Modeling Emissions of Construction and Mining Equipment by Tracking Field Operations

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ABSTRACT

Construction and mining industries are using more than 20% of all non-road engines and listed as the third largest contributor to greenhouse gases (GHGs) emission globally. GHGs emitted from engines in construction and mining sites have not been fully investigated yet. Normally, government agencies and construction contractors estimate emitted pollution approximately based on consumed fuel for emission tax purpose. Despite the research conducted in this area in recent years, there is no accurate model to measure different GHGs emitted at operational level. This paper aims to develop an integrated framework to estimate emission rates of carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbon (HC) from machinery employed in construction and mining sites. Real-time engine and operational data collected by Data Logger and GPS/INS instruments are analysed to model the emissions. The results are further validated by comparing against the outputs from a portable emission measurement system (PEMS). Specific process was carried out to synchronize the raw data collected from three different channels. The emission measurement model also considers fuel-to-emission chemical relations, engine specifications and effective factors on different pollutants emission rate. The model developed in this research has been validated through comparing the estimation results with the data collected by PEMS in the laboratory experiments. As results show, the correlation coefficient (R^2) of ordinary least square (OLS) regression relations of emissions is higher than 0.9. Also, the results of the analysed data by SPSS Software show R^2 of engine load estimation model is 0.76.

Keywords –

Greenhouse gases; automated data collection; Portable emission measurement system; Pollutants emission rate; Construction and mining machinery; Emission regulation

1 Introduction

Construction and mining industries are two of the most significant sectors of heavy industry that include more than 20% of all non-road engines globally. The amount of emitted pollution from construction and mining operations is by far more than other industries. For example, the engine of a bulldozer with 130 kW power emits particulate matters (PM) nearly 500 times more than that of a private car [1]. Construction sector by itself accounts for 6% of emitted greenhouse gases (GHGs) of non-road engines and is ranked the third highest emitted pollution industry behind oil and gas sector and chemical manufacturing sector [2]. Also, construction and mining equipment emits 32% of nitrogen oxide (NO_x) and 37% of PM of all non-road engines [3].

In Australia, due to extensive mining operations and a large number of construction projects, the portion of these two sectors in pollution emissions is by far more than the average of the world. It is predicted that around 2020, the number of non-road engines in these two sectors will exceed 108,000 tones (accounting for 25% of non-road engines of this country) which will emit around 65% of all non-road engines pollution [4].

This research aims to develop a comprehensive model measuring different pollutants emission rate of construction and mining equipment at operational level. Several research efforts have been conducted in recent years to address affecting factors on non-road engines emission rate. The main challenge in this field is that researchers have mainly focused on one certain aspect of issue without considering the other areas. For example, some studies have only surveyed the effect of different parameters on emission, while others concentrated on different pollutants emission rate. On the other hand, in some studies, theoretical relations and issues have been considered for emission estimation, whereas some other researches are conducted completely based on the real-world monitored data. The lack of correlation and consistency amongst these researches is the main barrier for developing an integrated emission measurement model. Different parameters including engine specifications, environmental conditions and operational factors have to be considered and investigated in developing such an accurate emission model. Particularly, this research will:

- Review international regulations for on-road and non-road engines emission;
- Design and develop an integrated system for real-world data gathering based on the latest technologies readily available in the market;
- Identify and categorize different factors effecting on emission rate and pollutants;
- Develop a comprehensive model to estimate emission rate of various pollutants by considering affecting parameters;
- Validate the new model through comparing estimation results with real-world monitored data.

The methodology developed in this paper provides a working framework for accurate estimation of equipment's emissions. It has extensive applications in construction and mining projects. For instance, governmental agencies can apply the model for carbon tax calculation and air quality management in construction and mining industries. Machinery managers and operators can also adopt it as a guideline to minimize the amount of pollutants through optimal equipment operations and maintenance.

