stockpile Hard-to-cut Hard-to-drift Rock-ripped-blasted
	Dozing techniques	Slot-dozing Side-by-side

Results and Discussion

The CAT Performance Handbook gives 2,880 observations of bulldozer's activity, which is taken from the chart of off-the-job productivity rate, and by using operational factors such as job efficiencies, soilor terrain slope, skillof operator, type of soil or terrain, and dozing or hauling methods. Table 2 shows the result of regression analysis with significance level at α = 0.05.

Table 2. Regression Coefficients for Productivity – CAT

Variable	Coefficient	Parameter estimate	t-value	p-value
Intercept	β_0	-761.221	-10.28	<0.0001
Blade capacity	β_1	-7.937	-1.06	0.2896
Horsepower	β_2	1.502	3.56	0.0004
Dozing distance	β_3	-1.646	-39.06	<0.0001
Job efficiency	β_4	628.041	7.30	<0.0001
Soil grade	β_5	471.03	38.72	<0.0001
Skill 1	β_6	240.526	14.27	<0.0001
Skill 2	β_7	90.197	5.35	<0.0001
Soil type 1	β_8	342.568	17.6	<0.0001
Soil type 2	β_9	57.095	2.93	0.0034
Soil type 3	β_{10}	114.189	5.87	<0.0001
Dozing technique 1	β_{11}	20.044	1.46	0.1454

Table 3. Productivity Models for Bulldozer

Dozing Technique	Operator skill	Soil type	Productivity model
Slot	Excellent	Loose-stockpile	$Y = -158.1 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-cut	$Y = -443.62 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-drift	$Y = -368.5 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Blasted-ripped-rock	$Y = -500.7 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
	Average	Loose-stockpile	$Y = -308.4 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-cut	$Y = -593.9 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-drift	$Y = -536.8 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Blasted-ripped-rock	$Y = -651 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
	Poor	Loose-stockpile	$Y = -398.6 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-cut	$Y = -684.1 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-drift	$Y = -627 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Blasted-ripped-rock	$Y = -741.2 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
Side-by-side	Excellent	Loose-stockpile	$Y = -178.1 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-cut	$Y = -463.6 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-drift	$Y = -406.5 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Blasted-ripped-rock	$Y = -520.7 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
	Average	Loose-stockpile	$Y = -328.4 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-cut	$Y = -613.9 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-drift	$Y = -556.8 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Blasted-ripped-rock	$Y = -671 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
	Poor	Loose-stockpile	$Y = -418.6 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-cut	$Y = -704.1 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Hard-to-drift	$Y = -647 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$
		Blasted-ripped-rock	$Y = -761.2 + 1.5X_1 - 1.65X_2 + 628X_3 + 471X_4$

The overall productivity models for bulldozer from the data of CAT's performance handbook for all types of soil or terrain are shown in the Table 3.

Where: Y = productivity rate (lcy/hr); X_1 = engine horsepower (hp); X_2 = dozing distance (feet); X_3 = Job efficiency (%); X_4 = site slope

The overall calculation formula for obtaining the total fuel use and CO_2 emissions estimates are formed by combining the productivity rate models with fuel consumption rate for diesel fuel. In order to estimate the fuel use and CO_2 emissions from a certain quantity of soil performed by a bulldozer, the total duration of activity is needed. The total duration in hours (hr) can be obtained by dividing the total soil quantity with the productivity rate in loose-cubic yard per hour (lcy/hr). Once the total duration obtained, engine horsepower (hp) and fuel consumption rate (gal/hp-hr) is known, the total fuel use (gal) and total CO_2 emissions can be calculated.

$$Fuel\ (gal) = \frac{Soil\ Quantity\ (cy)}{Productivity\ Rate\ \left(\frac{cy}{hr}\right)} x\ engine\ horsepower\ (hp) x\ fuel\ rate\ \left(\frac{gal}{hp.hr}\right) \quad (1)$$

$$Fuel\ (gal) = Q/(-761 + 1.5HP - 1.65D + 628E + 471S + fd + fo + fs)\ x\ HP\ x\ 0.04\ gal/hp.hr \quad (2)$$

Where:

Q = soil quantity (lcy)
HP = engine size in horsepower
D = dozing distance (feet)
E = operation efficiency (%)
S = slope grade
fd = dozing technique factor (slot = 20; side-by-side = 0)
fo = operator's skill factor (excellent = 240; average = 90; poor = 0)
fs = soil type factor (loose stockpile = 342; hard cut = 57; hard drift = 114; rock = 0)

To demonstrate the total fuel use estimate for bulldozer, a case of 500 hp bulldozer, has to haul 5000 lcy loose stockpile in 300 feet is presented. The operation efficiency is set at 0.75 at the flat soil surface (slope grade 1), using side-by-side dozing technique, and operated by average skill of operator. The results showed that the productivity rate is 868 cy/hr and it needs 5.76 hours to complete the work. The total fuel consumed to complete 5000 cy loose stockpile is 115 gallons or equals to 436 liter. From its fuel use, the bulldozer emitted nearly 1.2 tons of estimated CO_2 emissions. Table 4 shows the estimated productivity, work duration, total fuel use, and CO_2 emissions of bulldozer using various size of engine and types of soil.

