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Estimating the emissions of nitrogen oxides (NO_X) and particulate matter (PM) from diesel construction equipment by using the productivity model

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Abstract

Purpose – This paper aims to present a synergistic approach that combines both construction and environmental expertise to lay the groundwork for a model that can be used to estimate the productivity rate and emissions from construction equipment activities.

Design/methodology/approach – The proposed estimating tool is developed by combining the productivity rate model from a reliable construction estimating data sources and the calculation algorithm employed by the EPA's NONROAD model. In order to develop productivity models, simple earthwork activities involving bulldozer, excavator, and dump truck were selected.

Findings – The MLR approach proved to be a useful alternative for estimating productivity rate of three pieces of equipment. The MLR models for the productivity rate can explain high percentage of the variability in the data. The models are good to be used as a benchmark for estimating NO_X and PM emissions from some certain types of construction equipment performing earthwork activities. The productivity rate from this model (lcy/hr) is used with emission factors (g/hp-hr) from EPA's NONROAD model to estimate the total emissions.

Practical implications – The estimating tool proposed in this paper will be an effective means for assessing the environmental impacts of construction activities and will allow equipment owners or fleet managers, policy makers, and project stakeholders to evaluate more sustainable alternatives. The tool will help the contractor to estimate the total expected pollutant emissions for the project, which would be valuable information for a preliminary environmental assessment of the project.

Originality/value – Although there are already methods and models for estimating productivity for construction equipment, there currently is not a means for doing estimates of air pollutant emissions at the same time, particularly for NO_X and PM.

Keywords Construction equipment, Productivity, NO_X emissions, PM emissions, Construction industry, Productivity rate, Particulate air pollutants

Paper type Research paper

Introduction

Air pollutant emissions from diesel construction equipment have become an important concern for human health and environment. From diesel equipment tailpipes, there are two main pollutants dangerous for human health: nitrogen oxide (NO_X) and particulate matter (PM). NO_X is responsible for formation of ground-level ozone, which can trigger some respiratory diseases such as asthma, damage in the linings of lungs, and in a long-time exposure might lead to permanent changes in lung tissue. PM can cause a lung cancer and other respiratory symptoms. It is also harmful for heart and can increase the risk of premature mortality. In broader environmental effects, these two pollutants can cause the visibility impairment, crop damage, and acid rain. The US Environmental Protection Agency (EPA) reported that the construction sector is a

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significant contributor to approximately 32 and 37 percent of all mobile source of NO_X and PM emissions, respectively (EPA, 2007).

Construction professionals have long been able to estimate the productivity rate associated with construction equipment activities. Air pollutant emissions are direct by-products of fuel consumption, and fuel consumption is dependent upon equipment productivity. Most construction estimating tools accurately address productivity rate, but not equipment emissions. Conversely, most models that estimate emissions inventories of construction equipment, do not address productivity rate because their focus is only on environmental issues (Lewis and Hajji, 2012a). Although there are already methods and models for estimating productivity for construction equipment, there currently is not a means for doing estimates of air pollutant emissions at the once, particularly for NO_X and PM. This paper presents a synergistic approach that combines both construction and environmental expertise to lay the groundwork for a model that can be used to estimate the productivity rate and emissions from construction equipment activities.

Related works

Productivity (P) is simply defined as the ratio of the quantity (Q) of work completed to the duration (D) of time that it took to complete the work (Lewis and Hajji, 2012b). For construction equipment activity, 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 reveals that the duration of a construction equipment activity is inversely proportional to productivity – as productivity decreases, the activity duration increases. When the duration increases, it will result in higher fuel consumption and higher emissions. Thus, it is necessary to predict the construction equipment productivity rates in order to estimate its emissions. To predict productivity rates from construction equipment, this paper uses multiple linear regression (MLR) analysis. MLR analysis is a powerful tool that provides a simple method for establishing a functional relationship between predictor and response variables. It has been used frequently to conduct construction-related studies (Akinsola, 1997; Akintoye and Skitmore, 1994; Edwards *et al.*, 2000; Lowe *et al.*, 2006). Furthermore, the use of deterministic MLR analysis is well-established in construction engineering research, particularly in predicting productivity (David and Gary, 1993; Dunlop and Smith 2003; Han and Halpin 2005; Ok and Sinha 2006; Smith, 1999). In this paper, MLR is used to determine the statistical relationship between productivity rate as response variables, and construction equipment working attributes, such as engine horsepower, distance, and soil types as explanatory variables.

Some methods have been studied to estimate emissions from construction equipment by using models or simulations. Some studies used engine parameters, or fuel characteristics, or type of equipment's activities to estimate or predict the emissions rates. Discrete-event simulation (DES) can be used as an approach to estimate emissions (Ahn *et al.*, 2010). DES can simulate a project or operation by running chronological occurred events. By calculating durations of work package, DES will estimate the emissions (Pan, 2011). Li and Lei (2010) studied the use of DES in estimating and analyzing CO_2 emission during earthwork construction. Ammouri *et al.* (2011) proposed a model capable of estimating the total carbon footprint of a construction project taking into consideration the size, landscape, and material of construction. Thompson *et al.* (2000) used the artificial neural network (ANN) modeling to predict relationship between the output torques and exhaust emissions from heavy duty diesel engine with limited use of dynamometer testing. The result showed that the ANN was able to predict the instantaneous emissions of hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), NO_X, and PM and opacity for an equipment engine. In concern with fuel properties, Karonis *et al.* (2003) used ANN to model the exhaust emissions from a single-cylinder diesel engine with some of the most important properties of fuels. The US EPA's NONROAD model estimates air pollutant emissions from nonroad equipment based on fleet average emission rates. It estimates emissions for different fuel types including gasoline, diesel, compressed natural gas, and liquefied petroleum gas; pollutants include NO_X, HC, CO, CO_2, PM, and sulfur oxides (SO_2) (EPA, 2007). Key input variables for the model include equipment population distributed by age, power, fuel type, and application; average engine load factor based on a fraction of maximum power; rated engine horsepower; equipment activity in terms of hours per year; and the pollutant emission factor (EF) based on grams per horsepower-hour.