2 Literature Review

2.1 Previous Studies

Many efforts have been exerted to estimate the emitted pollution in construction and mining industries at several levels. EPA developed NONROAD model to predict different pollutants emission rate of machinery by considering activity hours, load and deterioration factor [5]. Then, by estimating the number of vehicles, EPA has ranked the contribution of construction machinery in emitting NO_x, CO, PM, as given in Table 1. URBEMIS model was proposed by Sacramento Metropolitan Air Quality Management District (SMAQMD) to estimate GHGs emission rate at project level for seven project phases [6]. This model, based on project size, employed equipment and emission factors, applies NONROAD and OFFROAD model to predict the total amount of emitted pollutions resulting from project execution. In a report prepared for AASHTO, Gallivan, after having extensive research on emission rates of different construction non-road engines, suggested using alternative technologies and fuels for mitigating GHGs emissions [7]. Lewis et al. defined engine mode factor for estimating fuel consumption of construction equipment. In this research, conversion factors were developed to estimate the amount of different pollutants emission rate based on consumed fuel [8]. Kim et al. developed a model to predict the amount of CO_2 emission at project level by using fuel consumption rate data published by Korean Institute of Construction Technology (KICT). The volume of work, operational efficiency and fuel to CO_2 emission coefficient were also estimated [9]. Then, this model was applied to compare the CO2 emission rate of 24 highway construction projects in Korea. Ahn and Lee modified the EPA NONROAD model through adding operating equipment efficiency (OEE) and idle to non-idle emission coefficient. They applied OEE to determine the optimum fleet size for having the least amount of emission [10].

The current approaches in emission modelling are classified to four main categories of aggregated, instantaneous parametrized, modal and simulation-based models [11]. In aggregated approaches like NONROAD and URBEMIS models, the overall

Table 1. EPA construction equipment ranking and contribution of NO_x, CO, PM

Equipment	NOx		CO		PM	
	Contribution	Ranking	Contribution	Ranking	Contribution	Ranking
Front-end loaders	14.5%	1	11.5%	3	11.2%	3
Bulldozers	12.5%	2	9.3%	4	9.1%	4
Excavators	11.4%	3	7.4%	5	8.6%	5
Off-highway trucks	11.0%	4	7.3%	6	6.6%	6
Backhoes	9.2%	5	16%	1	15.1%	1
Skid-steer loaders	6.2%	6	14.5%	2	13.6%	2
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

Table 2. Review of transportation and construction emission models

Transportation Models			Construction Models		
Model	Input	Application	Model	Input	Application
MODEM, DGV	Driving pattern	Urban traffic	NONROAD	Activity hours, engine size,	National level
PHEM	Driving pattern, gradient	LDV and HDV fleets	OFFROAD	Engine size, equipment type	State level
CMEM	Engine power	Vehicle level	URBEMIS	Project specifications	Project level
MOVES, ADVISOR	Speed, gradient, fuel kind	County level	Lewis	Power, mode and size of engine	Equipment level

emission rate is estimated roughly based on the distance and average travelling speed. Instantaneous parametrized models aim to provide more precise emission rate estimation by considering driving pattern in each second. MODEM and DGV models are the example of this approach applied for urban traffic emission estimation. In modal models such as CMEM, emission rate is estimated roughly in different operational modes. Simulation-based models map fuel consumption, exhaust emission and acceleration performance, e.g. ADVISOR and MOVES. Those models require equipment specifications and driving pattern as inputs for simulation models. Table 2 reviews the current emission models employed in transportation and construction fields for estimating emission rates of light-duty (LDV) and heavy-duty (HDV) vehicles [12].

There are a few studies conducted to gather and analyze real-world data from construction machinery. Clean Air Technologies International (CATI) measured emission rates of different Caterpillar equipment to evaluate the performance of diesel particulate filter technologies [1] [13]. Frey el al. conducted different field tests on numerous construction machinery to compare the effect of different fuels including B20 biodiesel, petroleum and diesel on emission [2] [13]. In this study, field data were used to develop emission coefficient for NOx, HC, CO, and PM for heavy duty trucks. EPA conducted Simple Portable On-Board Test (SPOT) to collect emission data of different non-road vehicles to develop motor vehicle emission simulator (MOVES) [3] [13]. Lewis applied Montana PEMS to measure the emission ratio of idle and non-idle engine modes [14].

2.2 Emission Regulations

Regulations and taxes are the main incentives for reducing pollution emissions. Each country has its own regulations based on development level and available engines. On the whole, emission regulations can be classified into two broad categories of emission and air quality standards. The aim of former is to restrict emissions from engines, while the latter restricts allowable level of pollutants in the atmosphere. Emission regulations consider the specifications and modifications of engines, fuel and the combustion process [8].

There are two main types of on-road and non-road standards. On-road regulations are applied for car and on-road trucks which is significantly more stringent than non-road standards. EU is the most well-known on-road regulation which was introduced in the early 1970 in European Union. Currently, most countries including Australia adopt and implement EU in their own regulations.

