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Optimal Driving Pattern of On-Road Construction Equipment for Emissions Reduction

Khalegh Barati[a], Xuesong Shen[b]*

[a]*Ph.D. Student, School of Civil and Environmental Engineering, UNSW,Sydney, 2033, Australia*
[b]*Lecturer,School of Civil and Environmental Engineering, UNSW, Sydney, 2033, Australia*

Abstract

Construction operations contribute to 6.8% of greenhouse gases (GHG) emissions globally, which is mainly due to the large number of heavy diesel-engine equipment involved in the construction industry. The current studies of emissions mainly focus on emission estimating of construction equipment, while how to reduce the emissions of such equipment needs more attentions. This paper aims to minimize the amount of emissions produced per travelled distance by developing an operation-level emission reduction scheme for on-road construction equipment. Three main parameters of speed, road slope and payload are considered as primary operational factors affecting emissions. Also, both engine load and engine size are investigated as affecting engine attributes on emissions. The Ordinary Least Square (OLS) and Multivariable Linear Regression (MLR) analyses were conducted on the field collected data to investigate the role of operation parameters on emission. Optimal driving speed is then determined based on given site operational conditions. The result analysis shows by increasing the payload of equipment and road slope, the emissions of equipment increase significantly while the optimal driving speed should be maintained lower accordingly. The emission reduction scheme developed in this research can be used as a guideline for construction contractors to minimize emissions of on-road construction equipment.

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Keywords: Construction project; Greenhouse gases emissions; On-road construction equipment; Operational parameters; Ordinary least square regression;

* Corresponding author. Tel.: +61-2-93850483; fax: +61-2-93856139.
E-mail address: x.shen@unsw.edu.au

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1. Introduction

The growth of population and industrialization has heightened demands on different sources of energies globally, which has increased the concentration of GHGs in the atmosphere. GHGs are mainly composed of carbon dioxides (CO_2), carbon monoxides (CO), hydrocarbons (HC), nitrogen oxides (NO_x= NO+NO_2) and general particulate matters (PM) pollutants. Those contaminants draw serious concerns for human health, ecosystem and environment, and are considered as potential causes of respiratory and cancer diseases [1, 2]. The awareness of the non-compensable effect of anthropogenic GHGs emissions on climate change and public health has brought global attention towards developing emission reduction regulations and guidelines. According to the United Nations Framework Convention on Climate Change (UNFCCC), all sectors in industrialized countries should follow regulations to decrease GHGs emissions [3]. US Environmental Protection Agency (EPA) and European Union (EU) have developed emission standards to restrict the GHGs emitted from on-road vehicles and non-road diesel equipment [1, 4]. Also, many limitations have been imposed by Intergovernmental Panel on Climate Change (IPCC) to minimize carbon foot prints through reducing activities causing large amount of emissions [5].

Construction industry is considered as a main contributor to GHGs production globally. According to EPA [6], construction sector accounts for 1.7% of total GHGs production and 6.8% of all industrial-related emissions which is ranked as the third largest GHG emitter after oil and gas, and chemical manufacturing industries [7, 8]. Based on the report prepared by EPA's Clean Air Act Advisory Committee (CAAAC) [9], construction sector accounts for 6% of light duty vehicles (LDV) and 17% of heavy duty vehicles (HDV) while producing 32% of NO_x and 37% of PM of all mobile source emissions [10]. In addition, it is estimated that this industry produces more than 100 million tons of CO_2 annually, the most abundant GHG, which is around 7% of total CO_2 emitted across the world. The construction sector has also been ranked as the third highest CO_2 emitter per used unit of energy after cement and steel production industries [11, 12]. The majority of emissions in construction sites are produced from on-site equipment operations. Developing reduction strategies for such equipment can have significant effect on total amount of emitted pollutions [12]. As an illustration, if the idling time of construction equipment reduces by 10%, the emission of CO_2 decreases for around 0.8 million tons per year [7]. Furthermore, it is predicated if the fuel consumption of equipment involved in construction sites decreases by 10%, the corresponding CO_2 reduction in each year would be approximately 6.7 thousand tons [13]. In addition, equipment compatibility and efficiency are two crucial parameters have considerable effect on produced emissions per unit of conducted work [14]. Large construction projects normally involve a variety of type and number of equipment, and therefore hold flexibility in selecting equipment to work on a given activity.

