Emissions Modelling of Earthmoving Equipment

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Abstract –

Earthmoving operations produce high amount of emissions and are one of the main sources of air pollutants in construction and mining industries. Modelling and quantifying the emissions produced by earthmoving equipment is the first step for developing emissions reduction schemes. Currently, emissions of construction and mining equipment are mainly estimated through simulation or laboratory tests which may not represent the real-world situations. This paper presents a comprehensive methodology to predict emission rates of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxides (NO_x) of earthmoving equipment by considering operation modes and engine attributes. The developed framework includes three main processes of instrumentation, data collection and data analysis. Two instruments of portable emission measurement system (PEMS) and GPS aided inertial navigation system (GPS-INS) are proposed for conducting field experiments and collecting emission rates and operational parameters. Further, site observation is conducted to estimate the cycle time and time ratio of operation modes. An exploratory analysis method is then developed to process the gathered data and model emissions at operation and equipment level. The applicability of the developed methodology is finally verified through experimenting and modelling emissions of one loader and one excavator.

Keywords –

Emissions; Earthmoving Equipment; Field Experiments; Site Observation; Data Analysis

1. Introduction

In the previous two decades, climate change resulting from greenhouse gas (GHG) emissions has become a global concern [1]. The main compositions of GHGs are CO_2, CO, HC, NOx and general particulate matters (PM) pollutants. Construction and mining industries are two of the main sectors including more than 20% of all non-road equipment [2]. The machinery is mainly involved in large-scale earthmoving operations in which the emitted pollution is by far more than other vehicles. For example, the pollution of a 130 kW-power loader is nearly 500 times more than that of a private car [3]. Construction industry by itself is ranked the third highest emitted pollution industry behind oil and gas, and chemical manufacturing sectors, and also accounts for the third CO_2 emitter per unit of energy used just after cement and steel production industries [4]. Total GHG emission from construction and mining operations is estimated around 6.8% of all industrial emissions. According to the US Clean Air Act Advisory Committee (CAAAC), 32% of NO_x and 37% of PM emitted by all non-road engines result from construction and mining operations [5].

In spite of this significance, emissions of equipment involved in construction and mining sectors have not been precisely modelled yet. The main challenge in this field is that different researchers have been mainly focused on a certain aspect of issue. The lack of correlation and consistency amongst the conducted studies is the main barrier for modelling emission of equipment. Furthermore, the processes of instrumentation and data collection are challenging and error-prone to measure the exact amount of emissions produced by each type of equipment or operation mode. In addition, there are many parameters that their effects on emission have not been fully investigated yet.

This paper aims to develop a comprehensive methodology for emissions modelling of earthmoving equipment in construction and mining at operation and equipment levels through field data processing. This framework consists of three main steps of instrumentation, data collection and result analysis. After developing required instruments, field data need to be collected from in-use earthmoving equipment through experimentation. The methods of analysis are then presented for processing the collected data and developing emissions models at operation and equipment level. The case studies for emission modelling of one loader and one excavator are finally presented to verify the framework developed in the paper.

2. Literature Review

Many studies have been conducted by government agencies and scholars to model and estimate GHG emissions resulting from construction and mining industries at equipment, project and national levels. The NONROAD model developed by the United States Environmental Protection Agency (USEPA) can estimate emitted pollutions of equipment involved in construction industry at national level [6]. This model roughly estimates emission rates of six main pollutants of CO_2, CO, NO_x, PM and Sulphur oxides (SO_2) by considering some major affecting parameters, including engine size, equipment category, emission factors and activity hours [7]. Some of the inputs of this model such as emission factors have been determined based on laboratory tests which cannot provide the episodic nature of real-world operations [8]. Based on NONROAD model, the contributions to CO, NO_x and PM emissions by different types of equipment are compared in Table 1 [6]. The earthmoving machineries are found to be the main contributors to emissions in construction and mining industries. California Air Resources Board (CARB) developed OFFROAD model to estimate the emissions of non-road construction equipment in the California State. This model predicts five main GHG pollutants emitted from 94 machineries (17 categories) annually by considering engine power, annual activity and fuel-emission parameters [9]. URBEMIS is a project-level emission model developed by Sacramento Metropolitan Air Quality Management District (SMAQMD). This model takes into account of the project size, equipment specifications and fuel-emission factors developed by OFFROAD model to estimate the total air pollutants resulted from seven common construction projects [7]. Similar to URBEBIS, Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) model was developed by the University of California-Berkeley for estimating the emissions of road projects at equipment and material level [10].