Methodology

The proposed estimating tool is developed by combining the productivity rate model from a reliable construction estimating data sources and the calculation algorithm employed by the EPA's NONROAD model (Figure 1). In order to develop productivity models, simple earthwork activities involving bulldozer, excavator, and dump truck were selected. The data for these activities were collected from RSMeans Heavy Construction Data 2010. This is parts of RSMeans estimating references, which is widely accepted and used by most construction professionals. This data provide technical information required for preparing quantity takeoffs and complete construction estimates for major construction projects (RSMeans, 2010). It helps design and construction professionals compare the estimates of design alternatives, perform cost analysis and value engineering, and review estimates quotes and change orders prepared by others. The data also include information in sizing, productivity, equipment requirements, design standards, and engineering factors – all organized according to the latest 2004 Construction Specification Institute (CSI) Master Format classification system, which has 48 divisions ranging from general requirements to electrical power generation.

The selected activities are provided in RSMeans data on Division 31: "Earthwork". This division has sections representing major earthwork activities: clearing and grubbing, tree and shrub removal and trimming, stripping and stockpiling, grading, excavation and fill, erosion and sedimentation controls, soil treatment and stabilization, shoring, underpinning, dams, and tunnel construction. Bulldozer activities are provided in section 31.23.16.46, excavator in section 31.23.16.13, and dump truck in section 31.23.23.20. The activity input data for these three types of equipment are shown in Table I.

Based on the data from RSMeans, the productivity rate models were developed by using 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 that corresponds to the levels of explanatory variables x_1, x_2, …, x_p at the ith observation; $\beta_0, \beta_1, \beta_2, \ldots, \beta_p$ are the coefficients in the linear relationship. For a single factor ($p = 1$), β_0 is the intercept, and β_1 the slope of the straight line defined; ε_1, ε_2, …, ε_n are errors that create scatter around the linear relationship at each of the $i = 1$ to n observations. The regression model assumes that

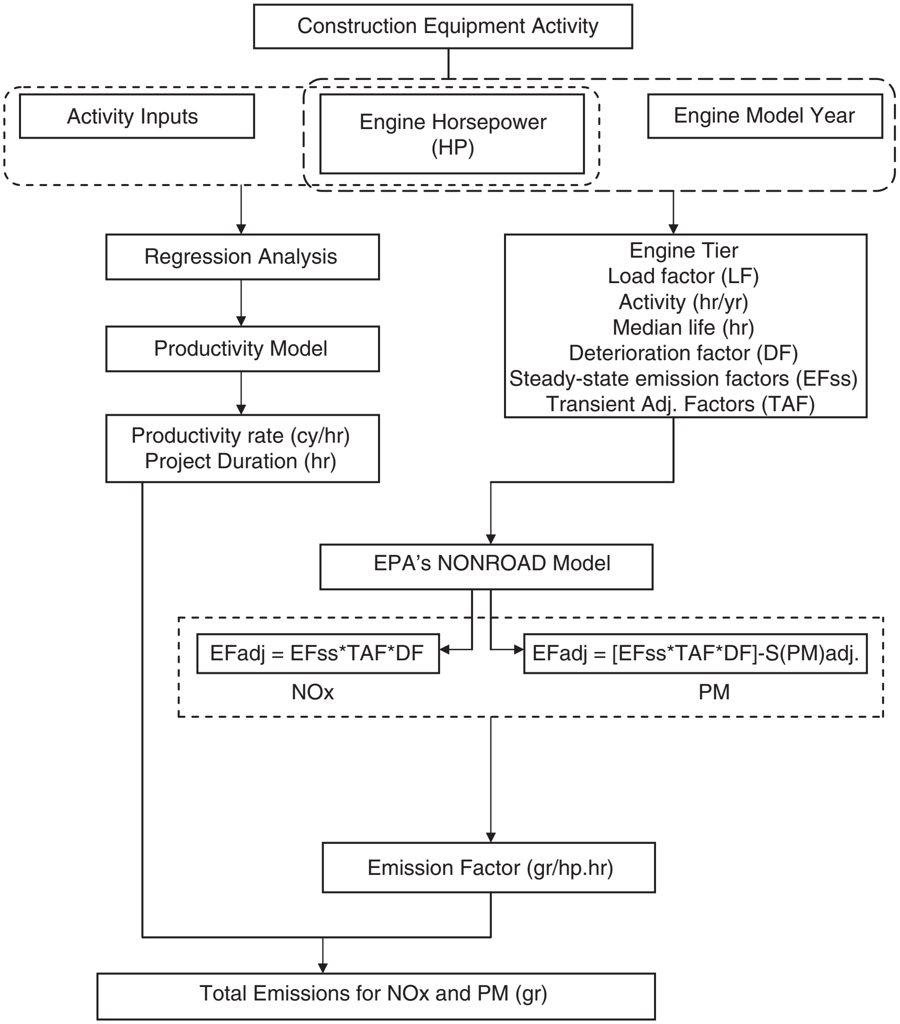

Figure 1.
NO_X and PM estimation methodology

these errors are mutually independent, normally distributed, and with a zero mean and variance σ^2. To make estimates of the coefficients in the regression model, the method of least squares is used.

