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A Critical Review and Analysis of Construction equipment emission factors

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Abstract

Diesel-powered construction equipment is the primary source of Green House Gas (GHG) and exhaust emissions during the construction stage of a large infrastructure project. The equipment pollutants such as nitrogen oxides, carbon monoxide, and particulate matter (PM 2.5 and PM 10) endanger people's health and surrounding environment. A critical review and analysis of factors affecting the amounts of construction emissions is conducted through literature review and a case study, four categories of factors including equipment and conditions, equipment maintenance, operating conditions, and equipment operations are reviewed. A case study is made on 14 wheel loaders with different makes and capacities with accumulated weekly data with the aim of determining the impact of emission factors on the weekly equipment emissions. It is found that equipment engine power, equipment conditions, and equipment operator skills are significant factors on average fuel consumption and emissions in the case study. Based on the findings from current research literature and the case study, some recommendations are made on how to reduce fuel consumptions as well as pollutant emissions for contractors and other equipment owning organizations.

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Keywords: Constrution equipment emissions; emission factor analysis;emission reduction

1. Introduction

Construction equipment contributes a significant portion of Greenhouse gas and air pollutions in urban areas during construction works such as site preparation, foundation works, road construction and maintenance. Carbon and pollutant emissions from diesel-burned construction equipment are also of increasing concern for the government and general public. Many countries have made it a legal requirement for construction equipment to be in compliance with a stipulated set of emission criteria. In some countries and metropolitan areas, contractors have to submit annual carbon emission reports, and the developers have to submit environmental impact assessment and mitigation strategies in for large infrastructure projects. Among all the emission reduction strategies, improving equipment maintenance and operations can be feasible, attractive, and cost effective approaches for implementation in emissions reduction.

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In Hong Kong, deteriorating air quality and slow progress in meeting greenhouse gas emission reduction targets are a major environmental issue. As one of the significant pollution and emission sources, heavy construction equipment, powered by diesel engines, emit toxic pollutants including CO, NOx, HC, particulate matter, as well as CO2. Recent regulations on emission compliance for non-road mobile machinery are mainly targeted at equipment newly imported to Hong Kong. Complete replacement of the current stock of 11,300 units working on construction sites will take many years due to their long service lives, if no environment regulations are imposed.

According to a government report, there are about 13,500 units of Non-road Mobile Machinery (NRMMs) operating in Hong Kong, among which 11,300 units, or 80%, are operating on construction sites [1]. Since most of the NRMMs are powered by diesel engines and emit the toxic pollutants carbon monoxide (CO), nitrogen oxides (NOx), particulate matter, and non-methane hydrocarbons (NMHC), in addition to the greenhouse gas, carbon dioxide (CO2). The NRMMs on construction sites, the airport and container terminals contribute about 7% (6,800 tonnes) of the local emissions of nitrogen oxides (NOx) and 11% (600 tonnes) of respirable suspended particulates (RSP) respectively. Since infrastructure projects are usually located within environmentally sensitive areas, operations of heavy construction equipment pose health hazards to construction workers and people nearby.

To reduce air pollutants from non-road diesel equipment and help to meet the government target in carbon reduction, the new Air Pollution Control (Non-road Mobile Machinery) (Emission) Regulation was approved by Hong Kong Legislative Council and took effect on 1 June 2015 after public consultation. Under this regulation, all newly imported NRMMS with rated engine power outputs between 19 KW and 560 KW have to meet the EU Stage IIIA, US Tier 3 or Japan MoE emission standards [1]. Existing NRMMs in use before 1 December 2015, however, are exempted due to strong resistance from the stakeholders of NRMMS. The estimated average age and average service life of the in-use NRMMs in Hong Kong are about 8 years and 14 years respectively. Although both the stakeholders of the construction equipment and the government have reached a consensus on emission controls of heavy construction equipment, the exempted equipment will operate on construction projects for many years until they are replaced by new low-emission units, if no immediate regulations are implemented and incentive measures taken.

It is a difficult task to estimate the accurate amount of emissions due to lack of measurement and monitoring information. Currently the emissions can only be measured based on specified emission rates, modified by load factors, operating time, equipment deterioration, etc. However, the emission rates themselves depend on equipment year of manufacture, engine power, engine conditions, etc. another approach is fuel-based estimation, i.e. the emissions are estimated based on the amount of fuel burned by the equipment in a particular period of time.

The aim of this paper is to discuss the factors affecting construction equipment emissions and propose to apply analytical approach to quantify the degree of impact from these emission factors, so that actions can be taken based on their priority in emission reductions and cost effectiveness.