Numerous studies were conducted to collect and analyze real-world emission data of construction equipment. Through doing field experiments on construction equipment, the manifold absolute pressure (MAP) was identified as the main parameter affecting emissions [7]. Ahn and Lee developed operation efficiency parameter to consider idling and non-idling emission coefficients. The parameter was then defined as the criteria to determine the optimum fleet size for producing least amount of emissions [5]. Abolhasani and Frey conducted field experiments to determine the effects of different fuels on four pollutants emission rates of NO_x, CO, HC and PM [11].

3. Methodology

The framework for emissions modelling of earthmoving equipment is developed in the research, as shown in Figure 1. The parameters affecting emissions are first identified and categorized. Then, by considering the latest off-the-shelf technologies, an integrated instrumentation system is developed to collect real-world data. The data on emissions, operation modes and equipment cycle time were collected through conducting field experiments and site observations. Analysis methods are then developed for emission analyzing of earthmoving equipment. The equipment's cycle time needs to be estimated through analyzing the data collected by employed instruments, site observations and using manufacturer's performance handbooks. The equipment-level emission model is finally developed by considering the emission rates in each operation mode and estimated cycle times.

Table 1. Construction equipment contribution in NO_x, CO, PM emissions

Equipment	NOx		CO		PM	
	Contribution	Ranking	Contribution	Ranking	Contribution	Ranking
Front-end loaders	14.5%	1	11.5%	3	11.2%	3
Backhoes	9.2%	5	16%	1	15.1%	1
Bulldozers	12.5%	2	9.3%	4	9.1%	4
Skid-steer loaders	6.2%	6	14.5%	2	13.6%	2
Excavators	11.4%	3	7.4%	5	8.6%	5
Off-highway trucks	11.0%	4	7.3%	6	6.6%	6
Generators	4.7%	7	5.1%	7	6.0%	7
Forklifts	3.9%	8	4.9%	8	4.6%	8
Scrapers	3.4%	9	2.7%	11	2.3%	12
Cranes	3.2%	10	1.5%	15	1.9%	14

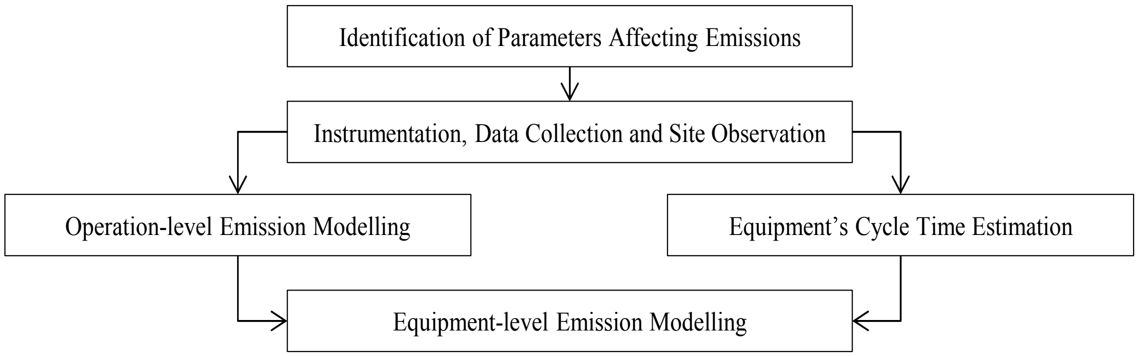


Figure 1. Developed research framework for emission modelling of earthmoving equipment

3.1. Affecting Parameters on Emissions

This section aims to identify and classify parameters affecting emissions of earthmoving equipment. Lewis investigated the effect of engine attributes including engine mode and engine size on emissions [7]. In NONROAD and OFFROAD emission models, three factors of engine size, average load factor and fuel-emission ratio were introduced as main affecting factors on emissions [6, 9]. Barati and Shen investigated the effect of acceleration, payload, speed and road slope as operational parameters for emission modelling of on-road construction equipment [12].

In this study, affecting parameters on emissions of earthmoving equipment are classified into two categories of engine attributes and operational parameters. As shown in Figure 2, engine size, engine load and fuel type are three main engine attributes affecting emissions. There is a direct relationship between engine size and emission rates. The engine load is defined as the amount of used power of engine over the maximum theoretical power as a percentage. The engine load of most construction equipment ranges approximately from 20% to 80% of the maximum engine power [13]. Barati et al. [14] showed a highly-correlated direct linear relationship between engine load and emission rates. Normally, construction equipment uses one certain type of fuel in their lifetime which has negligible changes in ingredients. So, engine fuel can be ignored as a parameter affecting emission rates for a certain piece of equipment. Since most of construction equipment consumes diesel, this research investigates the effect of diesel fuel on emissions modelling only.

