Modelling Traffic Conditions on Fuel Use and Emissions of On-road Construction Equipment

K. Barati[a], X. Shen[a]

[a]School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia
E-mail: Khalegh.barati@unsw.edu.au, X.shen@unsw.edu.au

Abstract –

The consumption of fossil fuels by on-road vehicles is a main source of air pollution specifically greenhouse gases (GHGs) worldwide. The construction industry, due to the use of a large number of heavy-duty equipment including haulage trucks, contributes to a significant amount of fuel consumption and consequent emissions production. Due to increasing number of vehicles on the road, traffic condition is becoming one of the main variables having a considerable impact on the fuel use and emissions of such vehicles. There is a lack of comprehensive studies in construction field quantifying the effect of road traffic on fuel use and emissions of construction equipment. This research aims to model the impact of traffic conditions on fuel use and emissions of on-road construction vehicles. The research framework is first developed to present the methodology of data collection and analysis, and then introduce the fuel use and emissions models applied in predicting the effect of traffic conditions. Three variables of driving speed, idling time and equipment stop are identified as representatives of traffic conditions, and their impacts on fuel use and emissions are quantified through conducting statistical analyses on collected field data. The achieved results found that by having more effective traffic management and planning, the fuel cost and consequent emissions can be reduced up to 9% due to the decreasing idling time of equipment. It is also indicated that by lowering the number of equipment stops, up to 0.66 l/100kW fuel is saved and up to 1.7 kg/100kW CO_2 is emitted less per each stop.

Keywords –

Construction Equipment; Traffic Condition; Fuel Use and Emissions; Construction Sector; Idling Mode; Equipment Stop

1 Introduction

The construction sector plays a significant role in fossil fuels consumption and the production of GHG pollutants. According to the Environmental Protection Agency (EPA), construction sector accounts for 1.7% of total GHG 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 [1, 2]. In addition, it is estimated that construction industry produces more than 100 million tons of carbon dioxides (CO_2) annually, and contributes to around 5% of global CO_2 emissions which is ranked as the third CO_2 emitter per utilized unit of energy after cement and steel production sectors [3]. According to the United Nation Framework Convention on Climate Change (UNFCCC), GHG emissions from construction operations account for around 6.8% of the total emissions produced by all industrial sectors [4]. The majority of fuel used and emissions produced in the construction sector is related to equipment operations. Construction equipment accounts for 45% to 48% of the total vehicular consumed fuel and emitted pollutions of all industries [5, 6]. The machinery is mainly involved in huge earthmoving operations which their emitted pollution is by far more than other vehicles. For example, the pollution production of a middle-sized loader is nearly 500 times more than that of a private car [7, 8]. Based on the report prepared by the EPA's Clean Air Act Advisory Committee (CAAAC), construction sector accounts for 6% of the light-duty vehicles (LDVs) and 17% of the heavy-duty vehicles (HDVs) while producing 32% of nitrogen oxide (NO_x) and 37% of particulate matters (PM) of all mobile source emissions [9]. In the construction projects, equipment operations and materials transportation account for the majority of fuel use and emissions production.

Improving traffic conditions can have a significant effect on decreasing the total amount of pollutions emitted by construction equipment. As an

illustration, if the idling time of construction equipment reduces by 10%, the emission of CO_2 decreases by around 0.8 million tons per year [10]. Furthermore, EPA estimates if the fuel consumed by construction equipment decreases by 10% through lowering the idling times and equipment's stop, around 5% of the entire energy used in the construction sector will be saved resulting in a reduction of 6,700 tons CO_2 production [1, 11]. The Australian Clean Energy Regulator Agency (CERA) predicts that by improving the traffic volumes and having a more effective traffic planning and control, over 3 billion liters fuel can be saved by on-road equipment involved in all industries including construction which approximately 8 million tones CO_2 is emitted less in Australia only [12].

In spite of the significance, there is a lack of comprehensive study on modelling the effect of traffic conditions of fuel use and emissions rate of on-road construction equipment as the primary strategy to improve the fuel efficiency of such vehicles. The current traffic modelling systems mainly have been developed in the transportation field take into consideration just the impact of traffic on small-sized urban vehicles. The main focuses in construction field are on engine attributes, fuel types and mechanical practices to decrease the amount of used fuel and emitted pollutions per specific trip cycle which are costly and not applicable for all equipment.

