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# COMPREHENSIVE REVIEW ON EMISSIONS MODELING OF CONSTRUCTION AND MINING EQUIPMENT

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## Abstract

Construction and mining operations generally include off-road equipment working in a load and dump point and a fleet of trucks cycling between these points. The equipment used in such operations consumes large amounts of fuel and produce various air pollutants, which have negative effects on the environment. This issue necessitates the need of reducing the emissions from these operations due to their negative impacts on the environment. Reduction may be via either improvement in technology or management of the operations. In this paper, previous studies on the fuel-based emissions of construction equipment are reviewed and evaluated. Additionally, some research involving the modeling and simulation of these operations is noted. At the end, the optimum points of cost and emission for varying fleet sizes in a case study (this includes an earthmoving operation involving a loader and a variety of trucks) are compared, and suggestions are made for future studies.

## Introduction

One of the environmental impacts of construction and mining operations is the pollutants emitted from machinery and equipment, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides ($NO_x$= $NO+NO_2$) and general particulate matters (PM). Construction and mining equipment and machinery are significant source of air pollution, and produce large amounts of emissions in comparison with on-road vehicles such as automobiles. For example, the amount of PM emitted from a bulldozer with a 175 hp engine is near 500 times more than that of a new automobile (EPA 2005b). The reduction of this pollution will provide a healthier air and decrease environmental problems. Because of the importance of this issue, numerous efforts have been made to estimate and reduce the level of pollutants produced by construction and mining equipment. Government regulations, fuel specifications, engine modifications, and construction fleet management are some approaches have been taken into account to decrease the pollution of such equipment (EPA 2005b).

In this paper, studies comparing emission ratios in government regulations and standards with actual emission data are first reviewed. Then, different types of fuels used in the engines of off-road equipment are assessed the compare the effect of different blends of biodiesel on emitted emissions. This is followed by an introduction to simulation methods that have been used for modelling and analysing the emissions of construction and mining operations. Finally, queuing analysis is used to estimate activity times in an earthmoving operation. By having times and costs, emissions of a loader and a fleet of trucks are estimated and the optimum points of cost and emission are obtained.

## Actual emissions versus regulations

Emissions from off-road construction vehicles presented in regulations and standards are usually quantified based on steady-state engine dynamometer tests, and hence are not representative of actual duty cycle emissions (Marshall et al., 2012; Kim et al., 2012). Estimating emissions on the basis of actual equipment activities is necessary. To address this issue, field measurements were performed by Frey et al. (2008) to obtain insight into the actual emissions of off-road equipment and to compare the emissions of B20 versus petroleum diesel. A portable emission measurement system (PEMS) was used to collect field data and emission rates of 15 off-road pieces of equipment including five backhoes, four front-end loaders, and six motor graders. Each piece of equipment was experimented once on petroleum diesel and once on B20 biodiesel. Emission rates were estimated on the basis of an engine-based and task-oriented approach and quantified with respect to time or fuel consumption. $NO_x$ emission rates for a backhoe according to an engine-based modal fuel use are shown in Fig. 1.