In this paper, MLR is used to determine the statistical relationship between a response (productivity rate) and the explanatory variables in construction equipment activities. The response variable is expressed in terms of loose cubic yard per hour (lcy/hr) as productivity rate.

The productivity models in this paper were built by using stepwise regression selection method and validated by using two methods: data splitting and a plot showing comparison of predicted and actual data. In data splitting method, the original data set are split into a model-building set and a validation set (Kutner *et al.*, 2005). If the number of data is within six to ten times the number of predictor variables, it is enough for making an equal data split. If the entire data are not large enough under

Table I.
Activity input of selected construction equipment

Equipment	Number of data	Activity input	Unit/type/range
Bulldozer	72	Engine size	80-700 horsepower (hp)
		Distance	50-300 feet (ft)
		Type of soil	Sand-gravel; sandy-clay loam; common earth; clay
Excavator	394	Bucket size	0.5-3.5 cubic yard (cy)
		Trench depth	1-24 feet (ft)
		Soil type	Sand-gravel; sandy-clay loam; common earth; clay
		Excavator type	Regular; with truck mounted; with trench box
Dump truck	240	Loading capacity	
		Distance	22-60 cubic yard (cy)
		Speed	2,000 ft – 4 miles (mi)
		Wait-load-unload	5-25 miles per hour (mph)
		time	15-25 minutes (min)

these circumstances, the validation set will need to be smaller than the model-building data set. The model-building set is used to develop the model. The validation set is used to evaluate the reasonableness and predictive ability of the selected model. A means of measuring the actual predictive ability is to use the model to predict each case in the validation data set and then to calculate the mean of the squared prediction errors, denoted by MSPR or mean squared prediction error. The MSPR is calculated as:

$$MSPR = \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n} \tag{2}$$

where Y_i is the value of the response variable in the ith validation case; $\hat{Y}_i$ the predicted value for the ith validation case based on the model from using the model-building data set; n the number of cases in the validation data set.

If the MSPR is fairly close to the mean squared errors (MSE) based on the regression fit to the model-building data set, then MSE for the selected regression model is not seriously biased and gives an appropriate indication of the predictive ability of the model. The plot showing the predicted versus the actual result of productivity model is used to identify the accuracy, precision, and bias of the model. Ideally, a plot of the predicted vs the actual results will produce a line with a slope of 1.0 (accurate), $R^2 = 1.0$ (precise), and y-intercept $= 0$ (no bias).

The information about rated engine horsepower (HP) and engine model year of the equipment will be used to estimate the emission rates. In order to estimate the total emissions, EF was needed. This factor is approximations of amount of all pollutants emitted by a particular type of equipment during a unit of use. The EF for this estimation was based on the calculation algorithm used by the EPA's NONROAD Model (EPA, 2010). EF for pollutants are reported in grams per horsepower-hour (g/HP-hr), which are based on engine dynamometer test data and adjusted accordingly to account for in-use operation that differs from the typical test conditions. For NO_X, the

EF for a specific type of construction equipment with a particular model year and age is calculated as follows:

$$EF_{adj(NOx)} = EF_{ss} \times TAF\, x\, DF \tag{3}$$

where EF_{adj} is the final EF used in NONROAD, after adjustments for transient operation and deterioration (g/HP-hr), EF_{ss} the zero-hour, steady-state emission factor (g/HP-hr), TAF the transient adjustment factor (unitless), and DF the deterioration factor (unitless).

The zero-hour EF_{ss} is a function of the engine's model year and HP rating, which defines the engine tier category (Tier 0, 1, 2, 3, or 4). TAF are applied to Tier 0-3 engines but are not applied to Tier 4 engines because transient emission controls will be a part of all Tier 4 engine design considerations. TAF are calculated as the ratio of the transient EF to the corresponding EF_{ss}, and maybe greater or less than 1.0. DF are used to account for increases in emissions over time above a new engine's base emission level. This increase might be caused by engine wear, poor maintenance, or modifications. The DF used by NONROAD is based on well-maintained engines and are a linear function based on engine age, which is represented by the fraction between cumulative hours use at specified load factor and its median life at full load (in hours). Because the engine life varies with engine type and power level, NONROAD model uses median life as the expected life estimates. The TAF and DF used in the calculations were found in *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition* (EPA, 2010).

Since PM emissions are dependent on the sulfur content of the fuel consumed by the engine, the calculation for EF of PM is as follows:

$$EF_{adj(PM)} = EF_{ss} \times TAF \times DF - S_{PMadj} \tag{4}$$

where S_{PMadj} is the adjustment to PM EF for variations in fuel sulfur content (g/HP-hr).

The adjusted sulfur content is subtracted from PM EF to account for variations in fuel sulfur content. S_{PMadj} corrects PM emissions from the default fuel sulfur level to the episodic fuel sulfur level.

Results and discussion

The MLR approach was successful in providing model for predicting productivity rate for the bulldozer, excavator, and dump truck activities. Based on the value of R^2, the MLR equation for predicting productivity rates can adequately explain the variability of the data. With $\alpha = 0.05$, all parameters (excluding the intercept) in the models had p-values < 0.0001 and were statistically significant to be included in the models. For bulldozer, in the result of original regression function, it was found that the plot of residuals against the predicted values showed evidence of unequal variance. The unequal error variances and non-normality of the error terms frequently appear together. To remedy the non-normality in the data, a Box-Cox analysis has been conducted and the result recommended the best λ for transforming the response variables (Y) is 0.2. Thus, for bulldozer the form of transformed regression function for productivity can be written as:

$$Y^{0.2} = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip} + \varepsilon_i \tag{5}$$

$$Y = \left(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip} + \varepsilon_i\right)^5 \tag{6}$$

The overall results of MLR analysis and validation results of productivity models for bulldozer, excavator, and dump truck are shown in Table II.