Operation efficiency, cycle time and operator skill are the three main operational parameters affecting emissions of earthmoving equipment. Operation efficiency is defined by efficient operating time versus non-efficient idling time. It is obvious that as equipment operates more efficiently, the emission rates at equipment level will be higher. Total cycle time and the ratio of time in each operation mode are the other operational parameters affecting equipment level emission modelling of earthmoving operations. The effect of minor factors on emission rates, such as material type, swing angle and fleet position is considered in the parameter of cycle time. Operator skill is a main parameter affecting the time ratio and cycle time of equipment. Also, this parameter has significant effect on emission rates in operation modes.

3.2. Instrumentation and Data Collection

As shown in Figure 3, three instruments are required for emission modelling of earthmoving operations. The main instrument is a PEMS which measures real-world emissions of the equipment's exhaust. The instrument can measure CO_2, CO, HC and NO_x emission rates in each second using a sample probe inserted in the tailpipe. The model of PEMS is MEXA 584L automotive emission analyzer manufactured by the HORIBA Ltd. GPS-INS is the other multipurpose instrument used in the research. GPS-INS system combines accelerometers, gyroscopes and magnetometers with a commercial grade GPS receiver. GPS-INS is embedded to the boom or stick of earthmoving equipment and provides three-dimensional position and movement in each second. The GPS-INS system proposed for this study is SPATIAL-EK manufactured by Advanced Navigation Pty Ltd. The measured data by PEMS and GPS-INS instruments need to be transmitted through RS-232 serial data communication port to an industrial Tough Pad. Panasonic FZ-G1 is the industrial Tough Pad utilized to analyse the collected field data. Analysis of data collected by GPS-INS system determines the cycle time and operation efficiency of earthmoving equipment.

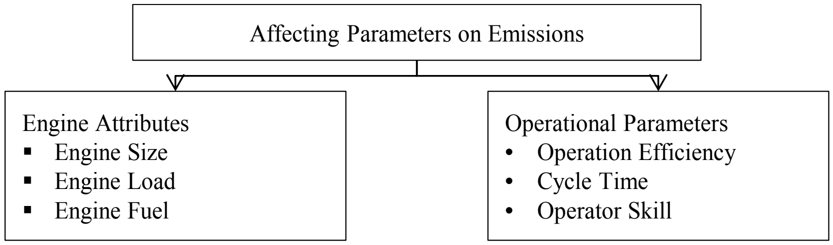


Figure 2. Parameters affecting emissions of earthmoving equipment

Figure 3. Instrumentation for field data collection

Due to main contribution of earthmoving equipment in producing NO_x, CO and PM_{10} pollutants [6], the aim of this study is to develop comprehensive methodology to model the emissions of two main types of construction equipment of loader and excavator. Data collection in this research is conducted in two steps of laboratory and field experiments. The laboratory experiments were conducted to verify the performance of instruments employed and synchronize the raw data. The data synchronization process shows that data measured by PEMS are around 8 seconds behind engine data retrieved from the engine data logger. This can be due to having 5 m long sampling tube and the time needed for gas analysis in PEMS. The data of the laboratory experiments can be used for developing the initial framework of emission model.

In the next step, field experiments were conducted to collect real-world data from in-use earthmoving equipment on construction and mining sites. Equipment with different brand, model year and size was experimented for representing the effect of engine technology, age and size on emissions. In this study, the field experimentation process was conducted on one loader and one excavator with approximately 3,000 data points collected from the PEMS and GPS-INS instruments. The data collected were then analyzed to model emissions of these two machineries at operation and equipment level.

4. Result Analysis

In this section, the method of data processing is developed for analyzing the emission data at operation and equipment levels. As discussed before, two main instruments of PEMS and GPS-INS are used to collect emission and operational data from earthmoving equipment. The data measured are transmitted and stored in the Tough Pad. The raw data were reviewed to identify any potential errors or problems occurred in the process of field experiments. Data filtering was also carried out to correct errors in certain points or remove invalid records [16]. In the next step, an exploratory analysis is conducted to model CO_2, CO, HC and NO_x emissions at operation level. Finally, the emissions of earthmoving equipment are estimated at equipment level by knowing cycle time and time ratio of operation modes. IBM SPSS Statistics V22 and Microsoft Excel software were used for data analysis.