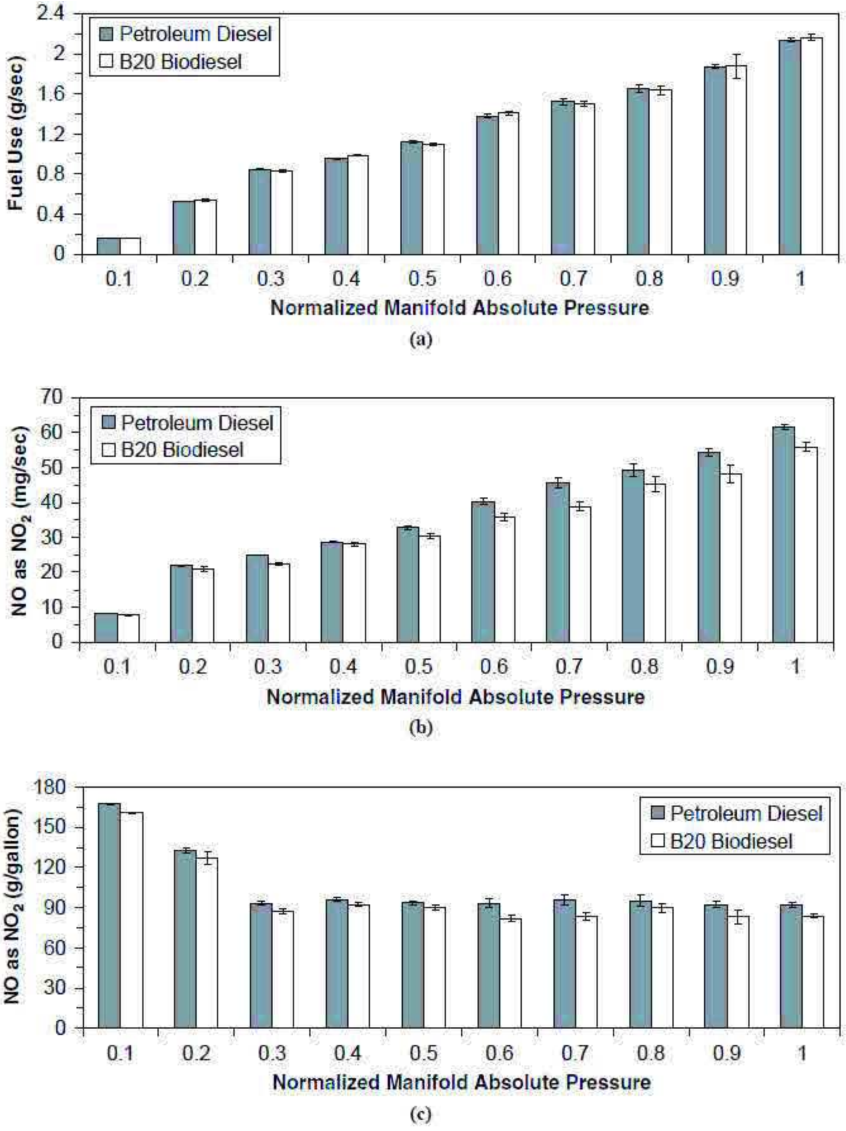
As it can be seen in Fig.1, the fuel use rate for B20 is similar to the fuel use rate for petroleum diesel. This is due to the similarity in energy of these fuels.

Fig.1. Comparison between petroleum diesel and B20 biodiesel of average fuel use and $NO_x$ emission rates for engine-based modes for backhoes:

(a) time-based fuel use rate,

(b) time-based $NO_x$emission rate corrected for ambient temperature and humidity, and

(c) fuel-based $NO_x$emission rate corrected for ambient temperature and humidity. (Frey et al., 2008)



*Source: Comparison of Real-World Emissions of B20 Biodiesel Versus Petroleum Diesel for Selected Nonroad Vehicles and Engine Tiers, Transportation Research Record: Journal of the Transportation Research Board, 2008, p. 33-42.*

Moreover, this figure shows that the NO$_x$ emission rates for lower Manifold Absolute Pressure (MAP) is approximately similar for the two fuels. For a higher MAP, however, the rate for petroleum diesel is a little higher than that of B20. This means that employing construction and mining machinery using B20 fuel will lead to a reduction in NO$_x$ emissions compared with using petroleum-diesel equipment. However, it may increase other emissions such as CO$_2$.In Table 1, average emission factors for excavators are tabulated on the basis of duty cycles, fuel type, and engine tires through collecting field data.

Table 1. Measured fuel-based emission factors for excavators: comparison of tiers, fuels, and duty cycles (Frey et al., 2008)