The first non-road emission regulation was introduced in 1994. The regulation was implemented in 1998 by EPA as Tier 1 to restrict the emission of main greenhouse gases for engines with power greater than 56 kW, as shown in Table 3. In Tier classification, the power and manufactured year of engine are considered. Then, in 2001 and 2006, EPA implemented two more stringent Tier 2 and 3 regulations on manufactured engines. Eventually, the most stringent regulation, Tier 4, was released from 2008 in two transitional and final phases. Except for European Union, most countries adopt this standard with the available engines and apply this standard as a reference to restrict emission. In Australia, more than 95% of all non-road engines and 100% of construction and mining engines comply with EPA regulation since the Australian government implements the regulation extensively after United States [4].

Table 3. EPA non-road emission standard

Engine Power	Tier	HC + NOx (g/kWh)	NOx (g/kWh)	CO (g/kWh)
56 ≤ kW < 75	1	-	-	-
	2	-	7.5	0.40
	3	-	4.7	0.40
	4	0.19	-	0.02
75 ≤ kW < 130	1	-	-	-
	2	-	6.6	0.30
	3	-	4.0	0.30
	4	0.19	-	0.02
130 ≤ kW < 225	1	1.3	-	0.54
	2	-	6.6	0.20
	3	-	4.0	0.20
	4	0.19	-	0.02
225 ≤ kW < 450	1	1.3	-	0.54
	2	-	6.4	0.20
	3	-	4.0	0.20
	4	0.19	-	0.02
450 ≤ kW < 560	1	1.3	-	0.54
	2	-	6.4	0.20
	3	-	4.0	0.20
	4	0.19	-	0.02
560 ≤ kW < 900	1	1.3	-	0.54
	2	-	6.4	0.20
	4	0.19	-	0.04
kW > 900	1	1.3	-	0.54
	2	-	6.4	0.20
	4	0.19	-	0.04

In regards to air quality standards, EPA established the first national ambient air quality standard (NAAQS) to control the concentration of dangerous pollutants and their effects on human health and environment. NAAQS is reviewed periodically and becomes more stringent over the time. On the whole, there are two primary and secondary types of air quality standards. Primary regulations which are more stringent mainly focus on the public health including people with respiratory problems. The aim of secondary standards is to implement limitation on pollutants concentration to protect public welfare like visibility reduction and damage prevention of environment. Currently, EPA imposes restriction on CO, lead, NO_x, PM, O_3 and SO_2 pollutants which are known as criteria pollutants. Engines are main contributors of CO, NO_x, PM pollutants which are considered in this research. Also, HC is considered in this study which is the main element of O_3 formation.

3 Methodology

This section describes the process of data measurement and analysis for developing an integrated emission estimation model. Firstly, different parameters affecting emissions are identified. Then, by considering required data and latest off-the-shelf technologies, a comprehensive instrumentation system is implemented for field data collection. In the next step, the real-world gathered data are analyzed and their effect on emission is determined to be considered in emission modeling.

3.1 Parameters Affecting Emission

Figure 1 summarizes different parameters affecting construction and mining equipment emission rate. Lewis introduced equipment attributes in [10], including equipment type, engine size and engine load as main affecting factors on emission EPA considered the effect of three main factors in developing the NONROAD emission estimation model, namely engine deterioration, fuel-to-emission ratio and engine load [5]. On the whole, affecting factors on emission can be classified into four categories of engine attributes, operational parameters, environmental factors and fuel type. Normally, construction and mining machinery consumes one certain type of fuel in their life time, or their fuels have negligible changes in ingredients. So, fuel type can be ignored as affecting factor on emission for a certain piece of equipment.

