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Alternative Configuration in Earthmoving Operations for Minimizing Unit Emissions and Unit Cost

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Abstract: Earthmoving operations commonly utilize a large range of equipment that generates a considerable amount of greenhouse gas (GHG) emissions. Identifying effective methods to improve the operational efficiency of equipment is important in order to reduce emissions in earthmoving operations. With most of the current efforts in construction have primarily been focused on improving performance in terms of production, cost and duration, this study examines the alternative configuration of earthmoving operations in terms of least unit emissions and minimum unit cost. The Monte Carlo simulation model in conjunction with field-measurement data are used to estimate and compare the optimum fleet size, minimum unit emissions and minimum unit cost for excavator-truck operation. It is demonstrated that by minimizing waiting time through double-sided loading practice leads to a decrease in emissions per production and cost per production in earthmoving operations. The results indicate the most environmentally friendly way to configure and manage earthmoving operations and will be of interest to the contractor who is looking to reduce construction emissions on site.

Keywords: Earthmoving, unit emissions, unit cost, single-sided loading, double-sided loading

1. Introduction

Earthmoving operations typically involve the cycling of trucks, repeatedly hauling between loading (at excavator) and dumping points. A considerable amount of research has focused on estimating earthmoving productivity not only determines the efficiency of operations but also identifies the potential way of minimizing cost and time. Recent attention has shifted to also include a minimum emissions criterion, in attempting to reduce the environmental impact of construction operations. Earthmoving operations commonly utilize a large range of equipment that generates a considerable amount of greenhouse gas (GHG) emissions. According to the EPA Clean Air Act Advisory Committee (CAAAC) [1], all types of off-road diesel engines from construction and mining operations emitted approximately 32% of nitrogen oxide (NOx) and 37% of particulate matters (PM) emissions [2]. Considering the significance of minimizing the environmental impact, there is an identified need to determine the possible way to reduce emissions in earthmoving operations.

A common loading practice can be described as when an operation of excavator-truck utilizes single-sided loading of trucks that requires the following truck to wait for the preceding truck to complete loading and the trucks get loaded fully in turn. In most cases, trucks are loaded on one side of the excavator. However, there are other possible loading practices that have been anticipated to improve the production and efficiency of earthmoving operations such as double-sided loading. For instance, the importance of positioning trucks relative to the loader to minimize maneuver time and maximize haul unit production has been discussed in [3]. In particular, Nunally [4] suggests that maneuver time can be reduced by having two trucks in position at the same time, which is almost similar to having double-sided loading. This

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situation reduces truck waiting time and leads to a reduction in the service time, with a consequent increase in production. Although previous studies have highlighted the advantages of double-sided loading on production [4]-[7], however, the implication of double-sided loading practice on the emissions and cost has not been previously explored. Therefore, this paper aims to examine the influence of loading practice on unit emissions and unit costs.

Using the single-sided loading from case study data as a benchmark, this paper compares production, unit emissions, unit cost, equipment utilizations and optimal fleet sizes between different loading practices of earthmoving operations. Monte Carlo simulation is used to provide the analysis to estimate the changed of unit emissions and unit cost for different truck fleet sizes. A cut and fill operation on a residential construction site provides case study data.

This paper has been divided into five sections. First, the background of study and the computational approach employed in this study are presented, followed by a case study using field measurement data. The next section discusses the effect of loading practice on production, unit emissions, unit cost and equipment utilizations. The final section presents the conclusions.

2. Background of Study

In earthmoving operations, substantial efforts have been made in determining the most appropriate fleet configuration to improve productivity and optimize resources. The analysis of excavator-truck operations has been performed in a number of approaches such as; knowledge-based expert systems [8-10]; discrete event simulation [11], [12]; simulation optimization [13], [14]; linear programming [15]; combined genetic algorithms with simulation [16]- [18]; match factor [19]; queuing theory [20], [21]; neural network [22] and linear regression analysis [23], [24].