To demonstrate another example for the total fuel use estimate and CO_2 emissions, a case of 250 hp bulldozer, has to haul 5000 lcy loose stockpile in 300 feet is presented. The operation efficiency is set at 0.75 at the flat soil surface (slope grade 1), using side-by-side dozing technique, and operated by average skill of operator. The results showed that the productivity rate is 493 cy/hr and it needs 10.14 hours to complete the work. The total fuel consumed to complete 5000 cy loose stockpile is 384 liter. From its fuel use, the bulldozer emitted 1 ton of estimated CO_2emissions approximately. Table 5 shows the estimated productivity, work duration, total fuel use, and CO_2 emissions of bulldozer using various dozing distance and types of soil.

This study used sensitivity analysis to investigate the magnitude of changes in independent variables against the dependent variables; total diesel fuel use and amount of CO_2 emissions. The analysis are useful to have a bigger picture of the environmental impact of a bulldozer's activity in different settings.

Table 4. Fuel Use and CO_2 Emissions of Side-by-side Bulldozer for 5000 cy soil; 300 ft distance; 0.75 operation efficiency; flat surface; average skill of operator.

Engine Size (HP)	Soil Type	Productivity (lcy/hr)	Duration (hr)	Fuel Use (Liter)	CO_2 Emissions (Kg)
250	stockpile	493.20	10.14	384.23	1028.99
350	stockpile	643.20	7.77	412.47	1104.63
500	stockpile	868.20	5.76	436.54	1169.09
600	stockpile	1018.20	4.91	446.67	1196.23
700	stockpile	1168.20	4.28	454.20	1216.40
800	stockpile	1318.20	3.79	460.02	1231.98
250	hard-to-cut	208.20	24.02	910.18	2437.56
350	hard-to-cut	358.20	13.96	740.65	1983.53
500	hard-to-cut	583.20	8.57	649.86	1740.40
600	hard-to-cut	733.20	6.82	620.29	1661.21
700	hard-to-cut	883.20	5.66	600.77	1608.92
800	hard-to-cut	1033.20	4.84	586.91	1571.82
250	hard-to-drift	265.20	18.85	714.56	1913.65
350	hard-to-drift	415.20	12.04	638.97	1711.22
500	hard-to-drift	640.20	7.81	592.00	1585.44
600	hard-to-drift	790.20	6.33	575.55	1541.38
700	hard-to-drift	940.20	5.32	564.35	1511.38
800	hard-to-drift	1090.20	4.59	556.23	1489.63
250	blasted rock	151.20	33.07	1253.31	3356.48
350	blasted rock	301.20	16.60	880.81	2358.90
500	blasted rock	526.20	9.50	720.26	1928.92
600	blasted rock	676.20	7.39	672.58	1801.24
700	blasted rock	826.20	6.05	642.22	1719.92
800	blasted rock	976.20	5.12	621.18	1663.59

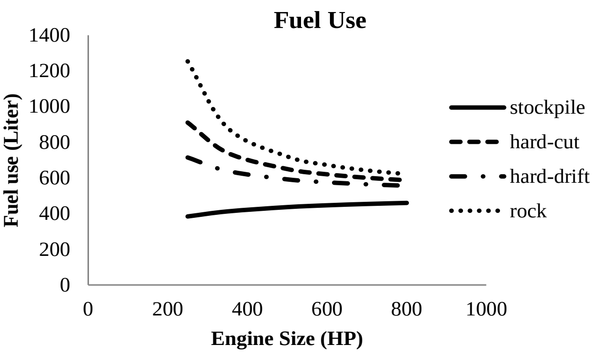

Figure 2. Total Fuel Use based on Engine Size for All Types of Soil

Table 5. Fuel Use and CO_2 Emissions of Side-by-side Bulldozer for 5000 cy soil; 250 HP engine size; 0.75 operation efficiency; flat surface; average skill of operator.

Distance (ft)	Soil Type	Productivity (lcy/hr)	Duration (hr)	Fuel Use (Liter)	CO_2 Emissions (Kg)
100	stockpile	823.20	6.07	230.20	616.50
150	stockpile	740.70	6.75	255.84	685.16
200	stockpile	658.20	7.60	287.91	771.04
250	stockpile	575.70	8.69	329.16	881.54
300	stockpile	493.20	10.14	384.23	1028.99
350	stockpile	410.70	12.17	461.41	1235.70
100	hard-to-cut	538.20	9.29	352.10	942.96
150	hard-to-cut	455.70	10.97	415.84	1113.67
200	hard-to-cut	373.20	13.40	507.77	1359.86
250	hard-to-cut	290.70	17.20	651.87	1745.79
300	hard-to-cut	208.20	24.02	910.18	2437.56
350	hard-to-cut	125.70	39.78	1507.56	4037.39
100	hard-to-drift	595.20	8.40	318.38	852.65
150	hard-to-drift	512.70	9.75	369.61	989.86
200	hard-to-drift	430.20	11.62	440.49	1179.68
250	hard-to-drift	347.70	14.38	545.01	1459.59
300	hard-to-drift	265.20	18.85	714.56	1913.65
350	hard-to-drift	182.70	27.37	1037.22	2777.78
100	blasted rock	481.20	10.39	393.81	1054.66
150	blasted rock	398.70	12.54	475.29	1272.89
200	blasted rock	316.20	15.81	599.30	1605.00
250	blasted rock	233.70	21.39	810.87	2171.59
300	blasted rock	151.20	33.07	1253.31	3356.48
350	blasted rock	68.70	72.78	2758.37	7387.19

