Civil Engineering Dimension, Vol. 21, No. 2, September 2019, 59-65
ISSN 1410-9530 print / ISSN 1979-570X online
DOI: 10.9744/CED.21.2.59-65

PEMS-on board and E3 Modeling: A Comparison between Real-World Measurement and Emissions Estimates from Construction Equipment

Hajji, A.M.[1]*, Larasati, A.[2], Lewis, M.P.[3], and Yue, H.[4]

Abstract: Vehicles in construction industry are typically powered by diesel engines and are considered to be an off-road source of air pollution. Air pollutant emissions include nitrogen oxides (NOx), particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO). Any engine that combusts a nonrenewable carbonaceous fuel will have net emissions of carbon dioxide (CO_2). Economic-Energy-Environmental (E3) model, a statistical-modeled tool, is developed by combining a multiple linear regression (MLR) approach for modeling equipment productivity with the emissions calculation algorithm from Environment Protection Agency (EPA)'s NONROAD model. This paper compares emissions data between the field data to E3 model outputs, and determines the similarity of the two sources of fuel use data. It is expected the two data are not narrowly similar since the field data are for individual vehicles, while E3 results are based on NONROAD model, which was intended to estimate average fuel use for a fleet of Heavy-Duty Diesel (HDD) equipment.

Keywords: Portable emission measurement system; emissions; construction equipment.

Introduction

The threat of air pollution forced by various human activities has been severely mounting at an alarming rate over the past decades. Evaluation and control of air pollutant emissions into the atmosphere can lead towards lowering the emission level. The construction industry is one of the main contributors to the global emissions due to the wide-ranging use of construction equipment, which is responsible for some air pollutant emissions and dangerous substances such as carbon monoxide, nitrogen oxide and particulate matter emission [1]. Nowadays in construction activities, with the growing industrialized construction work, the role of onsite equipment and machinery is vital in achieving productivity and efficiency. During the construction phase, the selection of the proper equipment has always been an important aspect in the success of any construction activities.

[1] Associate Professor at Department of Civil Engineering, Universitas Negeri Malang, INDONESIA
[2] Associate Professor at Department of Mechanical Engineering, Universitas Negeri Malang, INDONESIA
[3] Associate Professor at School of Civil and Environmental Engineering, Oklahoma State University, USA
[4] Senior Lecturer at Institute of Transport Studies, University of Leeds, UK
*Corresponding author: apif.miptahul.ft@um.ac.id

Note: Discussion is expected before November, 1st 2019, and will be published in the "Civil Engineering Dimension", volume 22, number 1, March 2020.

Received 01 July 2019; revised 23 July 2019; accepted 24 July 2019.

This selection method is usually made by corresponding equipment available in a fleet with the type of activities. The growing concept of sustainability in construction has underlined energy conservation, efficiency, green environment, economy, and human health. In this context, selecting the most appropriate construction equipment from the available options in the fleet is highly challenging [2,3] Abanda, et al. revealed that the construction activities, including infrastructure projects, is one of the highest users of natural resources. In construction projects, where the consumption rate of natural resources is high, greenhouse gases are emitted which have adverse effects on the natural environment [4].

Recent studies have shown the significant linkage between the quantification of energy used and greenhouse gases released in construction projects. Lewis, et al. [5] and Kim and Jang [6] offered methodologies for quantifying the impact of idling on National Ambient Air Quality Standards criteria pollutant emissions, including nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). A life cycle assessment (LCA) model can also be formulated to monitor energy use and greenhouse gas (GHG) emissions from pavement reconstruction projects. The LCA model analyzes the energy and GHG emissions associated with material production, construction, and pavement use, which also take into accounts the effects of pavement rolling resistance on construction equipment operation [7]. Some studies have measured carbon emissions by considering the inherent uncertainty during the building construction process that could lead to the misinterpretation of important aspects. To handle such weakness, a multi-method-based uncertainty analysis framework was formulated given the basic characteristics of the construction activity. This framework assimilates both deterministic and probabilistic approaches to enable the uncertainty assessment in quantifying carbon emissions and providing insights into the sensitive construction activities from the uncertainty perspective [8].