Despite of the significance, there is a lack of comprehensive strategy to reduce emissions resulting from the operation of equipment in construction projects. The current reduction schemes have mainly focused on engine and fuel attributes, and mechanical practices to decrease total amount of emitted pollutions. As a general guideline for construction firms, EPA has introduced engine upgrading and retrofitting technologies to reduce emissions which could be costly and not readily applicable for existing fleet of construction equipment [15]. Cleaner and renewable fuels have been introduced as an alternative source of energy over traditional diesel which may not be economically feasible due to the high cost and power loss of equipment.

The main objective of this research is to develop an operation level emission reduction scheme for on-road construction equipment. We first develop the methodology to collect and analyze field emission data from construction equipment. Then, the effects of main operation parameters are investigated on emission rates by OLS analysis. Finally, a case study on optimal driving pattern is presented by considering various operation parameters. The developed emission reduction scheme can be used by construction contractors as a guideline for driving at an optimal speed to minimize total emission produced under certain project settings.

2. Literature Review

Numerous efforts have been conducted by scholars and agencies on developing emission reduction schemes for the construction industry. Lewis et al. [1] emphasized on mitigating GHGs emissions resulting from construction activities by considering health problems and environmental impacts. Emission taxes and governmental regulations were selected as the main incentive and requirement for the emission reduction approach. Many international agencies such as EPA have established two types of technological and air quality standards to implement restrictions on the amount of emissions of non-road equipment. The technological standards impose limitations on emissions produced by equipment and engage manufacturers to build engine with higher level of performance [16, 17]. The purpose of air quality regulations like national ambient air quality standards (NAAQS) is to control the concentration of the harmful pollutants in the atmosphere [1, 4]. A number of studies have proposed low-cost emission reduction schemes in different fields such as fuel changes, equipment upgrading and operator training. Frey et al. [13] compared the emissions resulting from regular diesel and biodiesel fuels through collecting field data from motor graders, loaders and backhoes performing real-world duty cycles and activities. EPA and California Air Research Board (CARB) introduced ultra-low sulfur diesel (ULSD), and B5 and B20 biodiesels as main alternative fuels for construction equipment [15]. These fuels are the blend of renewable fuels made from crops with petroleum diesel which have much lower amount of sulfur. Although these fuels may cost up to 5% more, they have significantly reduced emission rate of CO, HC and PM pollutants [18]. It was also found that the oil change interval of equipment using such biodiesel can be approximately 35% longer than that required for vehicles consuming normal diesel [15].

2.1. Emission Reduction Approaches

As Table 1 shows, the current approaches in developing emission reduction schemes can be classified into four main strategies of operation, equipment, fuel and planning. Operation schemes mainly focus on driving patterns including operator training, decreasing idling time and increasing operation efficiency of equipment. These strategies are dependent of the skill level of operator and can significantly reduce fuel consumption and emissions of machinery. For example, decreasing one hour idling time of middle-size construction equipment reduces approximately 3.8 Liters fuel consumption and around 6.85 kg CO_2 emission production [10, 15]. Equipment strategies consider engine modifications and rebuilding schemes to reduce emissions which normally incur significant initial costs of investment. These schemes include using retrofit technologies, engine rebuilding, and electrification. Retrofit devices such as diesel oxidation catalysts (DOC) and diesel particulate filters (DPF) are inserted in the exhaust of equipment to mitigate pollutants. Engine rebuilding and upgrading e.g. repowering replace older engines with new ones with less emission or emission-reducing parts added.