To validate the model, plots in Figure 2 showing the estimated vs the actual results for the productivity models were made. The predicted results are those that were generated by the model and the actual are those that were taken from the RSMeans data. Ideally, a plot of the estimated versus the actual results will produce a line with a slope of 1.0 (accuracy), $R^2 = 1.0$ (precision), and intercept $= 0$ (bias). The plots from the models show that the bulldozer has the slope of 0.976, $R^2 = 0.9478$, and intercept $= 0.234$ cy/hr; the excavator has slope of 0.9195, $R^2 = 0.9195$, and intercept $= 6.26$ lcy/hr; and the dump truck has slope of 0.943, $R^2 = 0.9432$, and intercept $= 4.53$; thus, the models were considered to be accurate, precise, and had no bias.

Because all data set are large, the model was also validated by using cross-validation procedure or data splitting. As shown in Table II, the MSPR from the productivity model are fairly close to the MSE based on the regression fit to the model-building data set. The MSE for the regression models of productivity rate used here are not seriously biased and give an appropriate indication of the predictive ability of the model. The MLR analysis results of productivity models for bulldozer, excavator, and dump truck are shown in Table III.

Concerning the types of excavator, since the *p*-values of type of excavator are bigger than $\alpha = 0.05$, it can be concluded that different types of excavation do not significantly lead to different rate of productivity. However, since the type of excavator is categorical variable, it can be used to represent the categories of a qualitative explanatory variable in the regression model.

The NO_X and PM estimating formula were developed by using productivity models built from RSMeans Heavy Construction Data, combined with EPA's NONROAD model. In order to estimate the total emissions of NO_X and PM from a certain quantity of soil hauled by bulldozers, dig by the excavators, or hauled by trucks, the total

Table II.
Validation results of productivity models

Equipment	*n*	R^2	MSPR	MSE
Bulldozer	72	0.9534	0.0023	0.0061
Excavator	394	0.9195	214.5	225.52
Dump truck	240	0.9432	49.28	46.79

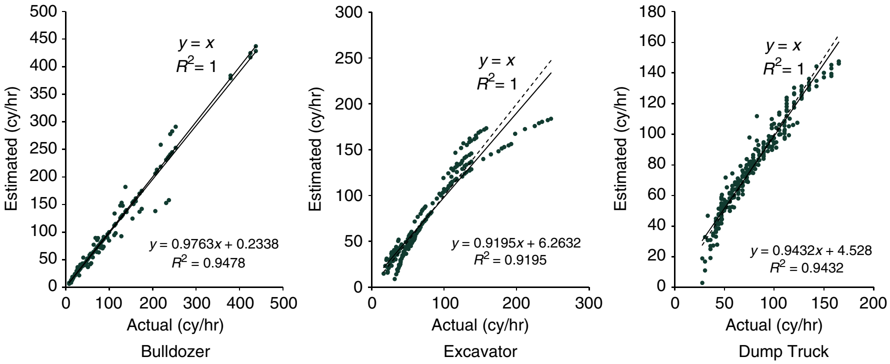

Figure 2.
Plots of estimated v. actual productivity rates for three equipment

Variable	Parameter estimates	p-value
Bulldozer		
Intercept	1.87859	<0.0001
Engine size (hp)	0.00350	<0.0001
Distance (ft)	−0.00240	<0.0001
Soil type 1 – sand-gravel	0.23656	<0.0001
Soil type 2 – sandy clay-loam	0.21667	<0.0001
Soil type 3 – common earth	0.16644	<0.0001
Excavator		
Intercept	−3.946	0.3656
Soil type 1 – common earth	8.465	0.0193
Soil type 2 – sandy clay-loam	14.907	<0.0001
Soil type 3 – sand gravel	16.412	<0.0001
Depth	−2.069	<0.0001
Bucket size	55.131	<0.0001
Excavator type 1 – regular	3.317	0.1676
Excavator type 2 – with trench box	4.166	0.4743
Dump truck		
Intercept	58.799	<0.0001
Loading capacity	2.079	<0.0001
Speed	1.625	<0.0001
Cycle distance	−12.056	<0.0001
Cycle time	−2.789	<0.0001

Table III.
Multiple linear regression results for productivity models of three equipment

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 bank cubic yard per hour (lcy/hr). Once the total duration obtained and engine HP is known, the total emission in grams (gr) can be calculated by multiplying the EF (g/HP-hr) from NONROAD with HP and duration (hr) as shown in the following basic formula:

$$\begin{aligned} E(\mathrm{gr}) = {} & \text{Duration (hr)} \times \text{engine horsepower (HP)} \\ & \times \text{Emission factor} \left(\frac{\mathrm{gr}}{\mathrm{HP.hr}}\right) \end{aligned} \tag{7}$$

$$\begin{aligned} E(\mathrm{gr}) = {} & \frac{\text{Soil Quantity (cy)}}{\text{Productivity Rate} \left(\frac{\mathrm{cy}}{\mathrm{hr}}\right)} \\ & \times \text{engine horsepower (HP)} \times \text{Emission factor} \left(\frac{\mathrm{gr}}{\mathrm{HP.hr}}\right) \end{aligned} \tag{8}$$

The overall formula for estimating NO_X and PM emissions are shown in Table IV-VI. To demonstrate the emissions for bulldozer, a case is presented where a 150 HP of bulldozer model year 2003 has to haul 1,000 cy of common earth in distance of 300 feet. The result showed that the estimated productivity of this bulldozer is 20.02 cy/hr and can approximately complete the job in 49.94 hr. Based on the engine size and model year, this bulldozer is categorized in Tier 2 engine level and has 0.59 of LF, and 936 hr of activity per year in average. This engine also has the EFss as follows: 4.1 g/HP-hr of NO_X, and 0.18 g/HP-hr of PM. When completing the job, this bulldozer was estimated to emit 29,183 gr of NO_X, and 1,502 gr of PM.