For vehicles used in the field, a portable emission measurement system (PEMS) is utilized to measure real-time emissions rate of carbon dioxide (CO2), nitrogen oxides (NOx), hydrocarbon, and carbon monoxide (CO) emissions from heavy construction equipment. The emission rate is expressed in mass of pollutant emitted per unit time and emission factors in mass of pollutant emitted per unit volume of fuel consumed under on-site project conditions [9-11]. The method and results were compared with emissions estimated by three different methodologies and models: NONROAD2008, OFFROAD 2011, and a modal statistical model. Real world measured emission rates settled with those three models of estimates for some types of equipment but were up to 100 times lower for other types. Main factors of the difference were determined by lower fuel consumption rates than estimated. The estimates of emission factors on idling and hauling positions varied significantly at a specific type of equipment and moving activities, such as digging and dumping. It appears that equipment operating conditions present considerable variability in estimated emission factors. PEMS is also useful for quantification of real-world vehicle activity, energy use, and emissions. PEMS typically include tail-pipe exhaust gas and particle analyzers, Global Positioning System (GPS) receivers, engine sensors, and electronic control unit (ECU) data loggers. Estimated fuel use and emission rates for light- and heavy-duty vehicles are sensitive to errors in intake manifold absolute pressure and engine revolutions per minute values and indicators of air-to-fuel ratio including carbon dioxide and oxygen concentrations [12].

Method

Economic-Energy-Environmental (E3) model is a statistical model that can be used to predict the productivity rate, construction activity duration, total fuel consumption, and total air pollutants from infrastructure project activities [13]. As shown in Figure 1, the model is developed by combining the multiple linear regressions (MLR) approach for predicting productivity with the EPA's NONROAD model. Some construction equipment data were selected to build the productivity model, and emission factors of all type of pollutants from the NONROAD model were used to estimate the total fuel use and emissions. The model proposed will be

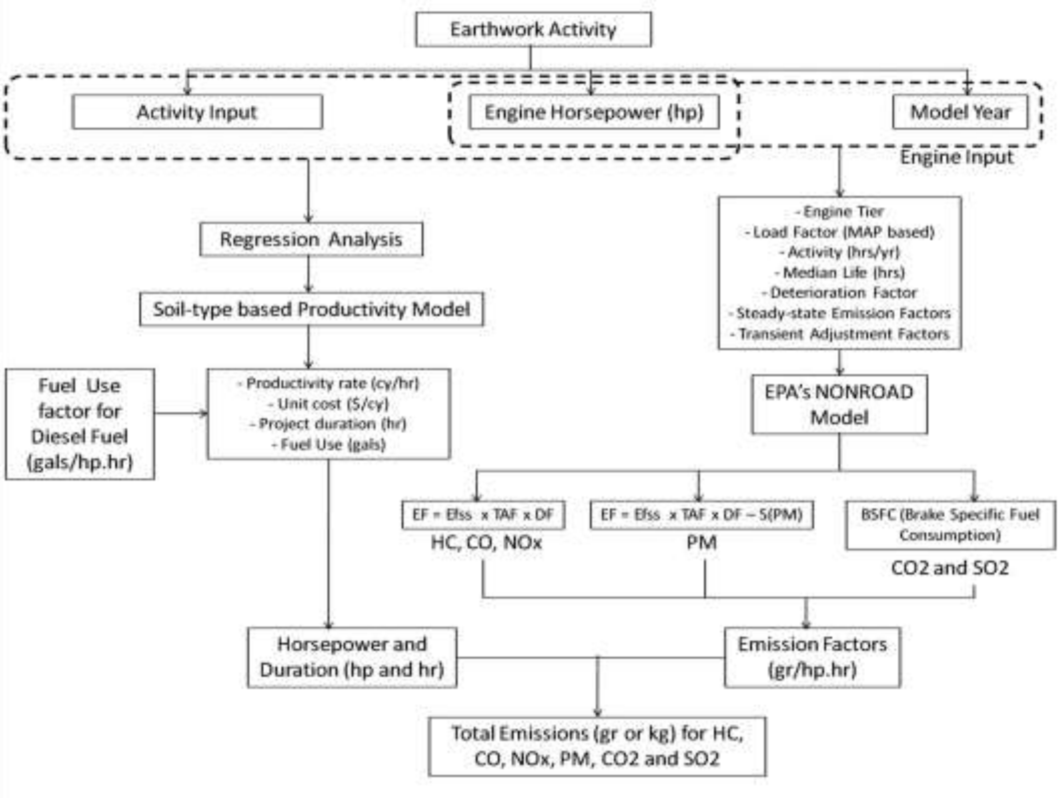

Figure 1. Development of E3 Model for Emissions Estimates [13]