The main goal of this paper is to model the effect of traffic conditions on fuel use and emissions production of on-road construction equipment. The comprehensive research framework is first developed presenting the methodology of data collection and analysis procedure. The operational level fuel use and emissions models applied in this study for modelling traffic conditions are then briefly introduced. This research continues with developing three variables of driving speed, idling time and equipment's stop representing the road traffic volume. The fuel use and emissions production of equipment at different speeds, idling mode and per each stop are measured in the next step using the developed fuel use and emissions model and equipment's specifications.

2 Background

Traffic management is one of the main challenges of the transportation field covering all moving vehicles. Traffic is a dynamic system which needs to be precisely modelled considering all affecting parameters including operators' driving patterns, road conditions and instantaneous traffic flow rate. It seems impossible to distinguish all factors affecting traffic conditions and model their impacts. Some models focus mainly on the driving pattern of each vehicle driver known as microscopic traffic models, while others concentrate on the average effect of factors at the macroscopic level and do not consider the dynamicity of traffic [13, 14].

As one of the major applications of the traffic models, fuel use and emissions rate of vehicles can be estimated based on the traffic flow. Different studies have been conducted to model the effect of traffic conditions on fuel use and emissions rate at both microscopic and macroscopic levels [15]. Microscopic fuel use and emissions models emphasize the instantaneous measurement of traffic variables plus the vehicle's specifications. The Motor vehicle emission measurement simulator (MOVES) is an example of such models that was developed by the EPA in 2004 to estimate the fuel use and different emissions (CO, NO_x, PM, CO_2, NH_3 and SO_2) of a variety of on-road motor vehicles. This model considers numerous parameters such as vehicle specific power (VSP), and derives second-by-second data from different programs such as US I/M240 and MOBILE6 [16]. MOVES simulator models the traffic conditions and driving cycles considering speed profile and distribution of the operation modes.

On the other hand, the macroscopic models have different inputs of average speed and vehicle group [13]. As an example of this modelling approach, the comprehensive modal emission model (CMEM) was developed by the cooperation of the University of California-riverside and the University of Michigan with the sponsorship of the National Cooperative Highway Research Program (NCHRP) in 1995. The prime objective of designing this model is to estimate fuel use and emissions rate associated with the operation modes of light-duty vehicles. CMEM simulates fuel use rate taking into consideration different readily-available parameters such as operating modes and specific vehicle factors, and calibrated parameters like fuel specifications and catalyst variables [13].

In addition to the traffic controlling and planning, numerous efforts have been devoted by scholars and international agencies to developing fuel use and emissions reduction schemes in the construction field. A number of studies have sought various means of reduction schemes, such as fuel changes, equipment upgrading and operator training. Avetisyan et al. developed a decision model to reduce fuel use and GHG emissions from transportation construction projects. Using the mixed integer programming (MIP), the optimization-based technique minimizes the emissions produced by the

equipment through considering numerous parameters, e.g. machinery availability, compatibility among equipment pieces and operation conditions [3]. Kaboli and Carmichael explored the relationship between the operation cost and produced emissions in the earthmoving activities using queueing technique. They concluded that by reducing emissions produced by machinery, the operation cost would decrease as well. It was also found that the minimal unit cost of emission and project cost are coincident, and this result does not rely on the operation conditions and equipment type [17].

3 Research Framework

As Figure 1 demonstrates, this section presents the methodology adopted in this study to model the effect of traffic conditions on fuel use and emissions of on-road construction vehicles. First, three instruments of the engine data logger, portable emission measurement system (PEMS) and GPS-aided inertial navigation system (GPS-INS) were developed to collect required field data including engine load (EL), fuel use and emissions rate in each second from in-use construction equipment. As shown in Table 1, during seven days of experimentation, eight HDVs with different classes, sizes and year models were tested to cover real working conditions in practice.