Table IV.
Productivity-based NO_X and PM emissions model for bulldozers

Pollutant(s)	Emission model
NO_X	$E = \frac{Q}{(1.876 + 0.0035HP - 0.0024D + fs)^5} \times HP \times EF_{ss} \times TAF \times DF \quad (9)$
PM	$E = \frac{Q}{(1.876 + 0.0035HP - 0.0024D + fs)^5} \times HP \times ((EF_{ss} \times TAF \times DF) - S_{PM}) \quad (10)$

Notes: *E* is the total emissions (grams); *Q* the quantity of soil dozed/moved/excavated (cy); HP the engine horsepower (HP); EFss the steady-state emission factor (g/hp-hr); TAF the transient adjustment factor (unitless); DF the deterioration factor (unitless); S_{PM} the adjustment to PM emission factor for fuel sulfur content (g/hp-hr); *D* the distance (ft); *fs* (soil type factor): sand and gravel = 0.236; sandy clay and loam = 0.217; common earth = 0.166; Clay = 0

Table V.
Productivity-based NO_X and PM emissions model for excavators

Pollutant(s)	Total emission model
NO_X	$E = \frac{Q}{(-3.9467 + fs - 2.069d + 55.13B + ft)} \times HP \times EF_{ss} \times TAF \times DF \quad (11)$
PM	$E = \frac{Q}{(-3.9467 + fs - 2.069d + 55.13B + ft)} \times HP \times ((EF_{ss} \times TAF \times DF) - S_{PM}) \quad (12)$

Notes: *E* is the total emissions (grams); *Q* the quantity of soil dozed/moved/excavated (cy); HP the engine horsepower (HP); EFss the steady-state emission factor (g/hp-hr); TAF the transient adjustment factor (unitless); DF the deterioration factor (unitless); S_{PM} the adjustment to PM emission factor for fuel sulfur content (g/hp-hr); *d* the trench depth (ft); *B* the bucket capacity (cy); *fs* (soil type factor): sand and gravel = 16.412; sandy clay and loam = 14.907; common earth = 8.465; Clay = 0; *ft* (excavator type factor): excavator = 3.317; truck-mounted = 4.165; trench-box = 0

Table VI.
Productivity-based NO_X and PM emissions model for dump trucks

Pollutant(s)	Total emission model
NO_X	$E = \frac{Q}{(58.799 + 2.079C + 1.625S - 12.056D - 2.78t)} \times HP \times EF_{ss}\ \mathrm{x}\ TAF\ \mathrm{x}\ DF \quad (13)$
PM	$E = \frac{Q}{(58.799 + 2.079C + 1.625S - 12.056D - 2.78t)} \times HP \times ((EF_{ss} \times TAF \times DF) - S_{PM}) \quad (14)$

Notes: *E* is the total emissions (grams); *Q* the quantity of soil dozed/moved/excavated (cy); HP the engine horsepower (hp); EFss the steady-state emission factor (g/hp-hr); TAF the transient adjustment factor (unitless); DF the deterioration factor (unitless); SPM the adjustment to PM emission factor for fuel sulfur content (g/hp-hr); *C*, loading capacity (cy); *S*, average hauling speed (mph); *D*, cycle distance (miles); *t*, load-dump time (minutes)

To demonstrate the models for estimating emissions from excavator, a case of a 400 HP – model year 2003 excavator is presented. The excavator has to dig a 100 feet long-10 feet wide-12 feet deep trench in sand-gravel soil with its 3 cy bucket. The results showed that the excavator has the productivity rate of 156.34 cy/hr or needs 2.84 hr to complete digging the trench. Based on the HP and model year, the engine is categorized as Tier 2 engine and has 0.59 of load factor, 1,092 hr activity per year on average, and steady-state EFs as follows: 4.3351 g/HP-hr of NO_X, and 0.1316 g/HP-hr of PM. When finishing the trench, this excavator released 4678.5 gr of NO_X, and 160 gr of PM.

To illustrate the emissions for truck, a simple case is presented as follows: a 535 HP – model year 2003 truck is used to haul 1,000 cy of soil in one mile of distance. The truck has 30 cy of loading capacity with average hauling speed of ten miles per hour. For loading and dumping the soil, the truck needs 15 minutes in average. The estimated productivity rate for this truck is 83.54 cy/hr, and for hauling 1,000 cy of soil, the truck needs 11.97 hr. Based on the HP and model year, the truck is categorized as Tier 2 engine, has 0.59 of load factor with 1,641 hr of activity per year in average and steady-state EFs as follows: 4.3351 g/HP-hr of NO_X, and 0.1316 g/HP-hr of PM. When the job is completed, the truck released 26,374 gr of NO_X and 902 gr of PM.

Sensitivity analysis

Sensitivity analysis is conducted to analyze the effect of changes in explanatory variables against the output NO_X and PM emissions. The analyses are useful to understand the environmental impact of a certain earthwork activity performed by construction equipment in different set of conditions.