| Pollutant | Engine Type | B20 | | | | Petroleum Diesel | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | LTC$^a$ | MEC$^b$ | MHC$^c$ | Average | LTC$^a$ | MEC$^b$ | MHC$^c$ | Average |
| NO (g/gallon) | Tier 0 | 118 | 104 | 102 | 108 | 115 | 101 | 98 | 105 |
| | Tier 1 | 83 | 84 | 88 | 94 | 99 | 100 | 104 | 104 |
| | | 87 | 104 | 119 | | 93 | 109 | 120 | |
| | Tier 2 | 96 | 92 | 108 | 97 | 100 | 96 | 110 | 99 |
| | | 94 | 92 | 104 | | 96 | 92 | 105 | |
| Opacity (g/gallon) | Tier 0 | 1.2 | 1.1 | 1.2 | 1.2 | 103 | 101 | 1.3 | 1.2 |
| | Tier 1 | 1.23 | 1.0 | 1.1 | 1.1 | 1.2 | 0.91 | 1.2 | 1.3 |
| | | 1.3 | 0.71 | 0.98 | | 1.6 | 1.7 | 1.3 | |
| | Tier 2 | 0.70 | 0.51 | 0.62 | 0.54 | 0.79 | 0.69 | 0.74 | 0.71 |
| | | 0.50 | 0.46 | 0.47 | | 0.70 | 0.66 | 0.66 | |
| HC (g/gallon) | Tier 0 | 12 | 14 | 15 | 14 | 13 | 16 | 17 | 15 |
| | Tier 1 | 15 | 9.0 | 11 | 8.5 | 15 | 11 | 13 | 10 |
| | | 4.3 | 5.9 | 6 | | 5.6 | 6.7 | 9.1 | |
| | Tier 2 | 3.3 | 3.2 | 3.9 | 5.8 | 8.6 | 11 | 10 | 10 |
| | | 8.3 | 7.1 | 8.8 | | 11 | 10 | 12 | |
| CO | Tier | 86 | 62 | 67 | 72 | 106 | 77 | 82 | 88 |

| | | B20 | | | | Petroleum Diesel | | | |
|---|---|---|---|---|---|---|---|---|---|
| Pollutant | Engine Type | LTC[a] | MEC[b] | MHC[c] | Average | LTC[a] | MEC[b] | MHC[c] | Average |
| (g/gallon) | 0 | | | | | | | | |
| | Tier 1 | 32 | 36 | 32 | 38 | 36 | 39 | 36 | 44 |
| | | 43 | 36 | 46 | | 54 | 45 | 53 | |
| | Tier 2 | 13 | 10 | 14 | 10 | 16 | 16 | 17 | 13 |
| | | 7.9 | 7.1 | 7.7 | | 9.1 | 8.4 | 9.3 | |

[a]LTC: load truck cycle.
[b]MEC: mass excavation cycle.
[c]MHC: material handling cycle.

*Source: Comparison of Real-World Emissions of B20 Biodiesel versus Petroleum Diesel for Selected Nonroad Vehicles and Engine Tiers, Transportation Research Record: Journal of the Transportation Research Board, 2008, p. 33-42.*

‘In-use evaluation of emissions from off-road diesel equipment using biodiesel fuel’ is another study that was done to assess the in-use performance of biodiesel blends in off-road vehicles (Hansen, 2008). Impacts of biodiesel fuel usage were then specified as achievement of this study. Evaluation comprised conducting field experiments on a front-end loader operating over a simple duty cycle. A variety of fuel types including ultra-low sulphur diesel (ULSD), a 50% biodiesel-ULSD blend (B50), and 100% biodiesel (B100) were used to assess the effects of different fuel types. The RAVEM system was utilized to measure gaseous emissions such as $CO_2$, CO, $NO_x$, and PM during the duty cycle. The mean results and the 95 percent confidence intervals for the in-use experimenting based on integrated and modal sampling tests are shown in Table 2. As can be seen, the emission values for PM, $CO_2$, and CO for B100 and B50 fuels are less than the equivalent value for ULSD, whereas $NO_x$ emissions for ULSD are more than $NO_x$ emissions for B100 and B50. The percentage reduction in emissions for B100 and B50 fuels compared to ULSD is shown in Table 3. The integrated data in Table 3 are used to estimate the percentage reduction in PM, $CO_2$, and CO emissions, while the percentage reduction in $NO_x$ emission is calculated by using the modal data.