Table 1. Overview of emission reduction strategies applicable for construction industry

Strategy	Method	Description
Operation	Idling time reduction	Causes significant reduction in fuel consumption and emissions. Increases engine life and decreases maintenance cost.
	Engine regular maintenance	Reduces PM, NOx, CO, and HC emissions and lower fuel consumption. Increases equipment life and prevents high cost engine failure.
	Operator training	Improves operation efficiency and reduces emissions and fuel consumption significantly.
Equipment	exhaust gas treatment Technologies	Physically traps diesel particulates and prevents their release into the atmosphere and can reduce PM emissions, but the total NOx emissions remain unchanged for diesel oxidation catalysts.
	Engine rebuilding and repowering	Reduces PM, NOx, CO, and HC emissions and lower fuel consumption. Improves engine reliability and lower maintenance costs
	Electrification	Reduces huge amount of PM, No_x, CO, and HC emissions. Hybrid electric vehicles have substantially lower fuel consumption
Fuel	Biodiesel	Derived from renewable sources such as vegetable oil, animal fat, and cooking oil. Reduces HC, PM, and CO emissions but produces more No_x emissions. Compatible for use with high-efficiency catalytic emissions–reduction technology.
	Ultra-low sulfur diesel	Reduces PM emissions and engine wear, corrosion and deposits. Enables the use of advanced technologies to reduce emissions.
	Fuel additive	Can reduce No_x, HC, PM, and CO emissions and improve fuel economy. Some additives might increase one or more pollutant emissions while reducing other pollutant emissions and increasing fuel efficiency
Planning	Compatibility between equipment pieces	Increases the operation efficiency of equipment by decreasing idling time, and reduces emissions and fuel consumption. Less equipment pieces are needed for doing specific task.
	Optimal equipment selection	Reduces the emissions and costs of construction operations by selecting equipment pieces with higher engine tiers and increasing compatibility between involved equipment.

Fuel strategies also have considerable impact on reducing emitted pollutants of construction equipment without any major investment. Changing fuel blends and alternative fuels are two most common practices for emission reduction. Diesel fuel can be blended with components like Puri NO_x and Biodiesel other than hydrocarbons to increase fuel performance and reduce emission rates. Biodiesels are the most common fuel blends that are made from renewable and biotic materials like cottonseeds and cooking grease. Increasing the percentage of biodiesels in fuel causes remarkable reduction in HC, CO and PM pollutants, but NOx emission can be increased by maximum 10%. Natural gas, propane and HCNG are main alternative fuels can be used by construction equipment to reduce amount of pollutants. Based on the research conducted in this field, using these types of fuels can dramatically decrease PM, NOx and Sulphur emissions without incurring any significant extra fuel cost [18].

Planning strategies concentrate on resource and machinery management to reduce total pollutants emitted from construction projects. Compatibility in the size and number of equipment pieces involved in sites is one of the main areas of planning that have dramatic effects on operation efficiency of equipment (OEE) and emission productivity [18,21-22]. The result analysis on some case studies conducted on earthmoving operations showed that the unit cost and unit emission are coincidently minimal at optimal fleet size of truck and excavator [18, 21].

3. Methodology

This section presents the methodology adopted in developing the optimal driving pattern to reduce emissions of on-road construction equipment by considering operational affecting parameters. First, the emission model used in this paper is briefly presented. The operation level emission model investigates the effects of various operation parameters on emissions. Then, by considering the payload of the equipment and slope of the road, the optimal speed is estimated to produce minimum emission per travelled distance. Finally, as a reduction scheme, the guideline is developed to present optimal driving pattern to minimize emissions of on-road construction equipment at operation level.

The model used in this text estimates real-time emissions of on-road construction equipment [23]. Four operating parameters of acceleration, speed, slope and payload have been considered as primary factors affecting emissions. In the developed model, engine load acts as a critical intermediate parameter bridging emission rates with affecting operation parameters. Eq. (1) estimates the engine load based on acceleration, slope and speed and load factor. As can be seen, there is multivariable linear function between operation parameters and engine load. The parameter of load factor is defined as the ratio of the current payload to the maximum allowable payload of equipment. Also, the constant value (C) shows the engine load of equipment in idle mode which is around 20%. The coefficients of investigated parameters in the developed engine load model are given in Table 2.

$$EL = (C_{AC} * AC) + (C_{SL} * SL) + (C_{SP} * SP) + C \quad (1)$$

Where:
EL: Engine load of equipment (%)
AC: Acceleration of equipment (m/s^2)
SL: Slope of road (degree)
SP: Speed of equipment (km/h)
C: Engine load of equipment in idle mode which is around 20%.