4.1. Operation-level Emissions Modelling

The emissions analysis of two pieces of earthmoving equipment is presented in this section. The emission rates of CO_2, CO, HC and NO_x of the equipment are estimated in four operation modes: idling, loading, swing (moving), and dumping. It is anticipated that there is much variation in the amount of emissions in each operation mode due to many parameters such as operator skill, material type and engine conditions. By conducting statistical analysis on the raw data, it is shown the relationship between the value of emission rates in each operation mode and their corresponding occurrence frequency is similar to a Beta (β) distribution. Based on the variability relations developed, mean (M) and standard deviation (σ^2) for emission rates of pollutants in each operation mode is calculated by using Equations (1) and (2).

$$M_{ij} = (A_{ij} + 4B_{ij} + C_{ij})/6 \quad (1)$$
$$\sigma_{ij}^2 = ((C_{ij} - A_{ij})/6)^2 \quad (2)$$

Where:

M_{ij}: Mean of pollutant *i* emission rate in operation mode *j* (g/kWh)

σ_{ij}^2: Standard deviation of the value of pollutant *i* in operation mode *j*

A_{ij}: The minimum value of pollutant *i* in operation mode *j*

B_{ij}: The most likely value of pollutant *i* in operation mode *j*

C_{ij}: The maximum value of pollutant *i* in operation mode *j*.

4.2. Equipment-level Emissions Modelling

In this section, the emissions of earthmoving operations at equipment level are modelled. The cycle time of earthmoving equipment and time ratio of each operation mode were estimated first. GPS-INS instrument was attached to the stick of equipment and measured its three-dimensional position and movement second by second. By investigating the position and movement of stick, total cycle time and the time spent in each operation mode were estimated. Also, the cycle time of earthmoving equipment can be calculated through analyzing the films recorded from machinery operations on site. There are many parameters affecting the cycle time including bucket size, swing angle, operator skill and hauler position. Also, the main construction machinery manufacturers such as Caterpillar and Komatsu companies publish performance handbooks for presenting equipment specifications and estimating production rate and cycle times based on working conditions [15]. Tables 2 and 3 show cycle time of the loader and excavator used in the study based on manufacturers' performance handbooks. It was found the bucket size is the main parameter affecting the total cycle time and time ratio of operation modes for the earthmoving equipment. These two tables were prepared using specific swing angle and depth of cut, and minimum distance to hauler.

Operation efficiency of equipment (OEE) is another affecting parameter needs to be considered in emission modelling earthmoving machinery at equipment level. OEE is defined as the ratio of efficient operation time over total operation time of equipment. Actually, this parameter divides the efficient operating time from idling time of the equipment. In practice, this parameter varies from around 5% to 30% for earthmoving equipment involved in construction and mining sites. Equation (3) estimates emission rates of earthmoving equipment in efficient operation time by considering the time ratio and emission rates of different operation modes. Also, Equation (4) presents the equipment-level emission model based on OEE and P_{ni}.

$$P_{na} = P_{nl}*TR_l + P_{nsm}*TR_{sm} + P_{nd}*TR_d \quad (3)$$
$$P_n = PW*(OEE*P_{na} + (1\text{-}OEE)*P_{ni}) \quad (4)$$

Where:

P_n: Equipment-level emission rate of pollutant *n* (g/h)

P_{na}: Average emission rate of pollutant *n* in working time (g/kWh)

P_{nl}, P_{nsm}, P_{nd}, P_{ni}: Emission rate of pollutant *n* in loading, swing (moving), dumping and idling operation modes (g/kWh)

TR_l, TR_{sm}, TR_d: Time ratio of loading, swing (moving) and dumping operation modes in cycle time

PW: Power of equipment (kW).

Table 2. Average cycle time for loaders with different bucket size

Bucket Size (m^3)	Loading (sec)	Moving* (sec)	Dumping (sec)	Total Cycle (sec)
0.75-2.75	9	18	3	30
3-4	10	21	4	35

*: minimum distance between loader and hauler has been assumed.