After obtaining the field data through experimentation, a data processing and synchronization procedure was performed to create a centralized database of all raw data gathered from the instrument. Database files were first created for storing the data collected from each piece of equipment. Data validation was then conducted to identify potential errors in the raw data. In the next step, the data gathered by instruments were synchronized. Since instruments did not have much delay in recording data, the simultaneous speed of the vehicle measured by both devices was used as a reference for data synchronization. The PEMS data were further processed to match with the data obtained from the other two instruments. One centralized database was then created with all field data of investigated parameters synchronized. The invalid data measured by each of the devices were finally detected and removed together with the corresponding data from other instruments.

Processing and analyzing the real-time obtained data, the fuel use and emissions rate of on-road construction vehicles were then modelled through investigating the effects of operational and engine factors on fuel use and emissions. Figure 2 shows some sample processed data used for modelling fuel use and emissions.
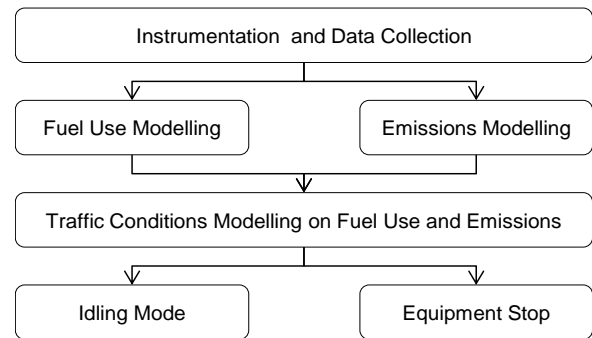

Figure 1. Research framework for modelling the effect of traffic conditions on fuel use and emissions rate of on-road construction equipment

3.1 Fuel Use and Emissions Models

The models developed in this text predict the fuel use and emissions rate of on-road construction equipment at the operation level [18]. There are numerous operational, environmental and engine parameters affecting the fuel use and emissions of equipment, but this study aims to focus on factors having a more significant effect and ignore parameters having a negligible impact. The initial analysis on the gathered raw data indicated that four operational variables of acceleration, speed, road slope and WF are the primary parameters affecting fuel use and emissions. The parameter of WF is defined as the combined weight of equipment (ton) should be carried per 100 kW of engine size [6, 20]. The combined weight refers to the total weight of the vehicle including equipment itself, trailers and payloads. Fuel type is another major factor influencing the fuel use and emissions rate. Different engine attributes also impact the fuel use and emissions including engine size, engine tier and engine age. In this study, the models consider the engine size, and estimate fuel use and emissions per kW of the engine. There are construction equipment pieces with three tiers of IV, V and VI engines in the market, but the tier V engine is currently predominant and is the main focus of this study. Engine age and maintenance conditions vary significantly from vehicle to vehicle and have minor effect of fuel use. Therefore, the parameters of engine age and maintenance have not been considered in this study at this stage. Construction equipment normally uses diesel as the primary fuel globally, and this research develops the models considering diesel fuel.

Table 1. Summary of field experimentation process conducted in this study

| Day	Vehicle	Model	Engine size (kW)	Empty Weight (ton)	Payload (ton)	Experimentation Time (min)
Day 1	Six-axle Trident	2014	400	17.7	30.3	235
Day 2	Six-axle Vision	2005	350	17.6	30.9	340
Day 3	Three-axle Granite	2010	345	9.5	13	270
Day 4	Seven-axle Trident	2013	400	18.8	31.7	310
Day 5	Seven-axle Granite	2010	345	16.6	33.9	260
Day 6	Six-axle Granite	2010	345	14.5	33.5	410
Day 7	Three-axle Trident	2013	400	11	11.5	205

(a)

(b)

(c)