The performance of earthmoving operations is influenced by numerous variables. Several established studies have discussed on the significant factors that affecting cost and productivity performance in earthmoving operations namely; payload [25]-[28]; load time [29], [30] and travel time [4], [31]-[33].

There are also some investigations about the loading characteristics that affect the efficiency of earthmoving operations. Peurifoy and Ledbetter [34] highlight the effect of maneuver time on the different truck size. For small truck, more total truck cycle time is lost in maneuvering due to a large fleet of size required to achieve the production. A study conducted by Smith et al. [5] indicate that maneuver time and load time is the most influencing factor that needs to be considered when designing for the maximum output of earthmoving systems. On the other hand, Stubbs [35] and Caterpillar Performance Handbook [36] discuss on the important of positioning trucks and loader to minimize the maneuver time and maximize the haul unit production. Hardy [6] draws attention to the opportunity of double-sided loading that could eliminate or reduce the loss of load time while waiting for truck exchange for loading. Nunnally [4] and Soofastaei et al. [7] propose the execution of double-sided loading to minimize the maneuver time and reduce the waiting time of trucks. Double-sided loading should be adopted to maximize the production and eliminate the truck waiting time in the case where operating conditions and the loading area are able to facilitate the desirable truck location and positioning.

While previous studies discuss on the significant factors affecting earthmoving performance, there is no reference considering the influence of loading practice on the optimum unit emissions and optimum unit cost in earthmoving operation, as covered in this paper.

3. Earthmoving Operation Modelling

The underlying models used in the paper's analysis for single-sided and double-sided loading is based on Carmichael and Mustaffa [37]. Monte Carlo simulation is performed to analyze production, equipment utilizations, unit emissions and unit cost.

3.1 Production

For a single excavator with bucket operation, the number of truck cycles (*NC*) is given as,

$$NC = \zeta - (K + 1) \tag{1}$$

where ζ is the total number of truck cycles and K is the truck fleet size (number of truck). Thus, the total duration (*TD*) is defined as,

$$TD = CUM(\zeta) + B(\zeta) - CUM(K+1) \tag{2}$$

Where $CUM(\zeta)$ is the cumulative time for the total number of truck cycles, *B*(□) is the back cycle time for the total number of truck cycles. The total production (*TP*) is given as,

$$TP = \sum_{NC} PROD(n) = (\zeta - K - 1)CAP \tag{3}$$

where *PROD(n) = CAP* is the capacity of a truck. The total production/unit time $(T_{P/D})$ is given by,

$$T_{P/D} = \frac{TP}{TD} \tag{4}$$

The server (excavator) utilization (η) is the proportion of time that the server is non-idle. It is calculated from,

$$\eta = \frac{\sum_{NC} S(n)}{TD} \tag{5}$$

where *S(n)* is the service time. The truck utilization *(u)* is the proportion of time that trucks are either in service or travelling with respect to total truck cycle time (the proportion of time that the truck is non-idle). It excludes truck waiting time. It is calculated from,

$$u = \frac{\sum_{NC} B(n) + \sum_{NC} S(n)}{K \times TD} \tag{6}$$

where *B(n)* is the back-cycle time.

3.2 Emissions Per Production (Unit Emissions)

The total excavator emissions (TE_L) is calculated from,

$$TE_L = \sum_{NC} E_L(n) \tag{7}$$

where E_L is the emissions of loader and E_T is the emissions of truck. The total truck emissions (TE_T) is calculated from,

$$TE_T = \sum_{NC} E_T(n) \tag{8}$$

The total emissions per unit time $(T_{E/D})$ is given by,

$$T_{E/D} = \frac{TE_L + TE_T}{TD} \tag{9}$$

The total emissions per production is given by,

$$\text{Unit emissions} = \frac{T_{E/D}}{T_{P/D}} \tag{10}$$

3.3 Cost Per Production (Unit Cost)

The total cost per unit time $(T_{C/D})$ is given by,

$$T_{C/D} = C_L + KC_T \tag{11}$$

The total cost per production is given by,

$$\text{Unit cost} = \frac{T_{C/D}}{T_{P/D}} \tag{12}$$

4. Case Study

Site data were collected on cut and fill operation on a residential development construction site. The operation utilized a 1.5 m^3 bucket capacity excavator and five trucks with 9 m^3 capacities each to haul approximately 1.4 km from the loading to fill area. Table 1 shows the result of average truck cycle component times, giving a servicing factor (S/B), for the excavator as the server, of 0.37. The equipment characteristics are summarised in Table 2.