The sensitivity analysis for bulldozer are constructed by two different work conditions: first, as shown in Table VII, bulldozer has to haul 1,000 cy of soil in 300 feet of distance, using various size of engine and all type of soil; second, as shown in Table VIII, 564 HP bulldozer – model year 2003, has to haul 1,000 cy of all type of soil in various distance. Based on the information in Tables VII and VIII, there is an inverse relationship between productivity rate and the NO_X and PM emissions; that is, as the productivity rate decreases, the emissions increase. The productivity rate also decreases with the dozing resistance based on soil type; sand-gravel has the highest productivity rate whereas clay has the lowest. Likewise, the emissions all increase as the soil resistance increase. Furthermore, for a specific soil type, the productivity rate increases as engine size increases, and decreases as the dozing distance increases. Generally, the Table VII showed inverse relationship between engine size and total NO_X and PM emissions; that is, for all types of soil, as the bulldozer uses bigger size of engine or bigger-rated HP, the emissions become lower. There is little difference in NO_X and PM emissions for sand-gravel, sandy clay-loam, and common earth. The soil type with the highest estimated total emissions based on engine size is clay.

Table VIII shows the emissions impact of the bulldozer activity based on the dozing distance. For each soil type, the estimated productivity decreases as the dozing distance increase. The estimated productivity has relatively the same shape for all type of soil, with little difference of productivity for sand-gravel, sandy clay-loam, and common earth. Again, clay gives the lowest estimated productivity for the bulldozer activity based on dozing distance. Table VIII also shows the emissions impact of the bulldozer activity based on dozing distance. There are positive relationship between dozing distance and the emissions of NO_X and PM; that is, for all types of soil, as the

Horsepower	Type of material	Productivity (cy/hr)	NOx (gr)	PM (gr)
80	Sand and gravel	18.33	23,220.91	2,439.72
80	Sandy clay and loam	17.42	24,425.20	2,566.25
80	Common earth	14.88	28,598.58	3,004.73
80	Clay	7.85	54,205.85	5,695.18
150	Sand and gravel	24.37	23,972.16	1,233.77
150	Sandy clay and loam	23.24	25,144.50	1,294.11
150	Common earth	20.02	29,178.12	1,501.71
150	Clay	10.99	53,179.53	2,736.99
275	Sand and gravel	39.07	26,745.00	991.48
275	Sandy clay and loam	37.41	27,932.02	1,035.49
275	Common earth	32.69	31,971.68	1,185.24
275	Clay	19.03	54,922.25	2,036.06
400	Sand and gravel	60.14	27,391.50	936.60
400	Sandy clay and loam	57.79	28,504.33	974.65
400	Common earth	51.07	32,257.20	1,102.97
400	Clay	31.21	52,786.51	1,804.93
525	Sand and gravel	89.45	24,171.51	826.50
525	Sandy clay and loam	86.22	25,076.90	857.46
525	Common earth	76.93	28,106.83	961.06
525	Clay	48.95	44,166.89	1,510.20
600	Sand and gravel	111.90	20,885.45	755.09
600	Sandy clay and loam	108.03	21,632.76	782.10
600	Common earth	96.88	24,123.56	872.16
600	Clay	62.98	37,109.65	1,341.65
700	Sand and gravel	148.61	18,347.00	663.31
700	Sandy clay and loam	143.75	18,966.54	685.71
700	Common earth	129.70	21,021.41	760.00
700	Clay	86.49	31,525.50	1,139.76

Table VII.
Bulldozer – model year 2003; 300 feet distance; 1,000 cy soil

bulldozer has to haul longer distance, the emissions become higher. For all types of soil, the shapes are generally the same, and displays that clay gives the bulldozer the highest NO_X and PM emissions of all pollutants based on dozing distance.

The sensitivity analysis for excavator is applied in two different work scenarios: first, a 400 HP – model year 2003 excavator has to dig 100 feet long – 10 feet wide trench in various depth, using 3 cy of bucket size on all types of soil; second, the same excavator with various size of bucket has to dig 100 feet long – 10 feet wide – 12 feet deep trench on all types of soil as well. Based on the information in Tables IX and X, there is an inverse relationship between productivity rate and the emissions; that is, as the productivity rate decreases, the emissions increase. The productivity rate also decreases with the digging resistance based on soil type; sand-gravel has the highest productivity rate whereas clay has the lowest. Likewise, although in very little difference, the emissions of NO_X and PM increase as the soil resistance increase. Furthermore, for a specific soil type, the productivity rate increases as bucket size increases, and decreases as the trench depth increases. For all types of soil, the NO_X and PM emissions increase as the trench depth increase. As the excavator digs a trench not deeper than 12 feet, the estimated emissions for all types of soil are about the same (Table IX). Although the emissions from all types of soil start vary when the trench went deeper than 12 feet, particularly for hard clay and common earth, the overall estimated emissions are considered the same.