an effective predictive tool for monitoring the fuel use rate and air emissions of infrastructure project activities and will assist equipment owners or fleet managers, policy makers, and project stakeholders to evaluate their construction projects. The model will also help the contractors to estimate the fuel quantities they need and possible pollutant emissions, which would be vital information for a preliminary environmental evaluation of the project [14,15]. The MLR approach proved to be a useful alternative for estimating the productivity rate of some types of equipment. The MLR models for the productivity rate can explain the variability in the data. The models are useful to be used as a reference for estimating air pollutant emissions from some certain types of construction equipment performing earthwork activities. The productivity rate from this model (in loose cubic-yard/hour or lcy/hr) is used with emission factors (in grams per horsepower-hour or gr/hp-hr) from EPA's NONROAD model to estimate the total emissions.

An on-board portable emissions monitoring system (PEMS) was used to collect engine, fuel use, and emissions data directly from operating construction equipment. The PEMS used was the Montana System manufactured by CATI. The PEMS was secured to the body of the equipment. Using the Clean Air Technologies International (CATI) system, the PEMS measures second-by-second mass emissions

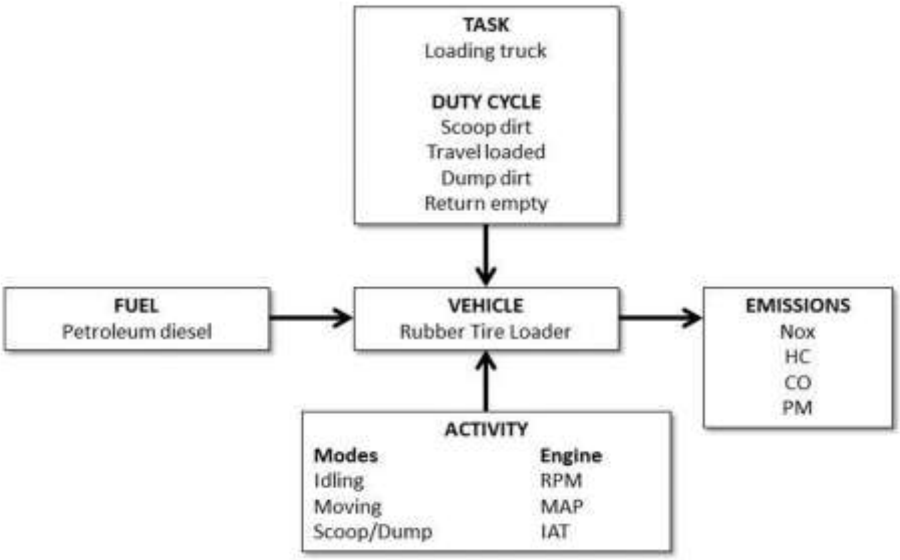

Figure 2. Input and Output Data for Measuring Emissions from in-use Equipment

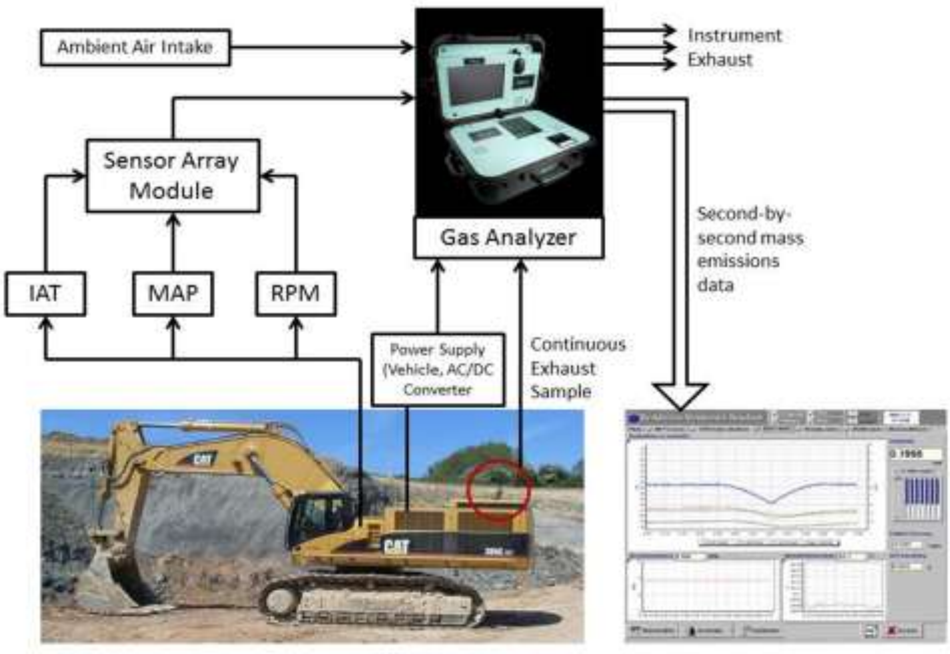

Figure 3. Installation of PEMS on Construction Equipment

released from vehicle's exhaust and some other information associated with the engine, such as manifold absolute pressure (MAP), rotation per minute (RPM), and intake air temperature (IAT) [16]. As displayed in Figure 2, sensors were connected to the engine to collect engine performance data related to engine speed, intake air temperature, and engine load. Tailpipe exhaust samples were drawn continuously to measure exhaust concentrations of NOx, HC, CO, CO_2, and PM. Second-by-second equipment fuel use was computed on a mass per time basis of grams per second (gr/s), based on the measured engine variables and exhaust composition. The average fuel use for each item of equipment is reported in units of gallons of fuel used per hour (gal/hr). The PEMS also measured the second-by-second emission rate of each pollutant on a mass per time basis of grams per second (gr/s). The average mass per time emission rate of each pollutant for each item of equipment is reported in units of grams per hour (gr/hr). Fuel-based emission rates, which quantify the mass of emissions per unit of fuel consumed, were estimated based on a carbon balance based on the exhaust composition and the fuel properties. The average of the mass per fuel used emission rates for each item of equipment is reported in units of grams per gallon of fuel used (gr/gal).