Table 2. The coefficients of parameters in engine load estimation model [23]

Model	Coefficients			
Load Factor	0	0.33	0.67	1
C_{AC}	15.65	19.36	24.8	27.37
C_{SL}	1.12	1.29	1.67	1.86
C_{SP}	0.41	0.52	0.57	0.64

CO_2 is the main GHG pollutant emitted by construction equipment and is mainly investigated in this study. The OLS analysis shows clear relationship between CO_2 emission rate and engine load with high accuracy. CO_2 emission varies between 45 g/Kwh in idle mode (EL ≈ 20%) to around 250 g/Kwh in full engine load.

4. Data Analysis

The operation level emission reduction scheme for on-road construction equipment has been developed through analyzing the experimental data and using explained emission model. The field collected data are classified into three main categories of operation, engine and emission. The operation level emission reduction scheme is developed by investigating the effect of three main operation parameters of speed, slope and payload (load factor) parameters on CO_2 emission. The collected field data showed that at limited time of operation, construction equipment is in acceleration (deceleration) mode, and these equipment have much less speed changes in comparison with urban cars. So, in spite of the fact that the effect of acceleration parameter is high on instantaneous emission rate; its average influence on total emission produced in a trip is negligible which was not considered in this study. The engine load and engine size are two engine parameters considered in this study. As was mentioned, engine load acts as an intermediate parameter linking investigated operation parameters to CO_2 emission.

As the first step of result analysis, the effect of speed and load factor parameters is concurrently investigated on CO_2 emission rate using Eq. (1). In this step, it is assumed that the equipment pieces are driven on a levelled route which slope parameter does not have any effect on engine load and emission. As shown in Fig. 1, based on different load factor coefficients, on-road construction equipment can be driven at optimal driving speed to produce minimum emission per travelled distance. It is found the optimal driving speed decreases by increasing load factor, while emitted CO_2 per travelled distance has been increased significantly. For example, for empty equipment (LF = 0), optimal driving speed and its corresponding CO_2 emission are around 79 km/h and 2 g/kW.km respectively. They are approximately 55 km/h and 2.9 g/kW.km for a fully loaded equipment (LF = 1).