Table VIII.
Bulldozer – 564 HP; model year 2003; 1,000 cy soil

Distance (ft)	Type of material	Productivity (cy/hr)	NOx (gr)	PM (gr)
50	Sand and gravel	305.24	7,609.55	260.19
50	Sandy clay and loam	296.60	7,831.46	267.78
50	Common earth	271.37	8,559.31	292.67
50	Clay	191.69	12,117.64	414.34
100	Sand and gravel	249.14	9,323.33	318.79
100	Sandy clay and loam	241.79	9,606.69	328.48
100	Common earth	220.40	10,538.87	360.36
100	Clay	153.31	15,150.50	518.04
150	Sand and gravel	201.60	11,521.74	393.96
150	Sandy clay and loam	195.40	11,887.36	406.46
150	Common earth	177.39	13,094.03	447.72
150	Clay	121.35	19,141.37	654.50
200	Sand and gravel	161.61	14,372.48	491.44
200	Sandy clay and loam	156.42	14,849.58	507.75
200	Common earth	141.38	16,429.79	561.78
200	Clay	94.95	24,462.55	836.45
250	Sand and gravel	128.24	18,112.89	619.33
250	Sandy clay and loam	123.93	18,743.21	640.89
250	Common earth	111.46	20,839.06	712.55
250	Clay	73.36	31,661.21	1,082.59
300	Sand and gravel	100.62	23,084.34	789.32
300	Sandy clay and loam	97.07	23,928.46	818.19
300	Common earth	86.84	26,747.25	914.57
300	Clay	55.89	41,557.40	1,420.97

Table IX.
Excavator – 400 HP; model year 2003; trench: 100 ft long-10 ft wide; 3 cy bucket size

Type of soil	Depth (ft)	Productivity (cy/hr)	NOx (gr)	PM (gr)
Common earth	2.5	168.05	906.05	30.98
Loam and sandy clay	2.5	174.50	873.10	29.85
Sand and gravel	2.5	176.00	873.10	29.85
Clay	2.5	159.59	955.47	32.67
Common earth	5	162.88	1877.99	64.21
Loam and sandy clay	5	169.32	1795.62	61.40
Sand and gravel	5	170.83	1779.15	60.83
Clay	5	154.42	1976.83	67.59
Common earth	8	156.67	3113.51	106.46
Loam and sandy clay	8	163.11	2981.72	101.95
Sand and gravel	8	164.62	2965.25	101.39
clay	8	148.21	3294.72	112.66
Common earth	12	148.40	4925.60	168.42
Loam and sandy clay	12	154.84	4727.92	161.66
Sand and gravel	12	156.34	4678.50	159.97
Clay	12	139.93	5222.13	178.56
Common earth	17	138.05	7511.96	256.86
Loam and sandy clay	17	144.49	7166.01	245.03
Sand and gravel	17	146.00	7100.12	242.77
Clay	17	129.58	7989.69	273.19
common earth	22	127.70	10493.68	358.81
Loam and sandy clay	22	134.14	9999.47	341.91
Sand and gravel	22	135.65	9884.16	337.97
Clay	22	119.24	11251.46	384.72

Type of Soil	Bucket Vol. (cy)	Productivity (cy/hr)	NOx (gr)	PM (gr)
Common earth	0.63	17.46	41892.34	1432.43
Loam and sandy clay	0.63	23.90	30607.93	1046.58
Sand and gravel	0.63	25.41	28779.36	984.05
Clay	0.63	9.00	81264.23	2778.67
Common earth	0.75	24.35	30031.36	1026.86
Loam and sandy clay	0.75	30.79	23754.92	812.25
Sand and gravel	0.75	32.30	22651.19	774.51
Clay	0.75	15.89	46027.22	1573.81
Common earth	1.00	38.13	19175.26	655.66
Loam and sandy clay	1.00	44.58	16407.70	561.03
Sand and gravel	1.00	46.08	15880.54	543.00
Clay	1.00	29.67	24644.49	842.67
Common earth	1.50	65.70	11136.15	380.78
Loam and sandy clay	1.50	72.14	10131.26	346.42
Sand and gravel	1.50	73.65	9933.58	339.66
Clay	1.50	57.23	12783.51	437.11
Common earth	2.50	120.83	6045.81	206.72
Loam and sandy clay	2.50	127.27	5749.28	196.59
Sand and gravel	2.50	128.78	5683.39	194.33
Clay	2.50	112.37	6507.07	222.50
Common earth	3.00	148.40	4925.60	168.42
Loam and sandy clay	3.00	154.84	4727.92	161.66
Sand and gravel	3.00	156.34	4678.50	159.97
Clay	3.00	139.93	5222.13	178.56
Common earth	3.50	175.96	4151.35	141.95
Loam and sandy clay	3.50	182.40	4003.08	136.88
Sand and gravel	3.50	183.91	3970.14	135.75
Clay	3.50	167.50	4365.50	149.27

Table X.
Excavator – 400 HP; model year 2003; trench: 100 ft long-10 ft wide-12 ft deep

The NO_X and PM emissions from excavator activity based on its bucket size are presented in Table X. The estimated emissions decrease dramatically while excavator digs the trench with bucket size < 1.50 cy. In this range of bucket size, clay has the highest emissions, while sand-gravel and sandy clay-loam has the lowest. However, when the bucket size used is bigger than 1.50 cy, the estimated emissions start decreasing slowly and shows that for all types of soil, the fuel uses are the same. It indicates that the productivity rate of excavator based on the resistance of soil or soil type varies only when the excavator uses small size of bucket. For bigger bucket size, the resistance of soil does not have impact on productivity rate.

The sensitivity analysis for truck is applied in two different work situations: first, a 535 HP – model year 2003 truck with 30 cy loading capacity has to haul 1,000 cy of soil in various distance, using various hauling speed, and has to wait for dumping and loading for 15-25 minutes; second, the same truck with various capacity of loading has to haul 1,000 cy of soil in one mile, using average hauling speed range of 5-25 miles/hr, and has to wait for loading and dumping for 15 minutes. Based on the information in Tables XI and XII, there is an inverse relationship between productivity rate and the NO_X and PM emissions; that is, as the productivity rate decreases, the emissions increase. For any speed the truck uses to haul the soil, the productivity rate increases as loading capacity increases, and decreases as the haul distance increases.