For diesel construction vehicle, the PEMS collects emissions by using sample probe inserted into the tailpipe for the gas pollutants (HC, CO, NOx, CO_2) and PM and connected to gas and PM analyzers. The illustration of installing PEMS instrument is shown in Figure 3.

Results and Discussion

The purpose of comparison between the fuel use from field data and E3 model outputs is to determine if the two sources of fuel used data were of a similar relationship. It is expected that the two data are not narrowly similar since the field data are for individual vehicles, while E3 results are based on NONROAD model, which was intended to estimate average fuel use for a fleet of heavy-duty diesel (HDD) equipment. Results comparison is conducted by comparing the total fuel use obtained from in-use HDD equipment in the field with those estimated by using E3 model. The fuel use factors and fuel use from in-use HDD equipment from field is measured by PEMS. The field HDD equipment used for this comparison are shown in Table 1.

The PEMS measures total fuel use of HDD equipment based on the fuel use factors at its rated engine horsepower in terms of gallons per time. Since the PEMS measurement is second-by-second data, the total duration used by the HDD equipment in seconds is converted to hours, and multiplied by the fuel use factors and engine horsepower to obtain the working total fuel use. The total fuel use from E3 model are calculated by multiplying the brake specific fuel consumption (BSFC), engine size, total duration, and equipment load factor. Table 2 shows the total fuel from two data sources.

In general, the average total fuel use from E3 model is relatively similar to those from field PEMS measurement. For example in Excavator 1, One hour fuel use obtained from PEMS is 10.24 gallons, while from E3 model estimation is 11.60 gallons. E3 model estimates 0.5 hours fuel use from Truck 3 as 6.45 gallons, while PEMS measures fuel use as 6.66 gallons. At some points, the fuel use estimates of E3 model are higher than PEMS measurement; however at some other cases the PEMS measurement gives higher output than E3 model. As shown in Figure 4, the average total fuel use estimates of bulldozer are 9% lower than those from PEMS measurement, while fuel use estimates of excavator and truck are 34% and 17% higher than the field data respectively. The overall average total fuel use estimates for these three HDD equipment is 14% higher than the field data.