Table 1 - Field-observed truck cycle component times

Truck cycle component	Mean (min)
Queue at load area	3.842
Maneuver at excavator	0.407
Load	1.912
Loaded haul	2.721
Maneuver at dump area	0.411
Dump	0.244
Return	2.872
Backcycle	6.248
Service (at excavator)	2.319

Table 1 - Field study equipment characteristics

Equipment	Truck	Excavator
Engine power (HP)	200	150
Engine tier	2	3
Volumetric capacity (m^3)	9	1.5

5. Results and Discussion

Based on the outlined analysis method and case study data of the previous section, production, unit emissions, unit costs and optimal fleet sizes for different loading practices can be established and compared in this section. Fig. 1 shows the production (expressed as m^3/h) plotted against truck fleet size for both single-sided and double-sided loading, respectively. Single-sided loading, based on actual field data, is a conventional loading policy where the excavator is idle while waiting for the following truck to maneuver into a loading position. With double-sided loading, the following truck arrives and starts its maneuver without having to wait for the preceding truck to finish loading. This approach reduces the idle time and maximizes the utilization of the excavator, which leads to higher production compared to single-sided loading.

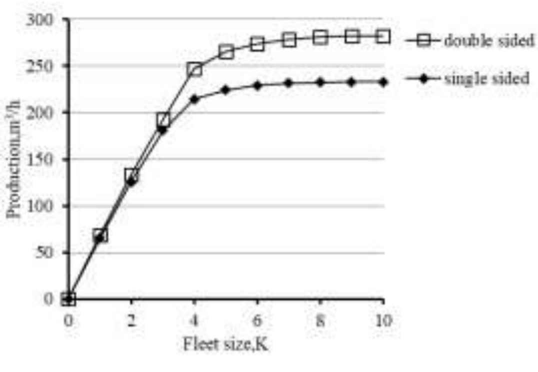

Fig. 1 - Production versus fleet size for different loading practice

A comparison of double-sided and single-sided loading for unit emissions is shown in Fig. 2. In the case of doublesided loading, reducing maneuver time through double-sided loading leads to lower unit emissions compared to singlesided loading.

As shown in Fig. 3, the trend of unit costs is consistent with unit emissions to those observed in Fig. 2. It is discovered that unit emissions and unit costs with the truck fleet size varied. On top of that, the optimum truck fleet sizes for unit cost and unit emissions for double-sided loading being greater than single-sided loading.