Table 2. Emissions resulting from field experimentation analysis (Hansen, 2008)

| | | Integrated Emissions | | | | Modal Emissions | |
|---|---|---|---|---|---|---|---|
| | | PM | $CO_2$ | CO | $NO_x$ | $CO_2$ | $NO_x$ |
| B100 | g/test | 0.45 | 8100 | 15 | 110 | 8300 | 110 |
| | g/min | 0.027 | 470 | 0.86 | 6.2 | 490 | 6.5 |
| B50 | g/test | 0.78 | 8700 | 29 | 89 | 8700 | 94 |
| | g/min | 0.046 | 510 | 1.7 | 5.3 | 510 | 5.5 |
| ULSD | g/test | 1.4 | 9200 | 35 | 84 | 9000 | 87 |
| | g/min | 0.082 | 540 | 2.1 | 5.0 | 530 | 5.1 |

*Source: In-use evaluation of emissions from non-road diesel equipment using biodiesel fuel, paper prepared for The NY state energy research and development authority, Albany NY, accessed 9 April 2010 from Google Scholar.*

Table 3. Percentage reduction in emissions in comparison with ULSD fuel (Hansen, 2008)

| | | PM | $CO_2$ | CO | $NO_x$ |
|---|---|---|---|---|---|
| B100 | g/test | 68 | 12 | 59 | 28 |
| | g/min | 68 | 12 | 59 | 28 |
| B50 | g/test | 44 | 5.5 | 19 | 8.5 |
| | g/min | 44 | 5.5 | 19 | 8.5 |

*Source: In-use evaluation of emissions from non-road diesel equipment using biodiesel fuel, paper prepared for The NY state energy research and development authority, Albany NY, accessed 9 April 2010 from Google Scholar.*

Regarding the presented data in Table 3, the percentage reduction from use of the biodiesel fuel for PM, $CO_2$, and CO is more significant compared to B50 fuel. Moreover, the percentage increment from usage of the biodiesel fuel for $NO_x$ is more significant compared to B50 fuel. In other words, although biodiesel will decrease some emissions, its usage will result in the growth in emitted $NO_x$. And so, evaluation of alternative fuels seems to be necessary before used in engines. This is because of the different effects of fuels on emitted pollutants. Furthermore, these results show a larger effect of biodiesel on PM and $NO_x$ emissions than the presented values in EPA studies (EPA, 2007). For example, percent reductions associated with the usage of biodiesel in EPA are 0 to 47% and -10 to 0% for PM and $NO_x$ respectively.

To cover the shortfall in off-road construction and mining equipment experimentation and to provide actual emission data, which are required for precisely modelling emission inventories, the exhaust emissions of diesel-engine off-road equipment were measured and evaluated by Gautam (2002).In this study which was performed for the California Air Resources Board (CARB) and the United States Environmental Protection Agency (USEPA), the exhaust emissions data of four off-road pieces of equipment were recorded during their operation. Next, the engines were removed from the vehicles and installed on engine dynamometer test beds. The engines were then operated under the test cycles prescribed by ISO 8178-6.3 Test Cycles Type C. Comparison of the derived results indicated that the steady-state 8-mode test cycle presented in ISO 8178 does not suitably depict the emissions produced by off-road vehicles. Moreover, it shows that exhaust emissions are very dependent on vehicle type. Thus, to have proper data for emission inventory purposes, a range of vehicle types and models should be tested. The four off-road vehicles including a street sweeper, a rubber-tired loader, an excavator, and a bulldozer examined could therefore not be regarded as being representative of all vehicles which are involved in construction activities.