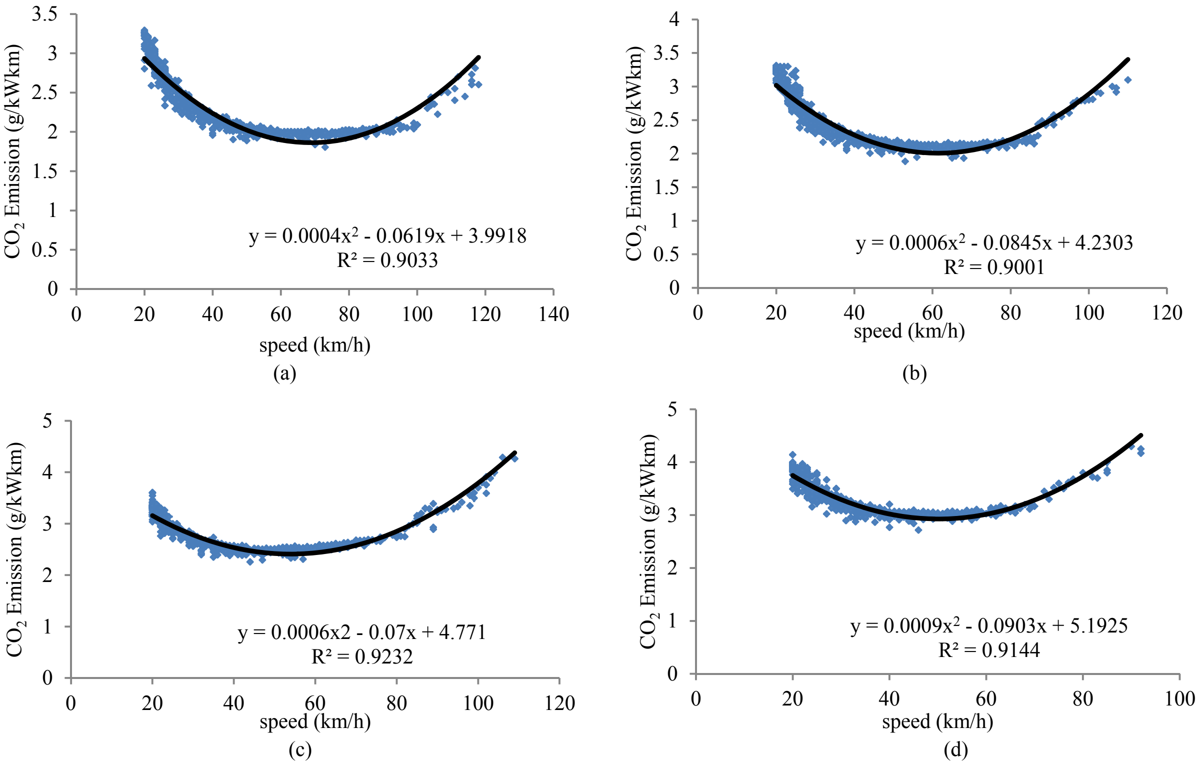

Fig. 1. The CO_2 emitted from on-road construction equipment driven at a levelled road in different payloads, a) LF = 0; b) LF = 0.33; c) LF = 0.67; and d) LF = 1.

Slope of road is another main operation parameter affecting emissions. The collected data from equipment pieces driven on the roads with different slopes were analyzed using Eq. (1). Fig. 2 estimates the optimal speed and CO_2 emission based on different road slope and payload. As can be seen, road slope has a significant influence on emissions produced per travelled distance. For example, an empty equipment driven in a levelled road (slope = 0) emits around 2 g/kW.km CO_2 at optimal speed of 79 km/h and, while the optimal speed and CO_2 emission change to 59 km/h and 3.5 g/kW.km respectively for road slope of 15 degree. Also, the comparison between Fig. 2a and Fig. 2b shows that by increasing the payload, the effect of slope on emission becomes much higher.

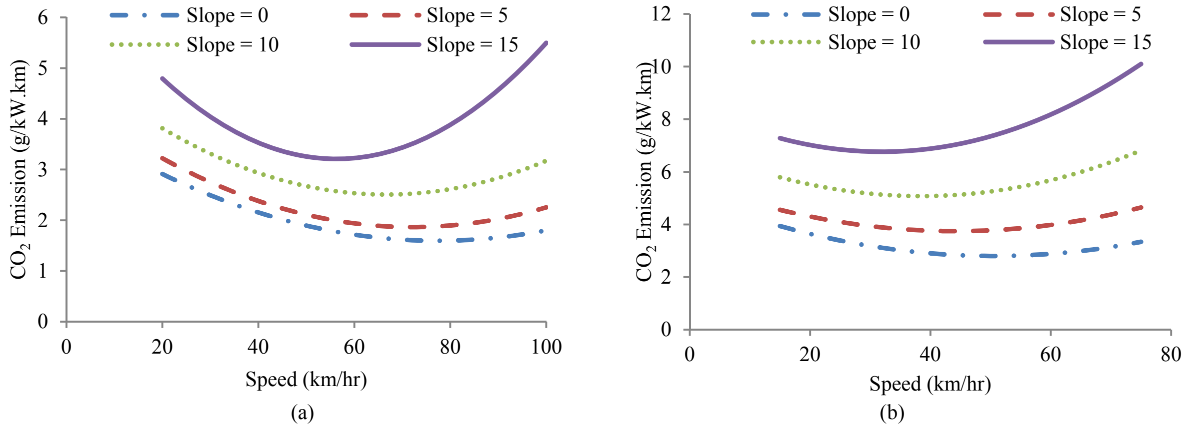

Fig. 2. The effect of road slope on optimal speed and CO_2 emission of equipment driven in different payloads, a) LF = 0 and b) LF = 1.

Fig. 3 presents the operation level emission reduction scheme developed in this study for on-road construction equipment. This graph estimates the optimal driving speed based on the available payload in the equipment and the slope of road. The developed scheme can be used as an operation guideline by construction contractors and equipment operators to operate in a way to minimize emissions produced per travelled distance. As can be seen, the increase of equipment payload and road slope reduces the optimal driving speed dramatically.