(d)
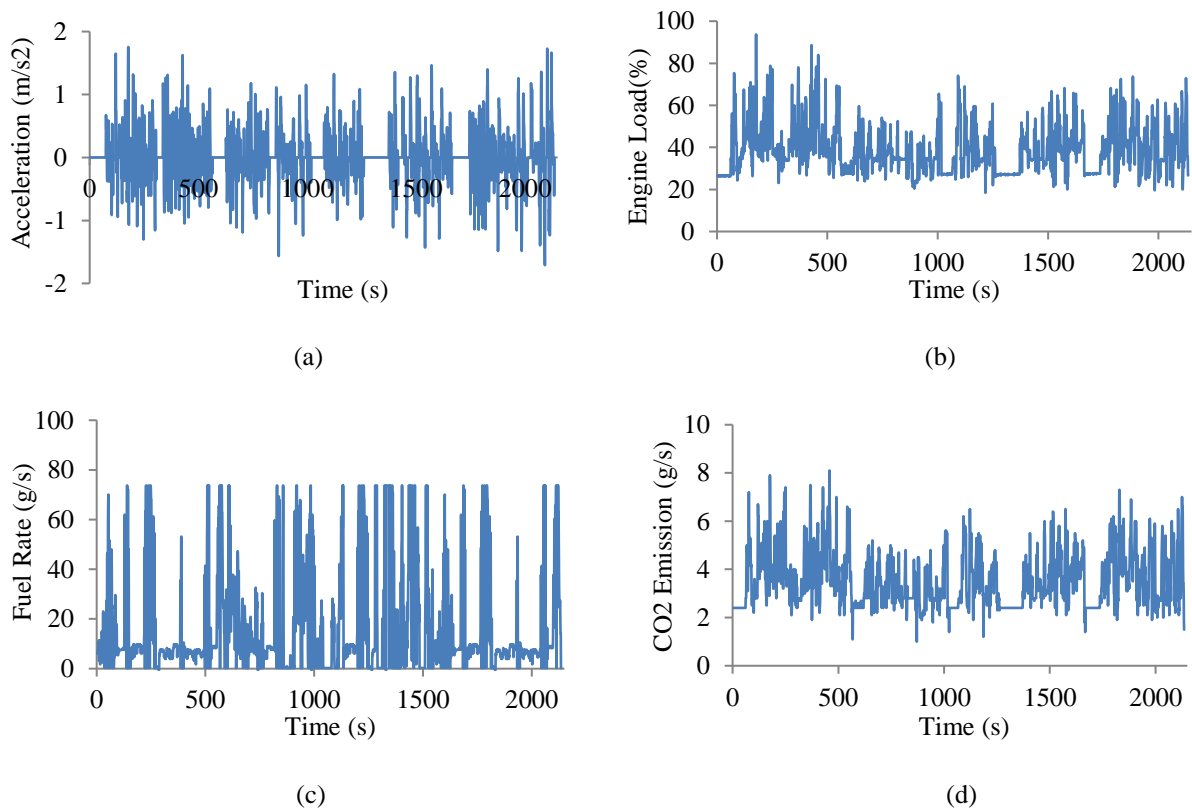
Figure 2. Samples of obtained data analyzed for developing fuel use and emissions model, (a) acceleration rate versus time, (b) engine load versus time, (c) fuel use rate versus time and (d) CO_2 emission rate versus time

In the devised models, EL acts as a critical intermediate factor bridging fuel use and emission rates with affecting operational parameters. Considering the internal specification of the engines, operational and environmental variables impact the engine power, and then engine power effects fuel use and emissions. Therefore, an intermediate parameter must be defined to link operational parameters to fuel use and emissions. Three engine variables of engine load, engine speed and manifold absolute pressure (MAP) were initially introduced as the used power of the engine, but the regression analyses on the collected data indicated that engine load is the best surrogate of the used engine power. Engine load is the percentage of used power of the engine and is defined as the ratio of the used power over the maximum available power of the engine.

The regression statistical method was the theory used in this study to develop the fuel use and emissions models. This method is more flexible compared to the other data analysis techniques. As one of the advantages, it is simple to add or remove some data after conducting an initial analysis. Using regression technique, it seems easier to find the differences among the developed relationships, and compare the results achieved from processing the data of various vehicles. Regression technique has other strong points such as level of familiarity, assumptions and use of multiple variables.

Equation (1) presents the function estimating the EL considering four factors of acceleration, road slope, driving speed and WF. As can be seen, there is a multivariable linear function between operational parameters and EL variable. Also, the constant value (C) shows the EL of equipment in idling mode which is around 20%. The coefficients of investigated factors in the developed EL model are presented in Table 2.

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

Where:
EL: Engine load of equipment (%)
AC: Acceleration of equipment (km/h.s)
SL: Slope of the road (degree)
SP: Speed of equipment (km/h)
C_{AC}, C_{SL}, and C_{SP}: Coefficients of acceleration, road slope and driving speed parameters given in Table 1,
C: EL of equipment in idle mode which is around 20%.