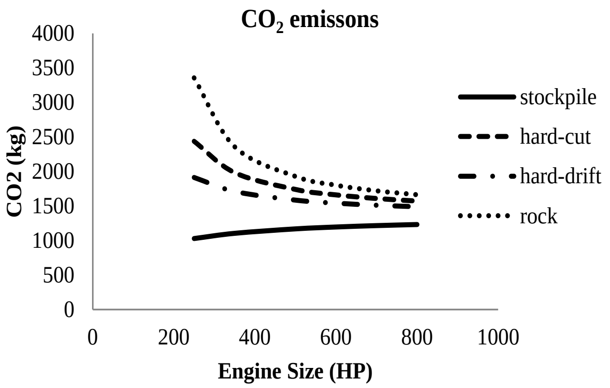

Figure 3. CO_2 Emissions based on Engine Size for All Types of Soil

The sensitivity analysis for bulldozer are constructed by two different work conditions: first, as shown in Figure 2 and Figure 3, a bulldozer has to haul 5000 cy of soil in 300 feet of distance, using various size of engine and all type of soil; second, as shown in Figure 4 and Figure 5, 250 hp bulldozer, has to haul 5000 cy of all type of soil in various distance. As displayed in Figure 2 to Figure 5, it is found that there is a reverse correlation between estimated productivity rate and the fuel use and CO_2 emissions; that is, when bulldozer has low productivity rate, the the diesel fuel use and CO_2 emission will be high. Bulldozer's productivity rate will also be lower with high soil resistance; loose stockpile type of soil gives the highest productivity rate for bulldozer, whilst blasted rock type of soil gives the lowest. Likewise, the CO_2 emissions will be higher as the bulldozer works on high soil resistance. Furthermore, higher productivity rate is achieved when bulldozer uses bigger engine size, and lower productivity rate is occurred when bulldozer has to haul longer distance. Generally, there is a reverse correlation between engine size and total fuel use and CO_2 emissions; that is, for all types of soil, as the bulldozer uses bigger size of engine or bigger rated horsepower, the emissions become lower.

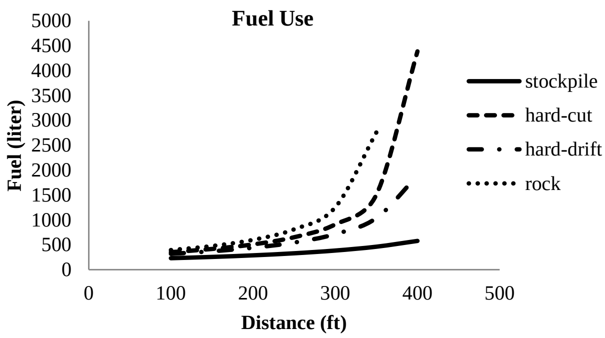

Figure 4. Total Fuel Use based on Dozing Distance for All Types of Soil

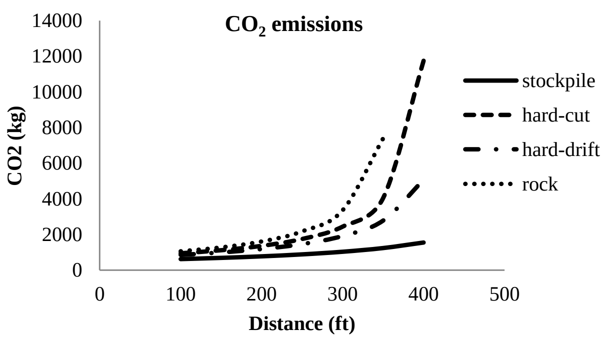

Figure 5. CO_2 Emissions based on Dozing Distance for All Types of Soil

Conclusion

This paper proposed a simple technique to estimate CO_2 emissions for bulldozer in infrastructure project activity. The MLR approach proved to be a useful alternative for estimating productivity rate of these equipment. The proposed technique is also useful as a platform to predict fuel use from different types of heavy construction equipment in infrastructure project activities. As presented in this paper, the results have shown tendencies of total emissions of the bulldozer. The results show that the total estimated emissions goes higher as the hauling distance goes longer, because longer distance will result in lower bulldozer's productivity.

The estimating technique presented in this paper can also be used for investigating the environmental impacts of infrastructure project activities and will assist construction equipment operators or fleet managers, construction industry policy makers, and construction professionals to assess more sustainable approaches. The technique will also help the construction estimators in predicting total expected air pollutant from infrastructure project, which is useful for a preliminary environmental assessment of the project.

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