Emissions, production and cost in construction operations

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EMISSIONS, PRODUCTION AND COST IN CONSTRUCTION OPERATIONS

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A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Abstract

The detrimental effects of carbon emissions on the environment have attracted significant interest from society in solving this matter. Recent attention has turned its focus on the potential emissions reduction in construction operations. In this light, this thesis aims to examine the emissions, production and cost for the purpose of developing the guidelines in reducing emissions.

First, this thesis establishes the quantitative model to measure the attitude of the industry towards emissions through the medium of utility functions. The findings highlighted that construction personnel are risk averse to emissions, but to differing degrees.

Next, this thesis aims to examine the operational strategies in minimizing emissions per production (unit emissions) and cost per production (unit cost) of construction operations. The performance of earthmoving operations, in terms of emissions, production and cost, is dependent on many variables and has been the study of a number of publications. Such publications look at typical operation design and management. To fill this gap in knowledge, this thesis examines alternative loading policies and their influence on unit emissions, production, unit costs and optimum truck fleet sizes. The underlying models developed using Monte Carlo simulation were used for the analysis in conjunction with field data. The findings demonstrate different penalties/bonuses associated with non-standard earthmoving loading policies on production, unit emissions and unit costs. It is also demonstrated that optimum unit emissions and optimum unit cost are coincident with respect to the fleet size for single-sided and double-sided loading policies.

The thesis also investigates the optima coincidence with respect to minimum unit emissions and minimum unit costs in concreting operations. The results demonstrate that the optimum truck fleet size for unit emissions is the same with the unit costs despite the different methods and operation parameters.

Overall, it can be concluded that by minimizing unit cost, as in traditional practice, the least impact on the environment is obtained while not minimizing unit cost will lead to unnecessary emissions.

The importance of this research lies in providing useful insights in assessing the most environmentally aware and economical way to design and manage construction operations in accordance with the sustainability practices.

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PUBLICATIONS

Some of the content of this thesis has been submitted or accepted in the following publications:

No.	Publication Details	Chapter
1	Carmichael, D.G. and **Mustaffa, N.K.** (2018), Emissions and Production Penalties/Bonuses Associated with Non-standard Earthmoving Loading Policies, *Construction Innovation*, Vol. 18, Issue. 2. https://doi.org/10.1108/CI-05-2017-0047 (Published online: 14 February 2018)	Chapter 4
2	**Mustaffa, N.K.** and Carmichael, D.G. (2018), Concreting Operations- The Relationship between Unit Costs and Unit Emissions, *International Journal of Construction Management*, pp. 1-9. https://doi.org/10.1080/15623599.2018.1452095 (Published online: 9 April 2018)	Chapter 6 and 7
3	Carmichael, D.G. and **Mustaffa, N.K.** (2018), Construction Emissions Attitudes – A Utility Measure, *Journal of Construction Engineering and Management,* (Submitted: 29 November 2017)	Chapter 3

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B	backcycle time; the sum of haul, maneuver, dump and return times for each truck cycle
C	owning and operating cost per unit time
C_L	cost per unit time of a loader/excavator
C_T	cost per unit time of a truck
CAP	capacity of a truck
CP	cost per production
CUM	cumulative time measure for each truck cycle
DUR	duration
E	emissions
EP	emissions per production
E[ ]	expected value, mean, average
K	truck fleet size
L, T	subscripts for excavator (loader) and truck respectively
LT	load time
M	maneuver time
n	truck numbering according to consecutive cycles, and not a particular truck identity; $n = 1, 2, \ldots., \zeta$
N, I	subscripts for non-idling emissions per unit time and idling emissions per unit time respectively
NC	number of truck cycles
P, C	subscripts for pump and crane respectively
PROD	production
S	service time; the sum of maneuver time M and load time LT for each truck for each loading; S = M + LT
S_s	service time corresponding to constrained minimum waiting time
TC	total cost
TD	total duration