2. Quantification of construction equipment emissions

The NONROAD2008a emission model published by the Environmental Protection Agency of USA [2] is the most comprehensive model for estimating emissions from non-road construction equipment. The emission factor is defined as the quantity of pollutants emitted by that particular type of equipment during a unit of service. The emission factor, after adjustments to account for transient operation and deterioration can be estimated as below:

For HC, CO, NOx, the exhaust emission factor for a given diesel equipment type in a given model year/age is calculated using eq. 1.

$$EF_{adj(HC,CO,NO_x)} = EF_{ss} \times TAF \times DF \quad (1)$$

EF_{adj} – Final emission factor for HC, CO, NOx after adjustment (g/hp-hr) [‘hp’ is horsepower]

EF_{ss} – Zero-state, steady-state emission factor (g/hp-hr), related to model year and horsepower category (technology type)

TAF – Transient adjustment factors (unitless), varying on equipment types, accounting for the difference between the steady-state and the transient state of the engine.

DF – Deterioration factor (unitless), related to technology type and age of engine

The particulate matter (PM) particles emitted from diesel engines are assumed to be smaller than 10 microns (PM10), among which 97% are smaller than 2.5 microns (PM2.5). PM emissions can be estimated by using eq. 2:

$$EF_{adj(PM)} = EF_{ss} \times TAF \times DF \times S_{PMadj} \quad (2)$$

EF_{adj} – Final emission factor of HC, CO, NOx after adjustment (g/hp-hr)

S_{PMad}j – adjustment to PM emission factor to account for variations in fuel sulphur content (g/hp-hr)

Emission factors for CO_2, SO_2, and HC are directly related to the brake-specific fuel consumption (BSFC), which is available from the EPA publication “Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling” [2].

Since EPA data sources are obtained from steady-state modal engine dynamometer tests, many researchers have measured the real world emissions data. Relevant research data and findings can be found from many publications such as Lewis et al. [3]; Abolhasani and Frey [4]; Lewis et al. [5]; Barati and Shen [6], etc.

The NONROAD2008a model is an emission model published by the US Environmental Protection Agency (2010), a compressive method for the estimation of construction equipment emissions, including Nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2), and Particulate matter (PM). California Air Resources Board (CARB) proposed the OFFROAD2007 model for off-road emission inventory estimation for various types of off-road equipment [7]. The California South Coast Air Quality Management District (AQMD) developed the California Emissions Estimator Model® (CalEEMod) to quantify criteria for pollutant and greenhouse gas (GHG) emissions associated with both construction and a variety of land use project operations [8].

Many researchers used portable systems (such as Portable Emission Measurement System) to measure real world emissions of construction equipment. For examples, Lewis and Rasdorf [5] studied the weighted average fuel use and emission rates according to engine types and tiers based on emissions data collected from in-use equipment. Abolhasani and Frey [4] presented emissions measurements for nine selected non-road construction vehicles, analyzed the variability in emissions with respect to engine operations and ambient conditions. Lewis et al. [3] discussed the quantification of emissions data for construction equipment and compared the EPA NONROAD model with emissions data collected in the field. It is concluded there are large discrepancies between measured emissions data and theoretical emission models such as NONROAD2008a. Estimation of fuel-based emissions gives much lower values than the results from emission models at the national level in USA [9].

3. Factors affecting the construction equipment emissions

There are a large number of factors affecting the exhaust emissions of construction equipment, many are difficult to measure and quantify their degree of impact on the rate of emissions. Overall the factors can be categorized into four groups as shown in Fig. 1.

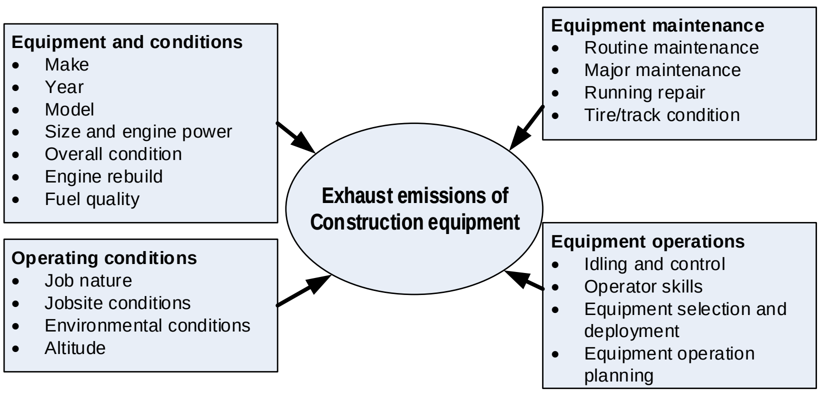

Fig. 1. Factors of impact on construction equipment exhaust emissions

3.1 Equipment and conditions

The rates of exhaust emissions from construction equipment are mainly determined by engine year of manufacture, engine model, engine size and horsepower. Different equipment manufacturers or makes can also contribute to variations in equipment emission due to their difference in engine design, automatic control system, and configurations. Engines of newer generations (for example, Tier 4 engines) can have significant reductions in emission rates and fuel consumption. However, the equipment replacement to newer generations is slow due to large initial investment and affordability for small to medium size contractors.