Table 1. HDD Equipment 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
Excavator 1	254	2001	1	1.027
Excavator 2	138	2003	2	4.312
Excavator 3	93	1998	1	4.994
Truck 1	306	2005	2	5.125
Truck 2	285	1998	1	1.117
Truck 3	285	1998	1	0.509

Table 2. Fuel use Comparison Between E3 Model and PEMS Measurement Results

Equipment	Fuel use			
	Fuel Use Factor (gal/hp-hr)		Total Fuel Use (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
Excavator 1	0.044	0.039	11.60	10.24
Excavator 2	0.044	0.017	26.47	9.86
Excavator 3	0.049	0.043	22.96	19.89
Truck 1	0.044	0.034	69.75	52.49
Truck 2	0.044	0.050	14.16	15.85
Truck 3	0.044	0.046	6.45	6.66

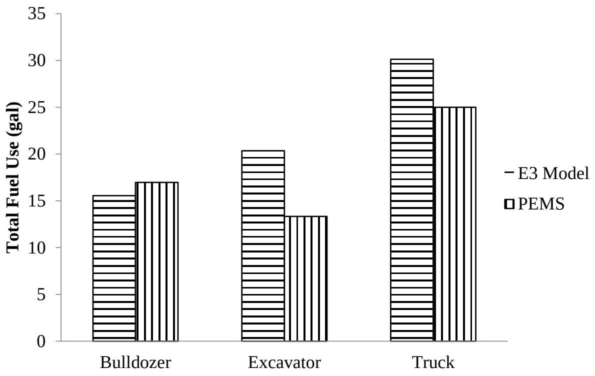

Figure 4. Total Fuel use Comparison – E3 Model and PEMS Result

The PEMS measures total emissions of HDD equipment based on the emission factors at its rated engine horsepower in terms of mass per time. Since the PEMS measurement is second-by-second data, the total duration used by the HDD equipment in seconds is converted to hours, and multiplied by the emission factors and engine horsepower to obtain the working total emissions. The total emissions from E3 model are calculated by multiplying the emission factors, engine size, total duration, and equipment load factor. Table 3 shows the total emissions from two data sources.

In general, the average total emissions from E3 model are relatively similar to those from field

Table 3. Total Emission Comparison Between E3 Model and PEMS Measurement

Equipment	Total Emission									
	HC (gr)		CO (gr)		NOx (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
Excavator 1	51.1	21.4	188.3	60.1	828.9	1186.5	60.1	14.2	82.4	108.8
Excavator 2	126.5	81.3	485.1	380.1	1372.6	798.2	85.5	7.3	187.8	104.0
Excavator 3	156.0	134.6	1102.3	204.9	1496.0	2186.4	236.2	20.6	162.9	210.8
Truck 1	164.4	404.1	1242.6	3028.1	3842.6	5447.7	159.6	59.1	495.7	552.1
Truck 2	65.4	59.7	259.9	173.3	1044.9	1365.6	111.4	14.7	100.6	167.5
Truck 3	29.8	25.9	118.3	71.9	475.7	717.4	50.7	6.1	45.8	70.6