The conducted ordinary least square (OLS) statistical analyses show there is a direct linear relationship between fuel use and emissions, and EL. The fuel use is around 0.02 l/kWh in idling mode (EL ≈ 20%) reaching approximately 0.12 l/kWh when the engine is fully loaded (EL ≈ 100%). CO_2 is the dominant GHG pollutant emitted by construction equipment and is the main focus of this study. CO_2 emission varies between 45 g/Kwh in idling mode to around 250 g/Kwh in full EL.

4 Modelling Traffic Conditions on Fuel Use and Emissions

Applying the presented fuel use and emission models, this section aims to model the effect of traffic conditions on fuel use and emissions of on-road construction vehicles. As discussed, traffic is a very complex dynamic phenomenon and there are numerous factors affecting traffic flow and its impact on fuel use and emissions. To simplify, three major variables of driving speed, idling time and equipment stop are distinguished and introduced as the representatives of traffic conditions in this study. There are absolutely other variables as the surrogate of traffic conditions, but these three parameters seem the most significant in the construction field. As demonstrated in the developed models, the effect of equipment speed as an operational parameter interrelated with WF has been estimated on fuel use and CO_2 emission. As indicated, by increasing the WF, the effect of speed on fuel use and consequently CO_2 emission linearly rises. In the following, the effect of idling time and stop on fuel use and CO_2 emissions are accurately estimated.

4.1 Fuel Use and Emissions in Idling Mode

Lots of operation times of construction equipment is spent in idling mode. The idling times are mainly due to traffic conditions, poor planning and low compatibility among involved equipment involved in the construction sites. As one of the factors in modelling traffic conditions, idling time of vehicles has considerable influence in fuel consumption and emissions production. It has been estimated if the idling time of construction equipment involved in construction sites decreases by 10%, CO_2 emission reduces approximately 800 million ton per year [1]. In this section, the fuel use and CO_2 emission production in idling mode of construction equipment are first estimated using developed models. Then, the additional fuel use and emissions production due to stop of on-road construction vehicles caused by traffic conditions are calculated.

Table 2. The coefficients of parameters in the EL estimation model

Coefficients	WF				
	2.75	4.5	6.5	13	14.5
C_{AC}	20.3	24.8	29.6	41.7	46.3
C_{SP}	0.20	0.25	0.31	0.42	0.47
C_{SL}	1.8	2.6	3.6	5.1	5.6

Figure 3 presents the fuel use and CO_2 emission rate of on-road construction vehicles in different operation modes. In comparison with other modes, vehicles consume much more fuel and produce much higher emissions in hauling mode due to using more power of the engine. As can be seen, the fuel use and CO_2 emission rate of construction vehicles in idling mode are 0.027 l/kWh and 0.073 kg/kWh respectively showing the high significance of lowering vehicles' idling time to reduce fuel use and emissions production. For example, by reducing the idling time of an equipment piece with the engine size of 400 kW for an hour, 10.8-liter fuel is consumed less resulting around 29 kg reduction in CO_2 production.

Figure 4 illustrates the average percentage of used fuel and emitted CO_2 in different operation modes of on-road construction vehicles. These results were achieved by analyzing collected raw data and using presented fuel use and emissions models. As shown, approximately 9% of used fuel and emissions of construction vehicles is in idling mode. This shows that by having more effective traffic management and project planning, the fuel cost and consequently emissions can be lowered up to 9%.
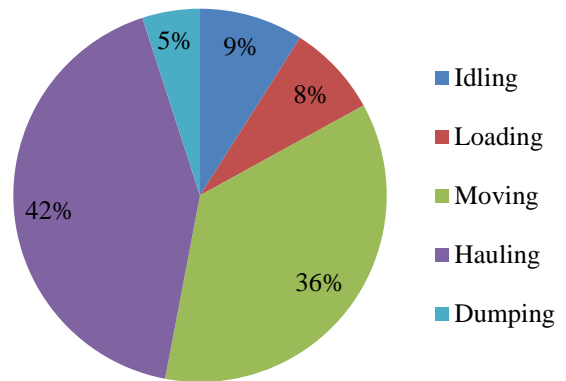