Table 3. Average cycle time for excavators with different bucket size

Bucket Size (m^3)	Loading* (sec)	Swing** (sec)	Dumping (sec)	Total Cycle (sec)
<0.75	5	7	2	14
0.75-1	6	7	2	15
1.5-2	6	8	3	17
2.25	7	9	3	19
2.5	7	10	4	21
3	7	11	4	22
3.75	8	13	4	25

*: depth of cut is 50% of maximum cutting depth **: swing angle is 45°

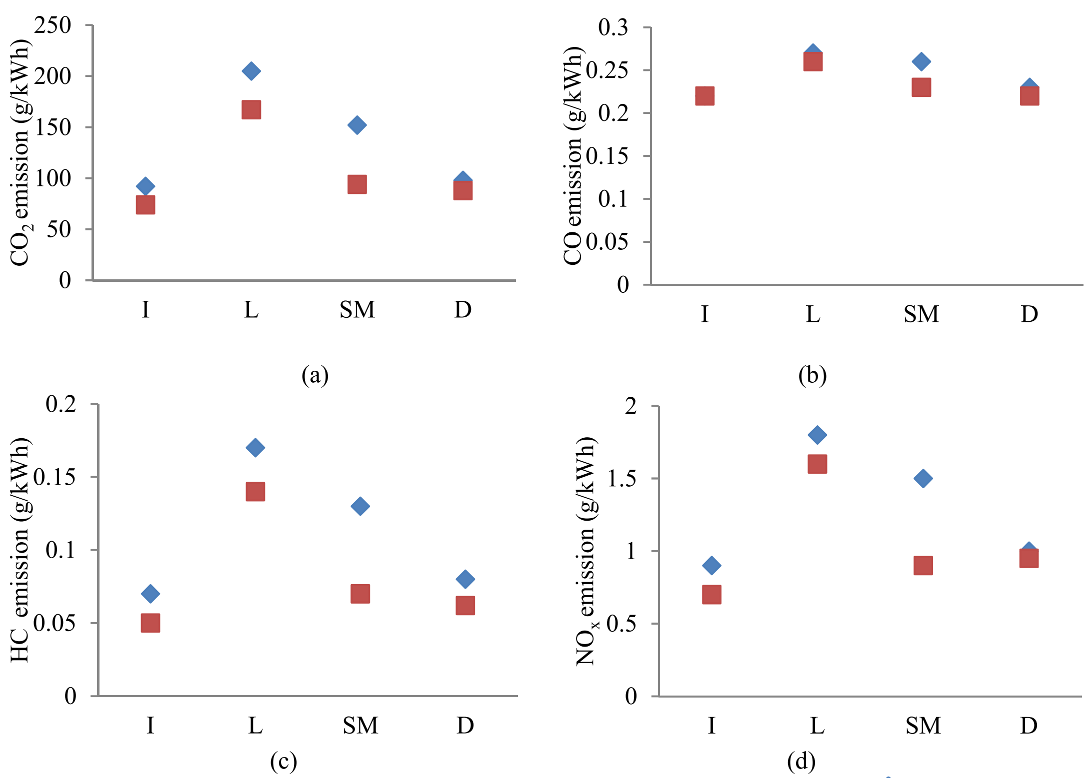
Based on Equations (3) and (4), the influence of many affecting parameters including time ratio of operation modes and OEE on emissions can be measured. Also, different ways are suggested to reduce emissions of earthmoving equipment by considering the production rate. OEE is the main parameter used for reducing total emissions. Based on Equation (4), as OEE increases, the non-efficient operation time of equipment decreases which causes the reduction of total emissions. Minimizing the distance from hauler or swing angle decreases swing (moving) time and consequently total cycle time which decreases total emissions as well. Bucket size is another parameter affecting total cycle time and emissions at equipment level. By considering Tables 2 and 3, it is recommended to use equipment with larger bucket size for reducing total emissions.

5. Case Study

In this section, the methodology developed is verified through experimentation and emission analysis of two in-use pieces of equipment of a loader and an excavator. The total experiment time lasted around one hour and, after data mining and filtering, approximately 3000 data points were collected. Table 4 presents the specifications and engine attributes of the equipment used as in the case study. By developing Beta statistical distribution and using equations (1) and (2), the emission rates were estimated for different operation modes. Figure 4 presents the mean emission rates of CO_2, CO, HC and NO_x for the excavator and the loader in idling, loading, swing (moving), and dumping modes. Figure 5 shows the photos of the equipment took during the experiment.