Equipment deteriorates when the equipment ages with more units of service accumulated, both equipment age and accumulated units of services (distance travelled or hours worked) are good indicators of equipment conditions. The equipment condition is also dependent on maintenance quality, daily care, and operation history. Equipment of good conditions is more fuel efficient with lower emissions in operations.

Use of low Sulphur or bio diesel can reduce emissions effectively. Use of low emission diesel has been compulsory with government incentives in some counties. Use of high quality diesel can help to extend equipment life and reduce emissions.

3.2 Equipment maintenance

Construction equipment maintenance should follow the manufacturer’s instruction manuals. Good maintenance strategy of the equipment keeps the equipment in good working conditions with efficient use of fuel in delivering output power. Both routine maintenance (changing of oil, grease, filters, clean-up etc.) and major matenance works such as engine overhall should be properly scheduled and implemented. There is already a concensus that delayed maintenance or run-to-failure maintenance is a poor maintenance stragety which can lead to higher equipment repair costs, resulting in higher rate of fuel consumption as well as high emissions due to clogged air flow and insufficient burning of engine fuel.

Any defaults in the engine, if not diagnosed and repaired immediately, can cause underperformance of equipment and increase the amount of exhaustive emissions.

Timely replacement of worn ground-engagements such as tires/tracks is important to reduce emissions from unproductive job activities.

3.4. Operating conditions

Off-road construction equipment is deployed for construction activities such as digging, loading, hauling, backfilling, compaction, lifting etc. Different job activities have different work conditions and requirements, which influence the time percentage of equipment working in different load conditions and engine status.

The fuel consumption and emissions of equipment inevitably increase in tough working conditions involving hills and slopes on jobsites, or medium to hard underground or ground soil conditions. The amounts of fuel consumptions or emissions can increase up to 2-4 times for heavy duty works, as compared with light duty applications for the same equipment, according to Caterpillar Performance Handbook.

Equipment operating in high altitude site also consumes more fuel and produces more emissions due to underperformance of engine. Also equipment operating in severe weather such as cold winter consumes more fuel with more emissions due to engine performance issues and longer time in engine startup and warmup to reach efficient working conditons.

3.5. Equipment operations

Equipment should be properly selected for a specific job. The equipment also works in fleet of proper configuration for productive use. If the equipment overmatches the site conditions and tasks or overloads, more fuel is burned with more emissions, in addition to higher equipment cost.

Idling time and operational skills are critical for equipment emissions. Reducing idling time and improving operator skills are favored by small to medium size contractors thanks to added benefits of fuel savings and lower costs. However, there is a lack of quantitative measurement on the effectiveness of improving operator skills to achieve emission reductions; some literatures give descriptive benefits or a range of cost savings or emission reductions.

The impact of equipment idling time has been studied much in related research, with a focus on minimizing equipment idling time by reasonably allocating equipment resources to reduce waiting and queuing time. In order to further save fuel and reduce emission, engines can also be shut down after a few minutes waiting time (either manually or automatically) with electronic control devices. On the other hand there is a misperception that skilled operators are expensive to hire and less skilled operators can achieve similar results and that preventive maintenance can be delayed or skipped without significant effects on equipment performance. This is especially true for small contractors who always try to achieve savings through any means.

Skilled and experienced operators can reasonably minimize idling time by reducing such interruptions as miscommunications, poor understanding of work tasks, and poor coordination with others. Skilled equipment operators consume less fuel compared with less experienced and average operators per operating hour as skilled operators take good care of equipment, identify equipment problems in a timely manner, reduce idle time, follow correct working procedures, and operate equipment in the smartest and most cost-efficiency way. Some factors affecting the operator skill level include:

- Years of education: the number of years the operator received formal education;
- Years of experience: the number of years the operator has operated the equipment with a license;
- Salary pay scale: different pay scales of the operator in the organization,
- Accumulated hours of training after being licensed: the hours the operator received continuous training in equipment operations.