Figure 4. The average percentage of fuel use and CO_2 emission in different operation modes of on-road construction vehicles

4.2 Fuel Penalty and Extra Emissions due to Equipment's Stop

Stops of on-road construction vehicles which are mainly due to congested traffic flows or traffic lights have a considerable impact on the increase of fuel use and emissions. In this step, it is focused to investigate the effect of equipment stop on the fuel consumption and CO_2 production of on-road construction vehicles. Figure 5 indicates the additional fuel use and CO_2 emission due to the equipment's stop.
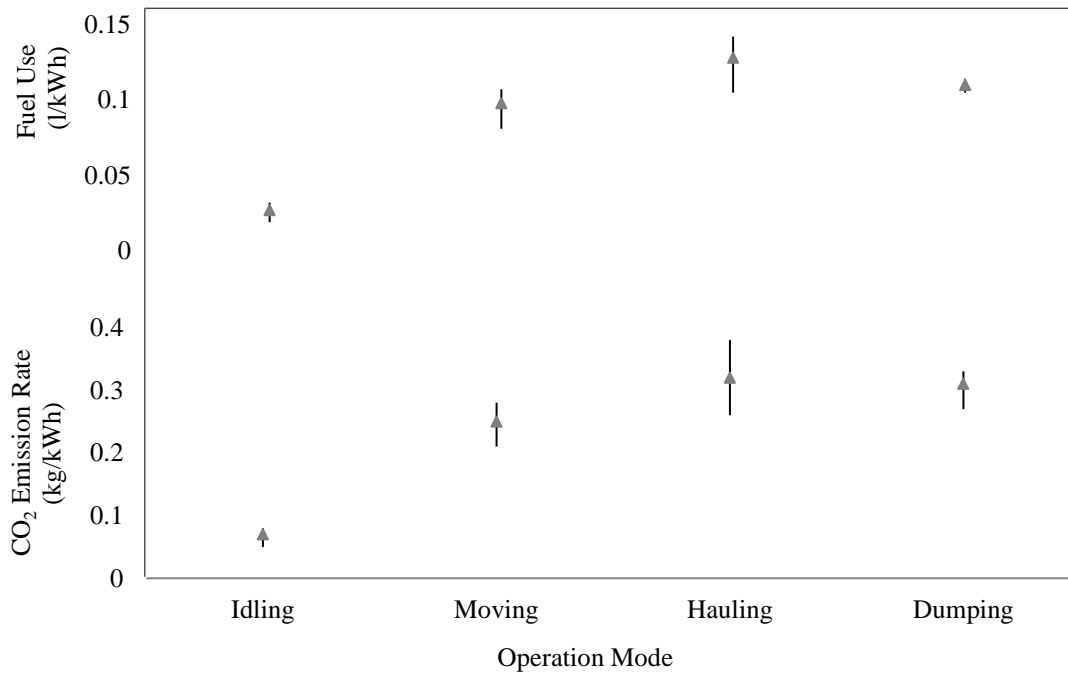