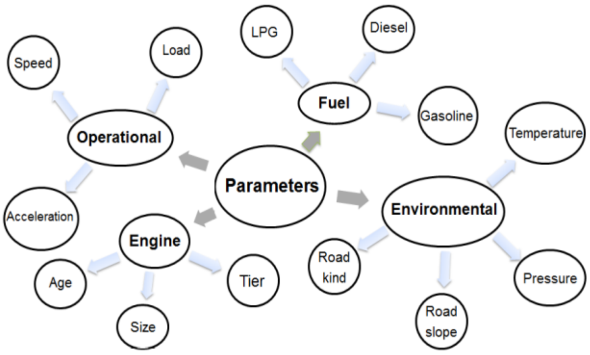


Figure 1. Different affecting parameters on emission

Three engine attributes affect emission rate, including engine size, engine age and engine tier. The engine size is one of the main affecting factors on fuel consumption and emission rate. Normally, the larger the engine is the more emission produced. Engine age and deterioration have direct effect on emission rate. As engines are used over time, they become weaker and

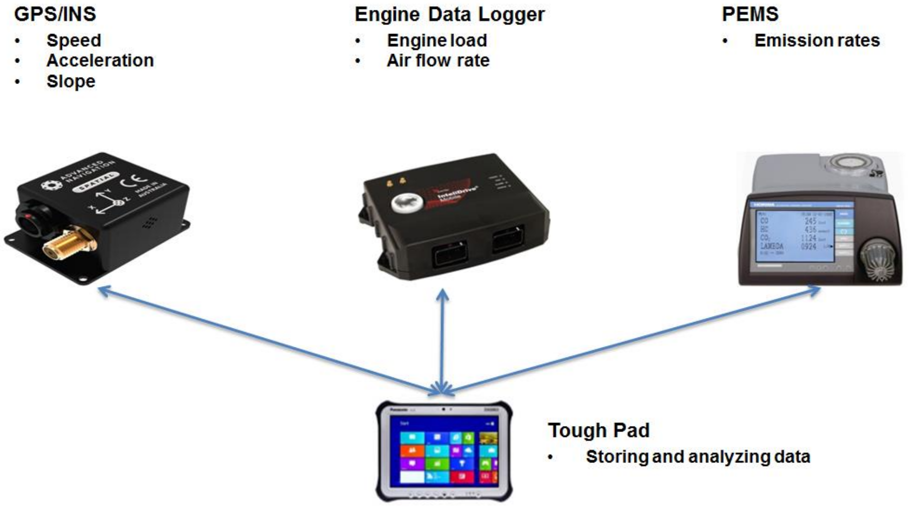


Figure 2. Instrumentation for field data collection

consume more fuel for the same load. Engine tiers refer to the compliance of engine with emission standards developed by EPA. Engines manufactured after specific date should meet the special emission level requirements. Engine tier is classified based on the engine size and the engine manufactured year. The higher tier engines are restricted to emit less emission.

Acceleration, speed and load of machinery are considered as operational parameters affecting different pollutants emission rate. In levelled travel route, it is obvious that the pollutants emission rate has relation with the speed, acceleration and load. In addition, the condition and slope of the road, weather temperature and ambient pressure are environmental parameters that can have significant effect on emission rate. The effect of slope can be translated to a force helping or prohibiting the movement of equipment. Also, when the ambient pressure decreases, it is predicted that air to fuel ratio (AFR) decreases and consequently, pollutants emission rate will increase.

3.2 Instrumentation

As shown in Figure 2, several instruments have been employed for measuring different parameter discussed in the previous section. The main instrument is a portable emission measurement system (PEMS) which measures emissions. PEMS measures and stores air to fuel ratio and different pollutants emission rates second by second using a sampling probe inserted in the tailpipe of construction equipment. The PEMS utilized in this research is MEXA-584L automotive emission analyzer manufactured by HORIBA Ltd. GPS aided Inertial Navigation System (GPS-INS) is the other multipurpose instrument used in this research. GPS-INS system combines calibrated accelerometers, gyroscopes, magnetometers and a pressure sensor with a commercial GPS receiver. After mounted and calibrated in the construction equipment, GPS-INS unit measures operational and environmental parameters on emission.

It provides three-dimensional position, speed and acceleration of equipment, as well as the slope of road and ambient pressure once per second. The measured data are transmitted through RS-232 serial data communication port to an industrial laptop. The GPS-INS system used in this study is SPATIAL-EK manufactured by Advanced Navigation Pty Ltd. Also, Data Logger is implemented to collect real-time engine data. This instrument is plugged into the OBD-II port and measures 23 parameters of operating engine. Engine speed, engine load, air flow rate and air intake temperature are four affecting parameters on emission measured by Data Logger in this research. Also, an industrial tough pad laptop is utilized to record, synchronize and analyze real-time gathered data.