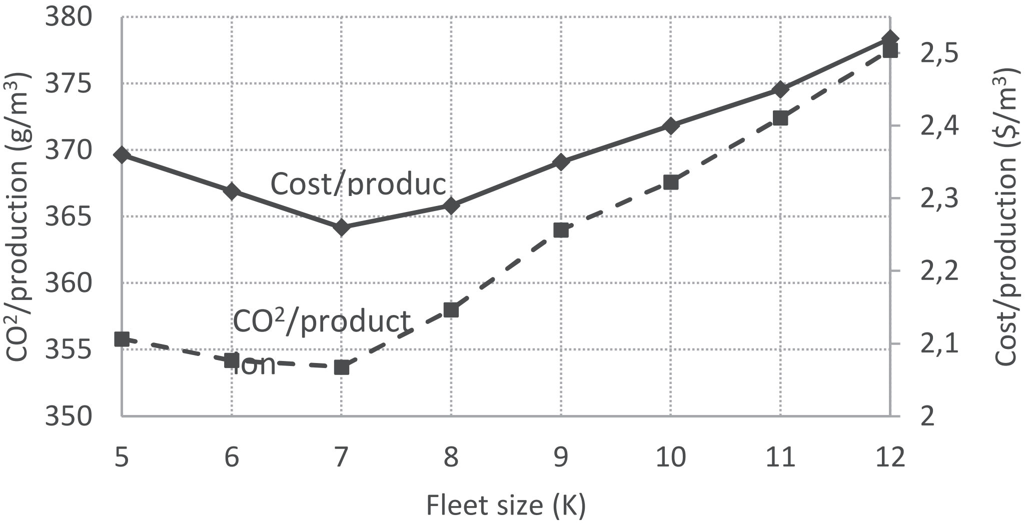
## Emission models

Estimating the emissions of construction equipment will result in better management. Various emission models estimate emissions of construction and miningequipment by multiplying the amount of consumed fuel with coefficients, which are not equipment specific (Ahn et al., 2009), while NONROAD (EPA, 2008b)and OFFROAD (CARB, 2009) models categorize emission rates of each type of equipment based on model years and horsepower group. The last models, also, provide load factor parameters, which are used to calculate emissions using the following equation (EPA 2004).

Emissions = Engine power (hp) * Operating hours (h) * Emission factor (g/hphr) * Load factor (1)

Other emissions models, such as URBEMIS developed by Sacramento Metropolitan Air Quality Management District (Rimpo and Associates Inc., 2007; SMAQMD, 2007), use this information and estimate emissions for land development projects. The models have limitations as a tool for environmental management of a construction operation (Ahn et al., 2009). In 2009, discrete-event simulation (DES) was used by Ahnet al. (2009) to present a model for estimating emissions from construction operations more accurately compared to then current models which used average production rates of equipment. The times of various duty cycles can be estimated by this model. Emissions from various construction equipment are obtained by multiplying these times with emission rates of various duty cycles, as presented by Lewis (2009) for different pieces of equipment. To illustrate the application of DES for estimating emissions, the sustainability of an earthmoving operation was analyzed by Ahn et al. (2009). In that study, two excavators and nine trucks were used to transport excavated soil from two loading places to a dump area. After running the simulations, the emissions of $CO_2$, CO, $NO_x$, HC and PM were estimated for different scenarios and combinations of excavators and trucks. Then the emission cost (emission of various pollutants per cubic meter of soil moved, measured as $g/m^3$) and the unit cost (measured as $\$/m^3$) were calculated and compared under various operation scenarios. For example, the CO2 emission cost and the unit cost for different numbers of trucks are shown in Fig. 2.

Fig.2. The optimum number of trucks for minimizing the emissions (Ahn et al., 2009)



*Source:Sustainability Analysis of Earthmoving Operations, Proceedings of the 2009 Winter Simulation Conference, IEEE, 2009, pp. 2605-2611.*

As plotted in Fig. 2, the optimum number of trucks for minimizing the emissions and the cost is the same in this study. However, this may not be so in other cases. Hence, further investigation is necessary to better understand this and to find a relationship between cost and emissions. However, this study shows, at least for the case studied, that an emission-effective operation can also be cost-effective. As well, the presented method in Ahn et al.'s research enables the designers of construction operations to approximately estimate the environmental impact of these operations in the preconstruction phase (Ahn et al., 2009).

## Parameters affecting emissions

Some theoretical studies have been developed for evaluating the effects of different parameters on emissions of construction and mining equipment. Lewis et al. (2012) presented a methodology for evaluating the impact of idling on fuel use and carbon dioxide ($CO_2$) emissions of diesel construction equipment. Kaboli and Carmichael (2012) examined the influence of heterogeneous fleets, including the effects of operation parameters such as payload, travel and load times, on unit emissions and unit costs in earthmoving operations. Truck dispatching is performed through linear programming (LP) by Kaboli and Carmichael (2013) and the effect of truck allocation on unit emissions and unit costs established.