4. Case study

Although construction equipment emissions vary with different engine operation modes and level of load, the amount of equipment emissions is highly correlated with the fuel consumption of the diesel-powered equipment on average. The daily fuel records of 14 pieces of wheel loaders with gross horsepower from 50 to 300 are retrieved from an equipment database along with the information on equipment information and operators. The daily diesel fuel records are accumulated to weekly basis to reduce the discrepancy between fuel records and fuel consumption. The aim of the case study is to explore the strength of the relationship between weekly equipment emissions and a set of explanatory variables including equipment age, engine horsepower, makes and operator skills through multiple linear regression (MRL) analysis.

Target variable: equipment rate of emissions. The amount of different types of equipment emissions is estimated based on the amount of fuel consumption, according to Table 1 extracted from [10]. The weekly fuel consumption is converted to weekly amount of emissions per engine horsepower output. The emission amount of Oxides of nitrogen (NOx) is chosen as a target variable for study, which is measured in Kgs of NOx per week per horsepower. Since the wheel loaders are used for similar purposes in highway construction in the case study, we assume the load factors and working efficiency keep consistent over the observation period with no significant variations.

Table 1: Emission factors (kg/kWh) for diesel industrial vehicle (wheeled tractor) exhaust emissions

Substance	Emission factor (Kg/Kwh)	Emission factor (Kg/litre)
Carbon monoxide	9.84×10^{-3}	3.25×10^{-2}
Oxides of nitrogen	1.60×10^{-2}	5.28×10^{-2}
Particulate matter 2.5 μm^2	1.56×10^{-3}	5.15×10^{-3}
Particulate matter 10 μm^2	1.70×10^{-3}	5.61×10^{-3}
Sulfur dioxide	7.26×10^{-6}	2.40×10^{-5}
Total volatile organic compounds	2.36×10^{-3}	7.79×10^{-3}

Source: Emission estimation technique manual for Combustion engines, version 3.0, Australian Government Department of Environment, Water, Heritage and the Arts

Explanatory variables:

- Equipment age: the years of equipment operations since its date of purchase. The equipment age is a factor reflecting the dominant engine conditions under normal operating conditions and routine maintenance.
- Equipment makes: the manufacturer of the equipment. The makes are from five major equipment manufacturers, i.e. Caterpillar, Case, Komatsu, John Deere, and Volvo. The variable is recoded into 4 binary variables to indicate manufacturers of the equipment.
- Equipment engine horsepower: Gross horsepower of equipment engine is used to measure the rated power output in operations by the engine, the gross horsepower is commonly used to estimate the engine fuel consumption, and emission rates. Since the load factor is not measured and recorded on the job site, we assume the average load factor is consistent over the weeks for similar job conditions.
- Equipment operator skills: equipment operator skills are classified into "low", "average", and "high", coded into "1", "2", and "3" by the equipment manager based on the operator's working experience, education and training, work attitude, personality, etc, to measure the efficiency of operations and skillset processed by the operator. The classification is based on the equipment manager's personal judgment based on the operator's background information.

Least square method is used to derive the multiple linear models with NOx emissions as the target variable and equipment make, gross horsepower of engine, equipment age, and operator skills, as explanatory variables. The following model is derived using SPSS statistical tool:

Table 2. Model summary

R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
				R Square Change	F Change	df1	df2	Sig. F Change
.524[a]	.275	.268	.146	.275	41.423	7	765	.000

Since F-test result F (7, 765) = 41.423, with probability of 0.000, the null hypothesis of the no linear relationship between predictor variables and target variable is rejected, and the model is valid.
The R-square of the model is 0.275, and adjusted R-square is 0.268 with consideration to the number of variables and cases, indicating that 26.8% variations are explained by the model. The adjusted R-square is not high as there are still many other explanatory variables not included in the model, however, the three included variables already explained nearly 1/3 of the variations in exhaust emissions.

Unstandardized coefficients:

Emission rate of NOx (Kg/wk*hp) = -0.107+0.002*[Gross Horsepower]+0.001*[Equipment age]
-0.030*[Operator skill]
+0.053*[Caterpillar]+0.220*[Case]-0.035*[Komatsu]+0.227*[John Deere] (3)

Standardized coefficients are obtained by centering the value of each variable by subtracting the mean and then divided by the standard deviation of the variable:

Emission rate of NOx = 0.647*[Gross Horsepower]+0.189*[Equipment age]-0.285*[Operator skill]
+0.156*[Caterpillar]+0.393*[Case]-0.085*[Komatsu]+0.386*[John Deere] (4)

The standardized coefficients reflect the influence of change in predictor variable variation on the variation of target variable, and therefore can be interpreted as the importance in causing fluctuations of equipment emissions. Among Standardized coefficients, it can be observed that the importance of predictor variables: gross horsepower, equipment operator skills, equipment age. The explanatory variable "Equipment make" cannot be interpreted, but on average, it is comparable to operator skills.