3.3 Field Data Collection

In this research, construction and mining equipment are prioritized for conducting field test based on EPA ranking report [1]. Non-road model has been applied to estimate the contribution of equipment in emitting NO_x, CO and PM_{10} pollutants. Before starting extensive tests in construction and mining sites, some lab trials have been conducted to test the instruments and validate the research methodology. In this process, time delays among different instruments have to be considered and calibrated. Data synchronization process indicates that PEMS measures data around 8 seconds behind Data Logger instrument due to having 5 m long sampling tube.

Table 4. Samples of raw data collected by PEMS and Data Logger Instruments

Date (DD/MM/YY)	Time (H:M:S)	PEMS				Data Logger		
		CO (%)	HC (ppm)	CO_2 (%)	AFR	Engine Speed (RPM)	Engine Load (%)	AFR (kg/s)
2/10/2014	9:1:17	0.02	0	14.62	15.2	744	25.49	0.010
2/10/2014	9:1:18	0.01	1	13.96	15.9	743	25.49	0.010
2/10/2014	9:1:19	0.01	2	13.6	16.2	742	25.49	0.020
2/10/2014	9:1:20	0.01	3	13.72	16.1	740	28.71	0.020
2/10/2014	9:1:21	0.01	4	13.92	15.9	741	28.71	0.010
2/10/2014	9:1:22	0.01	6	14.2	15.6	742	28.71	0.020

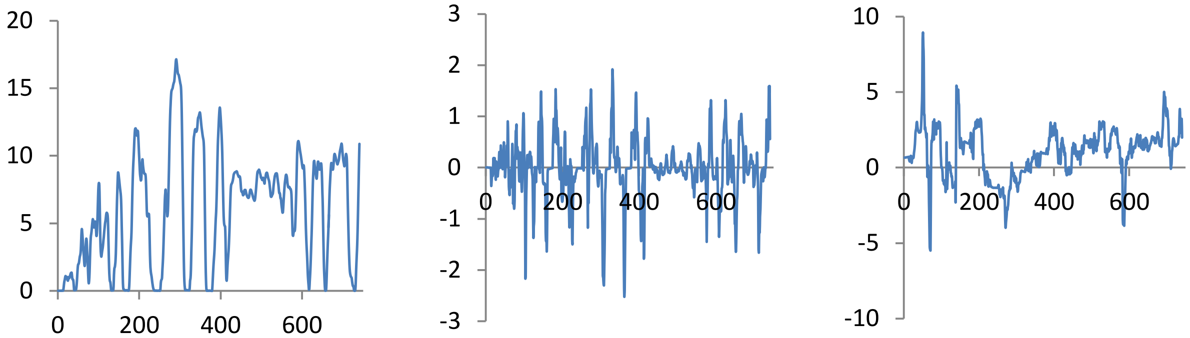


Figure 3. Samples of raw data collected by GPS-INS Instrument

4 Results Analysis

In this section, the results from laboratory tests are first presented. A comprehensive operational level emission model is then developed to estimate pollutants emission rate by considering main affecting parameters. As was discussed in the previous section, different instruments are implemented for data collection. In particular, PEMS measures real-time emission rate of CO, CO_2 and HC, as well as air to fuel rate. The data measured by PEMS are acquired by the Tough Pad and stored in the Excel database. Meanwhile, Data Logger measures four essential parameters of engine load, engine speed, vehicle speed and air flow rate second by second. These data are stored in the Data Logger memory during the tests and downloaded to Tough Pad afterward. Operational and environmental parameters such as speed, acceleration, slope of road and pressure are measured in each second by GPS/INS. The samples of data collected by different instruments are presented in Table 4 and Figure 3, respectively. The IBM SPSS Statistics V22 Software was used for data analysis.

Five laboratory tests were conducted on four utility and passenger cars for field data collecting. The model of cars varies from 2001 to 2013 with their engine powers ranging between 85 kW and 150 kW. One initial test was done for evaluation of the instrument performance. The data collected from the last test were used for validating the model developed in the research. The tests lasted around five hours with approximately 18,000 data points collected. For getting reliable field data, cars were drove at different speed, acceleration and slope during the tests.