The influence of a range of operation parameters including truck size, payload, fuel use, and travel and load times is studied by Carmichael et al. (2013). Kaboli and Carmichael (2014) investigated the effect of load time and fleet size on unit emissions, and what the corresponding optimal load time and fleet size might be in an earthmoving operation including scraper and dozer. Their research shows that the optimum scraper load time for unit emissions may be the same or slightly less than that for unit cost depending on the scraper type and operation, while the optimum fleet size in terms of minimum unit emissions, is slightly higher than or the same as that in terms of minimum unit cost.

Kaboli and Carmichael (2016) examined the earthmoving parameters of haul grade, payload and truck type and their little known influence on emissions. By doing so, they considered the assumptions behind, and suggested some improvements in the DRET (Department of Resources, Energy and Tourism of Australia) energy model. The theoretical method used in above research is the basis of the analyses given in the case study in this paper.

## Cost-emissions analysis methods

Several methods including DES, queuing analysis, and conventional factor-modified deterministic methods can be used for analysing construction and mining operations including estimation of cost and emissions. As mentioned above, DES was used by Ahn et al. (2013) for estimating the times of various duty cycles. However, due to limitations such as not being user friendly for operators, and the difficulties in investigating operational variables in factor-modified deterministic methods, queuing theory is suggested as a proper tool for analysing construction and mining operations (Carmichael et al., 2013). This method is analytical based and provides a proper understanding of operational patterns.

Carmichael (1988) used both random sampling and a variance reduction technique to develop a simulation approach and make a comparison with queuing theory for earthmoving, quarrying and open-cut mining. Monte Carlo simulation ideas were applied to establish the overall pattern of earthmoving operations. The approach presented by Carmichael (1988) is numerical-oriented, and can be developed for general multiphase cyclic operations. Easiness of using this approach makes it attractive for engineers; it is also compatible with queuing theory.

As mentioned before, different methods are used for construction and mining operations analysis, but, as noted queue simulation is an easy and proper tool for estimating operation times. The derived results can be used to estimate the costs as well as the emissions of construction fleets; the user is only required to multiply the operation times by emission factors given in regulations and previous studies.

## Case study

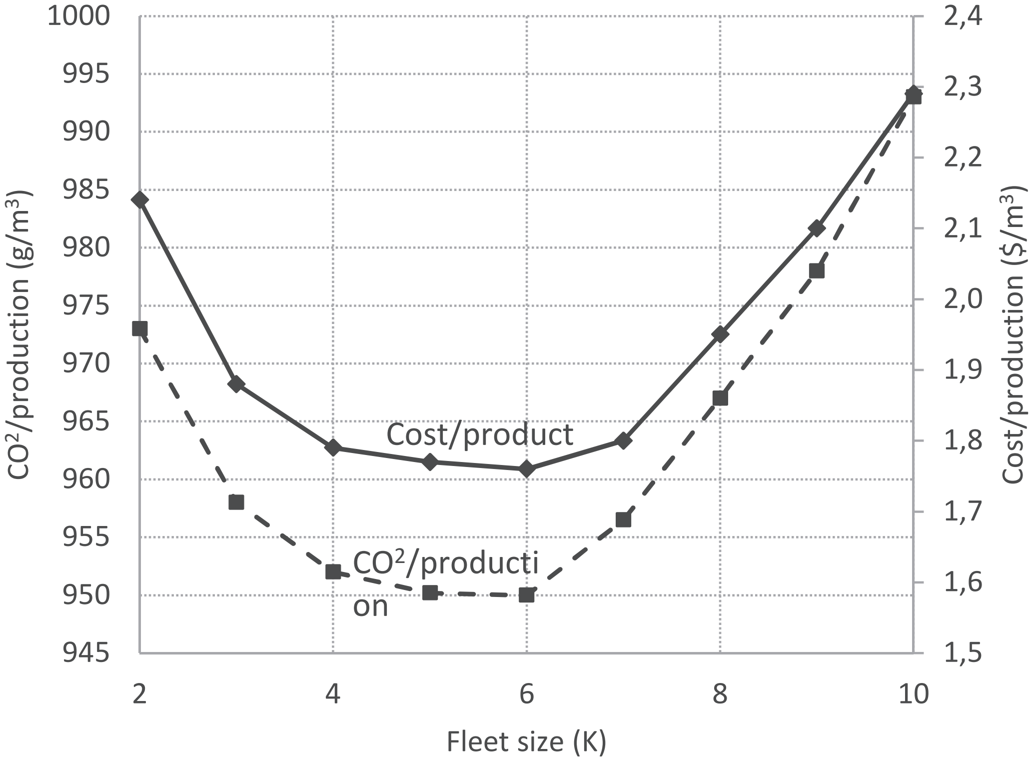
To examine the effects of fleet size on emissions and costs of earthmoving operations, an earthmoving operation involving a loader and trucks (2-10 trucks) is studied here. The case study particulars are presented in Table 4.