Distance (mi)	Load-dump time (min.)	Productivity (cy/hr)	NOx (gr)	PM (gr)
0.38	15	91.02	24,208.45	827.76
0.38	20	77.07	28,588.21	977.52
0.38	25	63.13	34,902.77	1,193.43
0.57	15	88.72	24,833.46	849.13
0.57	20	74.78	29,463.92	1,007.46
0.57	25	60.84	36,216.94	1,238.37
0.76	15	86.43	25,491.60	871.64
0.76	20	72.49	30,394.98	1,039.30
0.76	25	58.55	37,633.96	1,286.82
1	15	83.54	26,374.53	901.82
1	20	69.60	31,658.65	1,082.51
1	25	55.65	39,590.61	1,353.72
2	15	71.48	30,822.74	1,053.92
2	20	57.54	38,291.94	1,309.32
2	25	43.60	50,538.93	1,728.08
4	15	47.37	46,511.62	1,590.37
4	20	33.43	65,912.74	2,253.76
4	25	19.48	113,081.95	3,866.61

Table XI. Truck – 535 HP; model year 2003; 30 cy capacity; 1,000 cy soil; 10 mph of speed

Capacity (lcy)	Speed (mph)	Productivity (cy/hr)	NOx (gr)	PM (gr)
22	5	58.78	37,483.75	1,281.68
22	10	66.91	32,931.87	1,126.04
22	15	75.03	29,365.81	1,004.11
22	20	83.16	26,496.60	906.00
22	25	91.28	24,138.16	825.36
30	5	75.42	29,215.94	998.98
30	10	83.54	26,374.53	901.82
30	15	91.67	24,036.81	821.89
30	20	99.79	22,079.76	754.97
30	25	107.91	20,417.40	698.13
42	5	100.37	21,952.75	750.63
42	10	108.49	20,308.75	694.42
42	15	116.62	18,893.83	646.04
42	20	124.74	17,663.22	603.96
42	25	132.87	16,583.11	567.03
60	5	137.80	15,990.00	546.75
60	10	145.92	15,099.68	516.30
60	15	154.04	14,303.27	489.07
60	20	162.17	13,586.67	464.57
60	25	170.29	12,938.44	442.40

Table XII. Truck – 535 HP; model year 2003; one mile hauling distance; 15 minutes wait-dump time; 1,000 cy soil

The NO_X and PM emissions from truck activity based on cycle distance are shown in Table XI, analyzed using three different load-dump times: 15, 20, and 25 minutes. For all load-dump times, estimated emissions increase as the cycle distance increase. The longer the truck has to wait for loading and dumping, the higher the emissions. More productive supporting equipment (such as excavator or backhoes) for loading and unloading soil to truck is needed to shorten the load-dump time and improve the truck's productivity rate. The estimated emissions for three load-dump time have little difference when the truck has to haul within less than two miles. For hauling distance more than two miles, the estimated emissions vary for three different load-dump times. Truck with 25-minute load-dump time increases its emissions of NO_X and PM, very rapidly compared to 15- and 20-minute load-dump time, as the hauling distance increase.

The productivity rates and emissions impact of truck activity based on loading capacity, and analyzed using five different hauling speeds (5, 10, 15, 20, and 25 miles/hr), are shown in Table XII. For all hauling speeds, the estimated NO_X and PM decrease as the loading capacity increases. It is understood that the productivity rate of truck improves when using bigger loading capacity, and therefore shorten the hauling duration. Truck with highest hauling speed (25 mph) has the lowest emissions. The difference of emissions among all hauling speeds becomes smaller following the loading capacity; for instance, the difference of emissions at 25 cy loading capacity is bigger than those at 50 cy or more loading capacity. It indicates that using various speed of hauling does not have bigger impact on the estimated emissions if the truck uses bigger loading capacity.

Conclusion and future works

This paper presented a methodology for estimating NO_X and PM emissions for some common earthwork activities performed by bulldozer, excavator, and dump truck. The MLR approach proved to be a useful alternative for estimating productivity rate of three equipments. The MLR models for the productivity rate can explain high percentage of the variability in the data. The models are good to be used as a benchmark for estimating NO_X and PM emissions from some certain types of construction equipment performing earthwork activities. The productivity rate from this model (lcy/hr) is used with EFs (g/HP-hr) from EPA's NONROAD model to estimate the total emissions.

Based on the methodology presented in this paper, the results revealed several trends related to total emissions of the equipment. For example, the total emissions increase as the trench depth or hauling distance increase, because digging deeper trench or hauling further distance lead to lower productivity. Meanwhile, as the excavator's bucket size or bulldozer's blade or truck's capacity increase, the total emissions decrease, because the productivity gets higher when the equipment uses bigger attachment size.

After the estimating tool has been developed, it is recommended for future research to validate and calibrate the model by real-world fuel use and emissions data collected from construction equipment. This will be done by using a portable emissions measurement system (PEMS) that is able to record second-by-second fuel use, emissions, and engine data from the equipment performing earthwork activities. The field data collection and analysis process will permit evaluation of the variability in fuel use and emissions rates among equipment based on type, engine size, engine load, and usage.

The estimating tool proposed in this paper will be an effective means for assessing the environmental impacts of construction activities and will allow equipment owners or fleet managers, policy makers, and project stakeholders to evaluate more sustainable alternatives. The tool will help the contractor to estimate the total expected pollutant emissions for the project, which would be valuable information for a preliminary environmental assessment of the project.

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