4.1 Emissions Models with Engine Load

By analyzing the lab test data, engine load was determined as a critical parameter that links pollutants emission rate collected by PEMS with affecting parameters on emission measured by GPS-INS and Data Logger. The relationship between the engine load and exhaust air flow rate (AFR) is first investigated. Depending on the status of engine when running, engine load value ranges from 20% for idle mode to around 85% for full load mode. At the same time, AFR is around 100 g/kWh in idle mode. It reaches about 1,500 g/kWh when engine is running in full capacity. Emission rates for CO, CO_2 and HC are also found to be directed related to the changes of engine load. For example, relative volume of CO_2 is around 6% at 20% engine load, which increases to 17% almost linearly at the engine load of 85%. This trend is reversed for CO and HC pollutants. In idle mode, relative volumes of exhaust flow for CO and HC are maximum around 30 and 27 ppm, respectively. By increasing engine load to

85%, these rates decrease nonlinearly to 4 and 2.5 ppm for CO and HC.

Equation (1) is devised to determine the total emission rate of pollutants based on engine load, AFR and pollutants relative volume.

$$P_{ij}= AFR_j * (1/D_a) * V_{ij} * D_i \qquad (1)$$

Where:

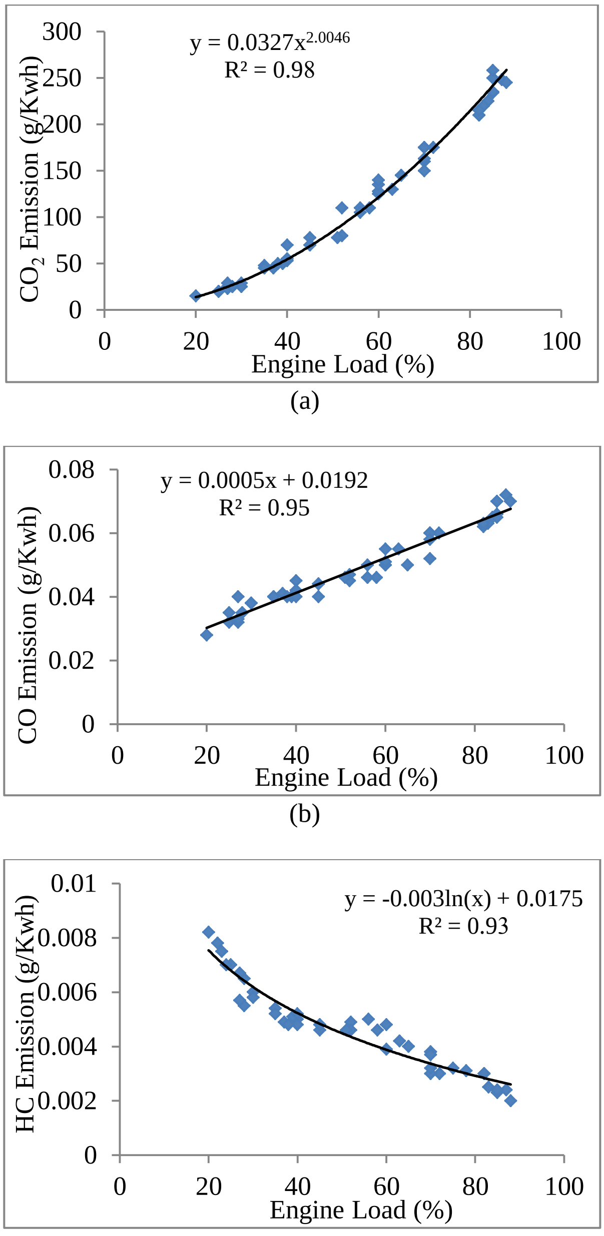
Pij: Amount of pollutant i in engine load j (g/Kwh)

AFRj: Air flow rate in engine load j (g/kWh)

Vij: Volumetric percentage of pollutant i in engine load j

Da, Di: density of air and density of pollutant i in normal temperature and pressure (NTP) condition

Figure 4 shows the total CO_2, CO and HC emission rates from the exhaust based on the engine load. For analyzing the statistical data calculated by the aforementioned equation, OLS regression method was used to find the best function for maximizing the correlation coefficient (R^2). As shown in Figure 4a, CO2 emission varies between 10 g/Kwh in idle mode to around 270 g/Kwh in full engine load of 85%. The test results show that the correlation of collected data is very high and R^2 value is around 0.98 for power function. Meanwhile, CO emission is minimum around 0.025 g/Kwh in idle mode. It increases to 0.07 g/Kwh in full load mode (see Figure 4b). A linear relationship between CO emission and engine load is defined with the highest correlation coefficient (R^2 = 0.95). Unlike CO and CO_2, HC emission decreased from 0.008 g/Kwh to 0.002 g/Kwh when engine load increased from 20% to 85%. As given in Figure 4c, logarithmic relation of HC emission and engine load is found and R^2 value is 0.928.