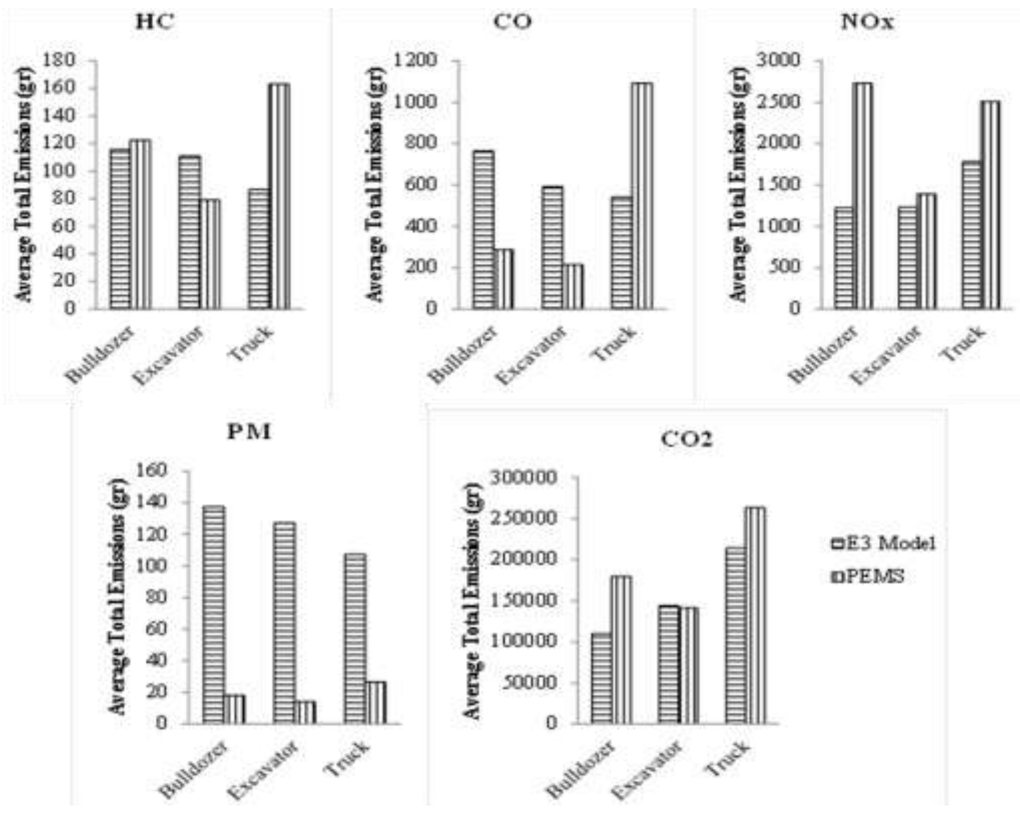

Figure 5. Total Emission Comparison – E3 Model and PEMS Result

PEMS measurement, especially for HC, CO, NOx, and CO_2. For example, in Bulldozer 2, 5.9 hours NOx emission obtained from PEMS is 1671 grams, while from E3 model estimation is 1767 grams. E3 model estimates 0.5 hours HC emission from truck 3 as 29.8 grams, while PEMS measures HC emission as 25.9 grams. At some points, the emissions estimates of E3 model are higher than PEMS measurement; however, at some other cases the PEMS measurement gives higher output than E3 model. As shown in Figure 5, the average emissions estimates of HC for bulldozers and excavators have similar magnitude with those from PEMS measurement. HC emission estimates for truck are much lower than the PEMS measurement. The overall average HC emission estimates for three HDD equipment is 22% lower than the field data.

The average emissions estimates of CO for bulldozers and excavators are higher than those from PEMS measurement; however, the CO estimates for trucks are much lower than the PEMS has. The overall average CO emission estimates of these three HDD equipment is 8% higher than the average of PEMS measurement results. For NOx emissions, the E3 model estimates of all three equipment are lower than those from PEMS by 59%. The average CO_2 emission estimates of excavators from E3 models have similar magnitude with the PEMS measurement results, but lower for bulldozers and trucks. Overall, this CO_2 emission estimates are 28% lower than the field data.

The biggest differences between these two sources of data occurred at PM emissions (Figure 5). The E3 model estimates PM emissions much higher than PEMS measurement for all type of equipment. The estimates are about 85% higher than the field data. According to PEMS system operation manual released by Clean Air Technologies 2003 and research conducted by Frey et al. [16], this is due to the fact that PM data are measured by a laser light scatter method, rather than by a filter-based method, and it makes a systematic measurement bias for PM concentration for this PEMS instrument.

Conclusion

Total emissions estimates are calculated by using the total duration of the activity obtained from productivity model and emissions factors obtained from NONROAD model. When compared to field data, results from E3 model give different magnitude of the average total emissions of each pollutant. 22% lower for HC, 8% higher for CO, 59% lower for NOx, 85% higher for PM, and 28% lower for CO_2. The NONROAD model data are also obtained from the standardized engine dynamometer tests in laboratory conditions. Meanwhile, results from PEMS are gathered from individual in-use HDD equipment when it is operating on various jobsite conditions. Although the results from E3 model do not represent actual working conditions on field, it can be used as a framework and practical tool to predict the emissions from HDD equipment, its fuel use, total duration, and productivity rate at the same time, which have not currently been available by previous models and methods.