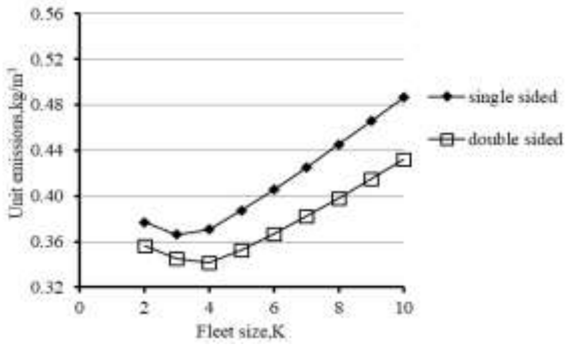

Fig. 2 - Unit emissions versus fleet size for different loading practice

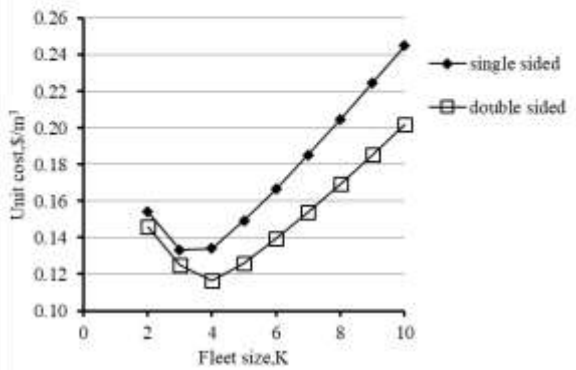

Fig. 3 - Unit costs versus fleet size for different loading practice

It is demonstrated that double-sided loading offers greater effect than single-sided loading practice. The results show that the double-sided loading practice gives maximum production, and results in lower unit emissions and unit cost. However, the implementation of double-sided loading at loading point is governed by a number of factors; including accessible space, site layout and equipment configurations. By having a clear maneuvering area, the following trucks can start maneuvering before the preceding truck completes the loading. The consideration of these factors in the planning stage may ease the implementation of such truck fleet configuration during the operational stage.

Fig. 4 demonstrates the idle and non-idle times of the excavator as a server for both single-sided and double-sided loading, respectively. As can be observed in the same figure, the increase of the fleet size causes the slopes of server non-idle time to increase and their idle time to decrease. Moreover, it is noticeable that the slopes are relatively flat nearing the matched point when the server reaches maximum utilization. This behavior is different from the proportion of truck cycle illustrated in Fig. 5. The truck idle times are observed to be constant at small fleet sizes and increase after the matched point, while the truck non-idle time decreases. Hence, this implies that there is a trade-off between truck and server proportion work-cycle. It is also shown that the truck idle times for double-sided loading are lower than single-sided loading. Notably, the decrease of idle time for trucks due to double-sided loading practice could be anticipated to increase the production and consequently decrease emissions and cost.

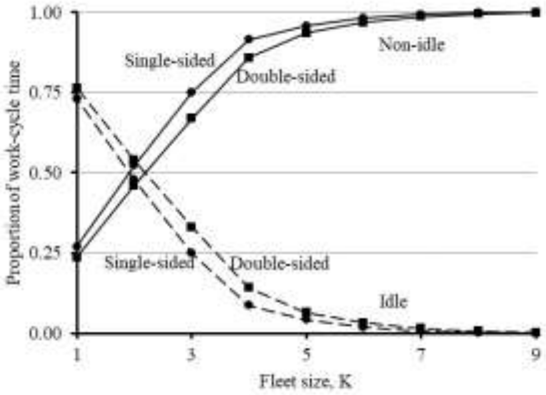

Fig. 4 - Idle and non-idle times of the excavator for different loading practice

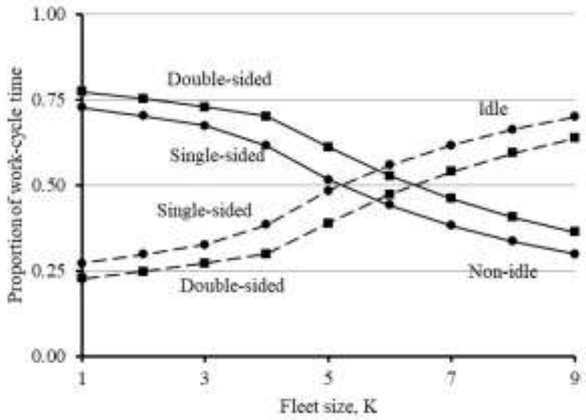

Fig. 5 - Idle and non-idle times of the truck for different loading practice

6. Conclusion

This paper determined the influence of earthmoving loading practice on productivity, optimum truck fleet sizes, unit emissions and unit cost. The Monte Carlo simulation model in conjunction with field-measurement data were used to estimate and compare the optimum fleet size, minimum unit emissions and minimum unit cost for excavator-truck operation. The results demonstrated that the idle time of excavator and trucks was minimized by reconfiguring the loading practice in earthmoving operations using double-sided loading. This unnecessary idling is believed will affect the equipment performance, fuel use, production, unit emissions and unit costs of the operation. It was also demonstrated that minimizing waiting time through double-sided loading practice leads to a decrease in emissions per production and cost per production in earthmoving operations.

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