(a)

(b)

(c)

Figure 4. The OLS regression relation of (a) CO_2 emission and engine load, (b) CO emission and engine load and (c) HC emission and engine load

Table 5. Variables coefficient

Model	Coefficients	Std. Error	Beta	t
Constant (%)	18	2.348	0	7.502
Speed (m/s)	1.25	0.179	0.496	7.036
Acceleration (m/s^2)	14.6	1.346	0.756	10.849
Slope (degree)	2.1	0.576	0.260	3.699

Table 6. Correlation coefficient of linear engine load estimation model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.872	.760	.746	7.182

4.2 Engine Load Estimation

This section investigates how the site operations will affect the engine loads of construction and mining equipment. The operational parameters studied in this research include traveling speed, acceleration and payload of equipment. The environmental factor of the slope of road is considered as well. Since engine age and engine tier are fixed parameters for a specific piece of equipment, they are ignored in the modeling of engine load.

In order to develop the engine load estimation model, data from Data Logger and GPS-INS instruments were synchronized and processed using SPSS V22 software. During the testing, the recorded highest traveling speed was 25 m/s or 90 km/h. Acceleration varied from -2 to +3 m/s^2. The range of slope of road measured in the test was from -7 to +10 degree. By conducting linear and nonlinear regression and fitting curve, a linear estimation model was adopted considering the highest correlation (R^2=0.76), as given in Equation (2). The variables and correlation coefficients of the developed model by SPSS are given in Tables 5 and 6, respectively.

$$\text{Engine load (\%)} = 1.25\times\text{Speed} + 14.6\times\text{Acceleration} + 2.1\times\text{Slope} + 18 \qquad (2)$$

In the estimation model of engine load, acceleration has the highest coefficient around 14.6. It means that accelerating equipment for 1m/s^2 increases engine load about 14.6%. Also, every one degree uphill will increase the engine load for 2.1%. Speed seems to have lowest effect on engine load among the considered parameters with the coefficient being 1.25. The constant value can be explained as the equipment's engine load in idle mode. The engine factor used in this model is 0.2, which is defined as the ratio of the current payload to the maximum allowable payload of the equipment.

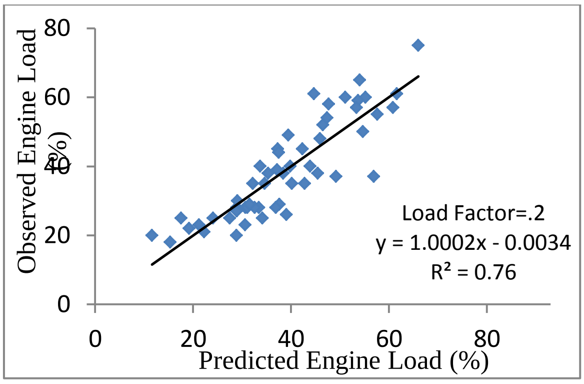


Figure 5. The OLS regression model of optimized engine load

To verify the estimation model, the predicted engine load (PEL) calculated by Equation (2) is compared with the real engine load value acquired by Data Logger instrument. As shown in Figure 5, by doing OLS linear regression analysis, Equation (3) is derived for estimating the optimized engine load (OEL) based on the engine load predicted by SPSS software (Equation 2).

$$\text{OEL} = 1.0002\ \text{PEL} - .0034 \qquad (3)$$

5 Conclusions and Future Work

This research has developed an operational level emission estimation model of construction and mining equipment. Various field data are required to effectively understand the effect of different parameters on pollutants emission rate. Three types of instrument of PEMS, Data Logger and GPS-INS were used to collect required emission, engine and operational data of equipment during operation. The emission models were developed in two steps. The effect of engine load on CO_2, CO and HC emissions was first investigated. Then, the effect of different parameters on engine load was determined, including operational parameters of traveling speed and acceleration, as well as environmental parameter of the slope of road.

Based on the models developed in this paper, total pollutants emission rate can be estimated for a specific piece of equipment or for the whole construction project. More field tests will be carried out in the near future. Also, the effect of engine age and tier will be determined on engine load and emission, respectively. The next step of this research will further investigate the effect of human behaviour on the total emission rate of construction and mining equipment.

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