Table 4. Equipment's specifications used for experimentation

Vehicle	Engine Size (kW)	Model	Bucket Size (m^3)	Experiment Time (min)
LCM LG966 loader	193	2010	3.4	24
Poclain 115 excavator	115	1998	0.8	27



Note: I: Idling mode, L: Loading mode, SM: Swing/Moving mode, D: Dumping mode, ◆: Loader, ■: Excavator
Figure 4. Mean emission rates of two loader and excavator equipment types in different operation modes for (a) CO_2, (b) CO, (c) HC, and (d) NO_x pollutants

Table 5. Mean and standard deviation of emissions value in different operation modes

	Operation Modes							
	Idling		Loading		Swing/Moving		Dumping	
pollutions	LO	EX	LO	EX	LO	EX	LO	EX
CO_2	92,14	74,11	205,78	167,47	152.42	94,23	98,19	88,12
CO	0.23,2a	0.22,a	0.27,7a	0.26,5a	0.26,4a	0.23,2a	0.23,3a	0.22,a
HC	0.07,3a	0.05,2a	0.17,9a	0.14,6a	0.13,5a	0.07,3a	0.08,3a	0.06,2a
NO_x	0.9,b	0.7,b	1.8,7b	1.6,4b	1.5,4b	0.9,2b	0.9,2b	0.8,b

Note: LO= loader, EX= excavator, $a = 10^{-5}$, $b = 10^{-3}$

Table 6. Emission rates of experimented machineries at equipment level

Vehicle	CO_2 (g/h)	CO (g/h)	HC (g/h)	NO_x (g/h)
LCM LG966 loader	28,409	48.52	23.66	261.90
Poclain 115 excavator	12,972	27.14	10.10	125.28

(a)

(b)

Figure 5. Equipment utilized for case study: (a) LCM LG966 loader, (b) Poclain 115 excavator

As shown in Figure 4, there is much variation in emission rates of earthmoving equipment in different operation modes. For loader and excavator, emission rates in loading mode are much higher due to more power of engine consumed. In the operation-level emission model developed by Barati et al., it was verified that there is a highly correlated relationship between the amount of used power of engine and emission rates [14]. It is also noteworthy that the emission rates in idling and dumping operation modes are relatively the same and minimum for both pieces of equipment considered in the study. Generally, excavators produce less emission per engine size in comparison with loaders, especially in swing/moving mode. It shows that the engine power of excavators is not used as much as loaders in earthmoving operations. The standard deviation of emission rates in different operation modes were calculated and given in Table 5. It is found the maximum standard deviation of all emissions for both excavator and loader is in loading operation mode. There are other parameters that may cause some variations in the amount of emissions in this operation mode, e.g. operator skill and material type.

In the next step, the emission rates of the loader and excavator are estimated at equipment level. Tables 2, 3 and 4 are used for estimating the cycle time and time ratio of different operation modes. The total cycle time for loader with 3.4 m^3 bucket size is 35 seconds, and loading, moving and dumping time take 10, 21 and 4 seconds respectively. Also, total cycle time of the experiment is 15 seconds (bucket size = 0.8m^3), and loading, swing and dumping modes take around 6, 7 and 2 seconds respectively. Site observations also found the experimented pieces of equipment were in idling mode for around 12 minutes per hour which means the OEE is 20%. By using Equations (3) and (4), the emission rates of two machineries are estimated. Table 6 presents the calculated emission rates of four pollutants investigated.

6. Conclusions

Earthmoving operations are one of the main contributors to GHGs emissions. The current models used for estimating emissions of such operations roughly estimate the pollutant emission rates at state or project level. This paper aims to develop a comprehensive methodology for emission modelling of earthmoving equipment at operation and equipment level. This framework involves three main processes of instrumentation, data collection and data analysis. The developed methodology is generic and can be used for other applications such as machinery maintenance and fuel use estimation.

Field data are necessary for modelling emission rates of earthmoving equipment and investigating the parameters affecting emissions. Three main instruments, a PEMS, a GPS-INS and a Tough Pad tablet PC were used in this study for collecting operational and emission data of in-use earthmoving equipment. Site observations were conducted to record videos of equipment operation for estimating cycle time and ratio of time spent in each operation mode. The developed methodology was successfully applied on one loader and one excavator with around 3,000 data point collected for data filtering and processing. IBM SPSS Statistics V22 and Microsoft Excel software were used to analyze the data gathered from the site.

Future studies will investigate the effect of operator skill on emissions of earthmoving equipment. This would provide better understanding of the significance of operation skill and also help developing guidelines and handbooks on how to operate equipment more efficiently to reduce emissions. More field experiments will be carried out to study the effect of engine tier on emissions as well.

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