Considering the fact that the relationship between the predictor variable and the set of explanatory variables might not be linear, neural network model is built and tested in SPSS, and model can achieve an accuracy of 55% if 70% selected randomly as training data and remaining 30% as test data. Nevertheless, the multiple linear regression model is preferred to fit the data as the data set is relatively small which makes it difficult to fit a nonlinear model. On the contrary, linear model can describe the general trend of the hidden relationship with less error in interpolation and extrapolation.

The following comments and observations are made based on the MLR model:

- The NOx emissions measured in kg/hp-wk accumulated to weekly total with no consideration to specific working efficiency and load factor assuming they are consistent over the operation period.
- There are many factors which are difficult to measure or no data are available and therefore they are not included in the model
- The equipment make, horsepower, age, and operator skills can be compared in terms of their contributions to the variations in weekly NOx emissions per hp power output.
- The equipment weekly fuel consumption and emissions will increase with the increase in engine gross horsepower. This finding is different from the characteristics of the break specific Fuel Consumption (BSFC) which actually decrease in large engines. Such difference is likely caused by different load factors, different working efficiency, different job natures, or difference in operation difficulty.
- Better equipment operator skills help to reduce the engine emissions.
- Equipment aging causes increase in engine emission, which is in line with the deterioration factor (DF) recommend in EPA 2008a model.
- Effects from equipment makes cannot be ignored; some manufacturers committed more to research and design to manufacture equipment that is fuel efficient with lower emissions. The contractor should compare different equipment makes in economic and environmental performance based on his own records.

5. Recommendations

The operation and maintenance of construction equipment is an important factor for achieving fuel economy and reducing exhaust emissions. Since other emission reduction strategies may involve large capital investment or financial spending, improving operations and maintenance practice has proved to be more feasible for equipment owning organizations, especially for small to medium size contractors.

It is cost-effective to take measures in training and education of equipment operators, implementing proactive maintenance strategies, and deploying right equipment for right jobs. Yet the actual equipment emissions are difficult to measure and fluctuate with many factors of impact. Analysis of equipment maintenance and operations data can help to identify the factors that contribute most to the fuel consumptions and emissions and determine the priority of emission reduction measures with consideration of cost effectiveness.

Equipment telematics are products that are built into the equipment or can be purchased separately and connected to the engine for collecting real time data on engine status, power output level, fuel and fluid level, location tracking, engine fault diagnostics, driver management, etc. Nearly all the major equipment manufacturers provide telematics products, including Product Link from Caterpillar [11], KOMTRAX from Komatsu [12], Modular Telematics Gateway, from John Deer [13]. Telematics are smart devices that can be used to collect data and transfer data to an equipment management information system. An equipment management information system stores equipment operation and maintenance data which can then be used for different statistical or advanced data analysis to evaluate the equipment productivity, engine performance, fuel consumption, etc. Since the emission related data such as fuel consumption, working hours, engine load, engine status (idling, full load, or other load levels) and durations are all captured in real time, the engine emissions can be analysed and reported with high accuracy on daily, weekly, or monthly basis.

6. Conclusions

Large infrastructure projects rely on construction equipment for construction. In the meantime, construction equipment emissions are a major concern to the construction personnel and general public, especially in densely populated areas. Stringent control and regulation of construction equipment emissions has been in legislation or already in effect in many countries and metropolitan areas. This paper discusses the factors that affect the rate of emissions from diesel-powered engines of construction equipment and organizes the factors into four categories: equipment and conditions, equipment maintenance, operating conditions, and equipment operations. Considering the fact that the current construction equipment cannot be replaced by new low-emission models or even engine rebuild in the near future, improvement in equipment maintenance and operations is more cost effective in emission reduction. A case study is used to demonstrate that factors on equipment fuel consumption and emissions can be identified and their degree of impact quantified through statistical analysis and modeling, and actions can be taken accordingly to reduce emission through improved maintenance and operations. The factors of impact on equipment emissions can vary with different projects, different equipment types, different organizations, therefore it is advised to collect and keep emission-related data and conduct analysis for diagnostics of emission fluctuations and corrective actions. Telematics and construction equipment management information system can help to provide more accurate estimation of activity-based and fuel-based emissions and fact-based decisions in emission reduction of construction equipment.

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