Figure 3. Comparison of fuel use and CO_2 emission of on-road construction vehicles in different operation modes
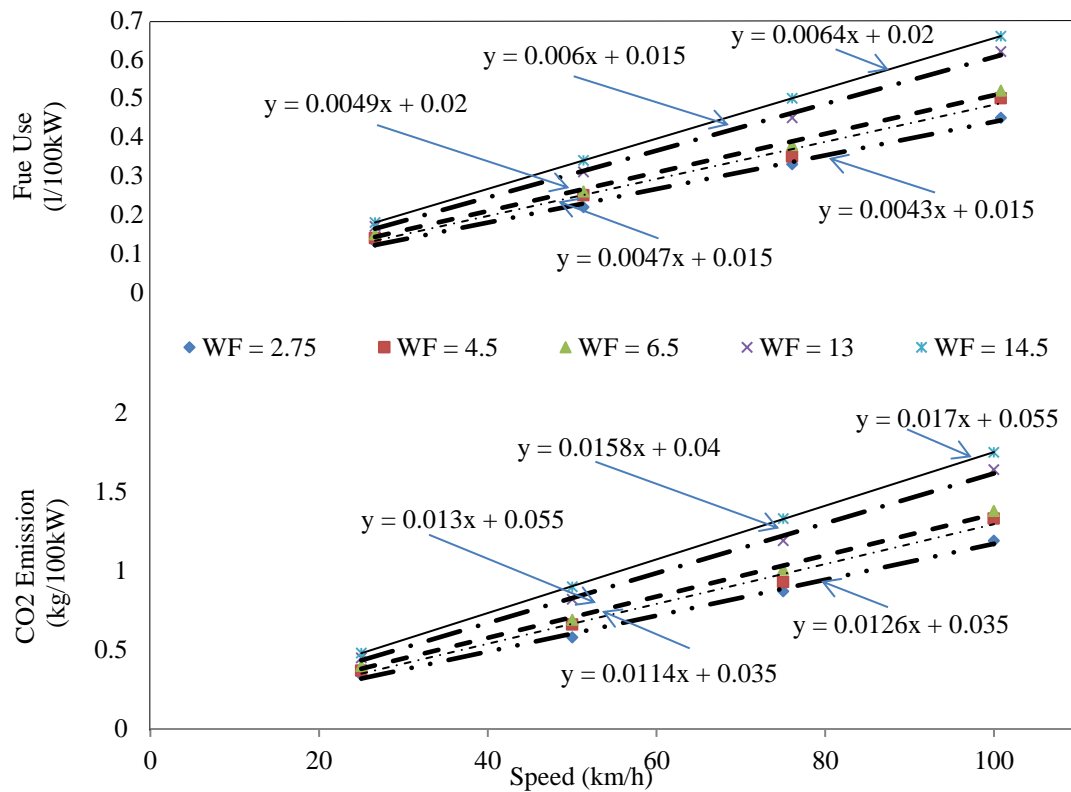
Figure 5. The fuel use and CO_2 emission due to stop of equipment with different WF values

The analyses were undertaken on various experimented equipment pieces. The effect of WF parameter was also taken into consideration in the data analysis process. In the calculations presented in Figure 4, it was assumed that during deceleration step to stop, the gas pedal is not pressed and EL is around 20% (like idling mode). Also, vehicles have three minutes stop, and then they start moving with the acceleration rate of 0.5 km/h.s to reach their previous speed. These assumptions have been made based on conducted observations, and it has been tried to simulate normal stop conditions of construction vehicles.

The equipment's speed and WF are the two main parameters influencing the additional fuel use and emissions in a stop. As shown, there is a highly-correlated direct linear relationship among vehicles' speed, WF and fuel use and emissions production. The additional fuel consumption and CO_2 emission due to stop vary from 0.13 l/100kWh and 0.35 kg/100kWh for the vehicles with the speed of 25 km/h and WF of 2.75 to 0.66 l/100kWh and 1.75 kg/100kWh for equipment with the WF of 14.5 driven with 100km/h speed. It shows the significant effect of vehicles' stop that must be considered by equipment's operators as a reduction scheme to lower fuel use and emissions at the operation level.

5 Conclusions

The construction industry is regarded as one of the major contributors to global energy consumption and GHG emissions due to the large engine size of involved equipment. Despite the significance, there is a lack of comprehensive schemes to indicate the effect of traffic conditions on extra fuel use and emissions production of construction equipment. Such guidelines can be broadly used by traffic planners and equipment operators to decrease the used fuel and emitted pollutions of construction vehicles. This research focused on modeling the effect of traffic conditions on fuel use and emissions of on-road construction equipment by analyzing collected field data and using devised fuel use and emission models.

As three prime parameters for modelling the traffic conditions, the effect of driving speed, idling time and full equipment stop on fuel use and CO_2 emission was investigated. To do so, the fuel use and CO_2 emission production of vehicles in idling operation mode were estimated using devised models. The analysis of raw data indicated that around 9% of used fuel and consequently produced CO_2 emission of construction vehicles are in idling mode showing the importance of lowering idling time

of equipment as a parameter representing traffic conditions. The impact of equipment's full stop on additional fuel use and CO_2 emission was also investigated. The achieved results indicated that by trying to have fewer stops during moving and hauling operation modes, up to 0.66 l/100kW fuel is saved and 1.7 kg/100kW CO_2 is produced less per each stop.