References

1. Sandanayake, M., Zhang, G., Setunge, S., and Thomas, C.M., Environmental Emissions of Construction Equipment usage in Pile Foundation Construction Process-A Case Study, *Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estat*e, Springer, Berlin, Heidelberg, 2015, pp. 327-339.
2. Waris, M., Liew, M. ., Khamidi, M.F., and Idrus, A., Criteria for the Selection of Sustainable Onsite Construction Equipment, *International Journal of Sustainable Built Environment*, 3(1), 2014, pp. 96-110.
3. Fu, M., Ge, Y., Tan, J., Zeng, T., and Liang, B., Characteristics of Typical Non-Road Machinery Emissions in China by using Portable Emission Measurement System, *Science of the Total Environment*, 437, 2012, pp. 255-261.
4. Abanda, F.H., Tah, J.H.M., and Cheung, F.K.T., Mathematical Modelling of Embodied Energy, Greenhouse Gases, Waste, Time-Cost Parameters of Building Projects: A Review, *Building and Environment*, 59, 2013, pp. 23-37.
5. Lewis, P., Rasdorf, W., Frey, H., and Leming, M., Effects of Engine Idling on National Ambient Air Quality Standards Criteria Pollutant Emissions from Nonroad Diesel Construction Equipment. *Transportation Research Record: Journal of the Transportation Research Board*, (2270), 2012, pp. 67-75.
6. Kim, B.S. and Jang, W.S., A Study on Comparing the CO_2 Emission Estimating Result for Construction Equipment, *Journal of the Korean Society of Civil Engineers*, 33(4), 2013, pp. 1675-1682.
7. Wang, T., Lee, I.S., Kendall, A., Harvey, J., Lee, E.B., and Kim, C., Life Cycle Energy Consumption and GHG Emission from Pavement Rehabilitation with Different Rolling Resistance, *Journal of Cleaner Production*, 33, 2012, pp. 86-96.
8. Hong, J., Shen, G.Q., Peng, Y., Feng, Y., and Mao, C., Uncertainty Analysis for Measuring Greenhouse Gas Emissions in the Building Construction Phase: A Case Study in China, *Journal of Cleaner Production*, *129*, 2016, pp. 183-195.

9. Heidari, B. and Marr, L.C., Real-time Emissions from Construction Equipment Compared with Model Predictions, *Journal of the Air & Waste Management Association*, 65(2), 2015, pp. 115-125.
10. Kousoulidou, M., Fontaras, G., Ntziachristos, L., Bonnel, P., Samaras, Z., and Dilara, P., Use of Portable Emissions Measurement System (PEMS) for the Development and Validation of Passenger Car Emission Factors, *Atmospheric Environment*, 64, 2013, pp. 329-338.
11. Lindgren, M., Arrhenius, K., Larsson, G., Bäfver, L., Arvidsson, H., Wetterberg, C., and Rosell, L., Analysis of Unregulated Emissions from an Off-Road Diesel Engine During Realistic Work Operations, *Atmospheric Environment*, 45(30), 2011, pp. 5394-5398.
12. Sandhu, G. and Frey, H., Effects of Errors on Vehicle Emission Rates from Portable Emissions Measurement Systems, *Transportation Research Record: Journal of the Transportation Research Board*, (2340), 2013, pp. 10-19.
13. Hajji, A.M. and Lewis, P., Development of Productivity-Based Estimating Tool for Energy and Air Emissions from Earthwork Construction Activities, *Smart and Sustainable Built Environment*, 2(1), 2013, pp. 84-100.
14. Hajji, A.M., Estimating the Emissions of Nitrogen Oxides (Nox) and Particulate Matter (PM) From Diesel Construction Equipment by using the Productivity Model, *World Journal of Science, Technology and Sustainable Development*, 10(3), 2013, pp. 212-228.
15. Hajji, A.M., The Use of Construction Equipment Productivity Rate Model for Estimating Fuel Use and Carbon Dioxide (CO2) Emissions, Case Study: Bulldozer, Excavator and Dump Truck, *International Journal of Sustainable Engineering*, 8(2), 2015, pp. 111-121.
16. Frey, H.C., Rasdorf, W., Kim, K., Pang, S.H., Lewis, P., and Abolhassani, S., *Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina,* Raleigh, NC: Dept. of Civil, Construction, and Environmental Engineering, North Carolina State University, 2008.