Table 4. Case study

| | |
|---|---|
| Loader | Caterpillar 980G |
| Engine | Tier 3 300HP |
| Cost ($/h) | 115 |
| Truck | Caterpillar D30D |
| Engine | Tier 3 285HP |
| Capacity | 15 m3 |
| Cost ($/h) | 90 |
| Service time | 120 sec |
| Back cycle time | 660 sec |

It is assumed that a truck will depart the server (loading place) once serviced, and will haul soil to the dumping area. At some later time, the truck will come back to the server again. Finding the idle and working time of the loader and trucks is necessary in order to estimate the emissions, cost and production of the operation. Queuing analysis is used to estimate the waiting times and cycle times in this study. The average of the exponential (M/M/1)/K and constant (D/D/1)/K queuing models is utilized to obtain the results. The emission factors from Lewis et al. (2009) are used to calculate the emissions of different duty cycles. By doing so, the emission factors of idling and non-idling activities from Lewis' study are multiplied by the fractions of times that each piece of equipment spends in different phases of its cycle.These phases include ‘waiting in queue’ or ‘hauling soil’ for trucks and ‘idling’ or ‘loading truck’ for the loader. The calculation of emissions in (g/h) is performed for all fleet size options. In addition to emissions, the cost of production in ($/h) is calculated by multiplying the cost ratio of the equipment with the fractions of times that each piece of equipment spends in different phases. The emissions and cost, then, are divided by production ($m^3$/h) for all fleet size options. The variation of $CO_2$/production and cost/production with fleet size are shown in Fig. 3.

Fig.3.Variation of $CO_2$/production and cost/production with fleet size.



As can be seen, the optimum point of $CO_2$/production and cost/production occur at 6 trucks. This trend can be seen in other emission types also. In other words, the minimum of emissions/production for other emissions such as $NO_x$, CO, PM, and HC, in this study, will occur when 6 trucks are used for moving the soil. This result shows the possibility that designing an emission-effective operation can be cost-effective also, and this is counter to a common belief that following sustainability requires additional resources.

## Conclusion and recommendations

Because of deficiency in actual data for estimating emissions from construction and mining equipment, field measurements have been undertaken by different researchers to compare actual emissions with equivalent values presented in regulations. A variety of fuel types including ULSD, B20, B50, B100, and petroleum diesel were used in the engines of machinery of various model years and tiers to assess the in-use performance of biodiesel blends in off-road vehicles. Derived results indicate that emissions are very dependent on vehicle type. Thus, to have a better insight about emission inventory, a diversity of machinery types and models needs to be experimented. As a consequence of government regulations and incentive programs, the reduction in emissions of vehicles by manufacturers will follow. Furthermore, managing vehicle fleets is crucial and will result in more reduction of these emissions in future operations. This includes field practices that lead to a reduction of engine idle time. Queue analysis can be used for estimating the times that equipment spends in each phase. By knowing this, construction fleet managers may be able to reduce the emitted pollution of vehicles. The result of this study shows that an emission-effective design can be cost-effective too. However, this result might be different for operations different to that studied. Therefore, finding a relationship between emissions and duty cycles is suggested in this paper will give better insight into reducing the emissions of construction activities.

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