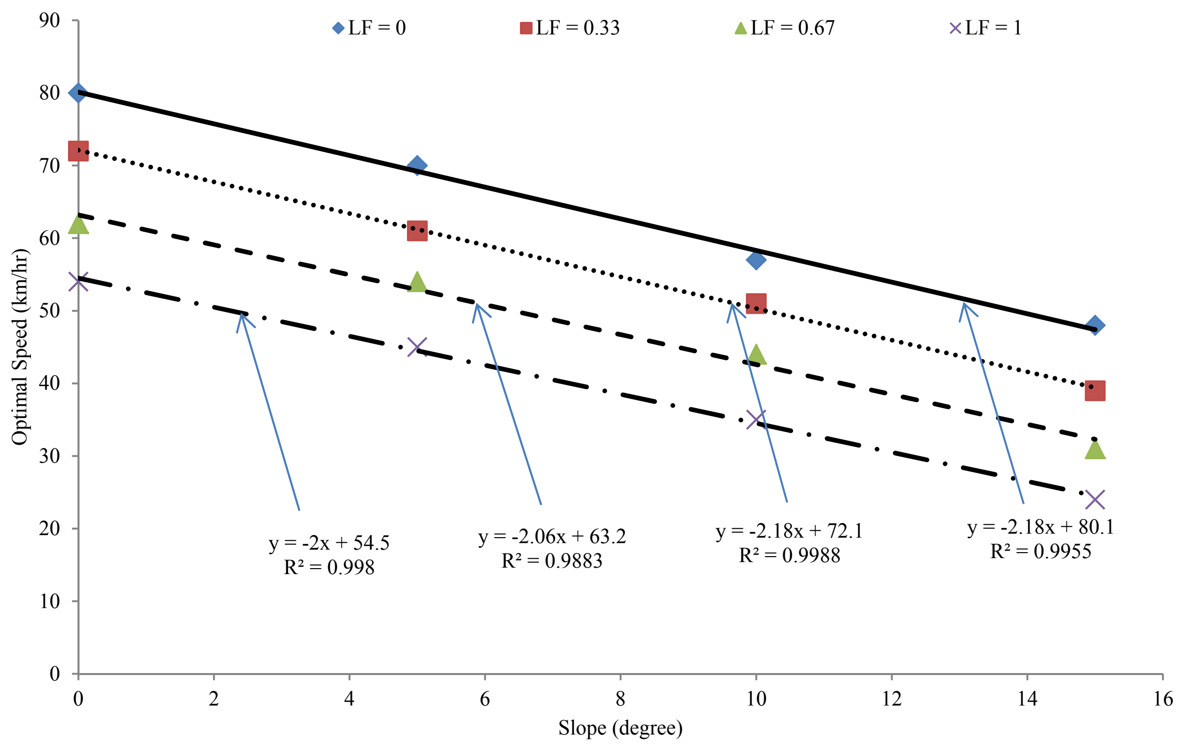

Fig. 3. Optimal driving speed based on the road slope and payload for having minimum CO_2 emission

5. Conclusions

Construction industry is regarded as one of the main contributors of global GHG emissions. Currently, most of scholars in this field have focused their research on estimating emissions of construction equipment. There is limited work done in the area of emission reduction schemes. This paper has developed an operation-level emission reduction scheme for on-road construction equipment by analysing field emission data and emission modelling. The emission reduction guideline developed optimal driving pattern that can be followed by equipment operators. The OLS analysis on the field collected data shows that the developed reduction strategy has high accuracy ($R^2 > 0.9$) in estimating optimal driving speed based on given operation conditions. Three operational parameters affecting emissions were investigated in this study, namely speed, road slope and payload. Despite significant effect of acceleration on instantaneous emission rate, this parameter was not considered in this study as the percentage of time that construction equipment pieces are in acceleration mode is negligible.

Based on the emission reduction scheme developed in this research, the CO_2 emissions on-road construction equipment can be estimated precisely. The optimal driving speed is determined to produce minimum level of CO_2 emissions. Future study will extend the operation-level emission reduction scheme to earthmoving equipment involved in construction projects, such as hydraulic excavator, wheel loader and dozers. Also, by relating emissions to fuel consumption rate, this study is readily applicable for operation-level fuel reduction strategy for construction equipment.

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