As the future study, this research aims to develop different fuel use and emissions reduction strategies and schemes at operational, equipment and planning level including trailer configuration, equipment's compatibility and engine upgrading to be used machinery manager, project manager and equipment worldwide as guidelines to deliver greater fuel efficiency and more sustainable operations.

References

[1] EPA. Office of Transportation and Air Quality, EPA NONROAD model updates, EPA-420-F-09-020, Ann Arbor, MI., 2009.

[2] Azzi M. Duc H. and Ha Q.P. Toward sustainable energy usage in the power generation and construction sectors-a case study of Australia. *Journal of Automation in Construction*, 59: 122-127, 2015.

[3] Avetisyan H.G. Miller-Hooks E. and Melanta S. Decision models to support greenhouse gas emissions reduction from transportation construction projects. *Journal of Construction Engineering and Management,* 138 (5): 631-641, 2012.

[4] Barati K. and Shen X. Operational level emission modelling of on-road construction equipment through field data analysis, *Journal of Automation in Construction,* (72):338-346, 2016.

[5] Lewis P. Rasdorf W. Frey C. Pang S.H. and Kim K. Requirements and incentives for reducing construction vehicle emissions and comparison of non-road diesel engine emissions data sources. *Journal of Construction Management and Engineering,* 135(5): 341-351, 2009.

[6] Barati K. and Shen X. Modelling emissions of construction and mining equipment by tracking field operations, In *Proceeding of 32nd International Symposium on Automation and Robotics in Construction and Mining*, pages 478-486, Oulu, Finland, 2015.

[7] Kaboli A.S. and Carmichael D.G. Emission and cost configurations in earthmoving operations. *International Journal of Organization, Technology and Management in Construction,* 4 (1): 393-402, 2012.

[8] Barati K. and Shen X. Comprehensive methodology for emission modelling of earthmoving equipment. In *Proceeding of 33rd International Symposium on Automation and Robotics in Construction and Mining*, pages 538-546, Auburn, United States, 2016.

[9] EPA. Clean Air Act Advisory Committee, Recommendation for reducing emissions from the legacy diesel Fleet, Washington, D.C., 2006.

[10] Barati K. and Shen X. Optimal driving pattern of on-road construction equipment for emissions reduction. *Journal of Procedia Engineering,* 180: 1221-1228, 2016.

[11] Barati K. and Shen X. Fuel use optimization of on-road construction equipment using artificial neural network. In *Proceeding of the Construction Research Congress*, pages 198-207, Louisiana, United States, 2018.

[12] Klein J. Shen X. and Barati K. Optimum driving pattern for minimizing fuel consumption of on-road vehicles. In *Proceeding of the 33rd International Symposium on Automation and Robotics in Construction and Mining*, pages 555-562, Auburn, USA, 2016.

[13] Zegeye S.K. De Schutter B. Hellendoorn J. Breunesse E.A. and Hegyi A. Integrated macroscopic traffic flow, emission, and fuel consumption model for control purposes. *Transportation Research Part C: Emerging Technologies,* 31: 158-171, 2013.

[14] Chen D. Zhang J. Tang S. and Wang J. Freeway traffic stream modelling based on principal curves and its analysis. *IEEE Transactions on Intelligent Transportation Systems*, 5(4), 246–258, 2004.

[15] Ahn K. and Rakha H. The effects of route choice decisions on vehicle energy consumption and emissions. *Transportation Research Part D,* 13(3): 151-167, 2008.

[16] EPA. Office of Transportation and Air Quality, Policy guidance on the use of MOVES for state implementation plan development, transportation conformity, and other purposes, Washington, DC, 2009.

[17] Kaboli, A.S. and Carmichael D.G. Truck dispatching and minimum emissions earthmoving. *Journal of Smart and Sustainable Built Environment*, 3(2), 170-186, 2014.

[18] Barati K. and Shen X. Weight estimation of on-road construction equipment based on operational parameters. In *Proceeding of the 34th International Symposium on Automation and Robotics in Construction and Mining,* pages 294-301, Taipei, Taiwan, 2017.