TE	total emissions
TP	total production
Var[ ]	variance
W	waiting time; the time between a truck arriving at the load point and the time maneuvering to load starts
W_q	average truck waiting time
α	a fraction, $0 \leq \alpha \leq 1$
ζ	total number of truck cycles
η	server utilization (proportion of time the server is busy)
$1/\lambda$	average backcycle time (the sum of times for: empty truck return, queue, maneuver, load/unload, and loaded haul)
$1/\mu$	average service time (the sum of truck maneuver time and load/unload time)

ABSTRACT

The detrimental effects of carbon emissions on the environment have attracted significant interest from society in solving this matter. Recent attention has turned its focus on the potential emissions reduction in construction operations. In this light, this thesis aims to examine the emissions, production and cost for the purpose of developing the guidelines in reducing emissions.

First, this thesis establishes the quantitative model to measure the attitude of the industry towards emissions through the medium of utility functions. The findings highlighted that construction personnel are risk averse to emissions, but to differing degrees.

Next, this thesis aims to examine the operational strategies in minimizing emissions per production (unit emissions) and cost per production (unit cost) of construction operations. The performance of earthmoving operations, in terms of emissions, production and cost, is dependent on many variables and has been the study of a number of publications. Such publications look at typical operation design and management. To fill this gap in knowledge, this thesis examines alternative loading policies and their influence on unit emissions, production, unit costs and optimum truck fleet sizes. The underlying models developed using Monte Carlo simulation were used for the analysis in conjunction with field data. The findings demonstrate different penalties/bonuses associated with non-standard earthmoving loading policies on production, unit emissions and unit costs. It is also demonstrated that optimum unit emissions and optimum unit cost are coincident with respect to the fleet size for single-sided and double-sided loading policies.

The thesis also investigates the optima coincidence with respect to minimum unit emissions and minimum unit costs in concreting operations. The results demonstrate that the optimum truck fleet size for unit emissions is the same with the unit costs despite the different methods and operation parameters.

Overall, it can be concluded that by minimizing unit cost, as in traditional practice, the least impact on the environment is obtained while not minimizing unit cost will lead to unnecessary emissions.

The importance of this research lies in providing useful insights in assessing the most environmentally aware and economical way to design and manage construction operations in accordance with the sustainability practices.

CHAPTER 1 - INTRODUCTION

1.1 Overview

The last two decades have witnessed a growing concern on the effect of climate change all over the world. In response to this, the latest convention known as the 2015 Paris Agreement, which resembles the Kyoto Protocol in 1997, managed to seal global efforts in combating the growing effects of climate change. Global warming and other possible weather characteristics are highly influenced by the increased emissions of greenhouse gas (GHG) (IPCC, 2014) and the construction industry is considered to be one of the major contributors of these GHG emissions. According to EPA (2008a), the construction sector generates a total amount of 131 million metric tonnes of CO_2-e in 2002, making it the third highest sector that releases GHG emissions.

The detrimental effects of GHG emissions on the environment have managed to attract a significant interest from society in solving this matter. According to UNEPSBCI (2009), a number of measures and targets have been initiated by governments and policy makers to allow an efficient decrease in emissions, which include institutional, policy, guidelines and regulatory frameworks. A number of not-for-profit and government as well as semi-governmental organizations and committees exist, along with international efforts to promote carbon emissions reduction and developing emissions standards, databases and reporting mechanisms (Ford, 2013; Jones, 2014; Wilcox, 2015; Cardno, 2015b; Walpole, 2016; Pascall, 2016). In spite of this, contractors have been observed to be slow in implementing emissions mitigation strategies, which is believed to be related to behavioral issues among the organization personnel who have a lack of belief in the real effect of the changes (Wong et al, 2013).

Reducing and mitigating GHG emissions during the construction phase could be considered prudent in improving the environmental performance of construction operations. Thus, it is important for future studies to place their focus on the construction phase instead of only emphasizing the design and operation phase in the effort of reducing emissions (Guggemos and Horvath 2006; Pena-Mora et al., 2009; Bilec et al, 2010; Ahn et al., 2010a; Carmichael et al., 2012; Ahn et al., 2013a; Arocho et al., 2014). Guggemos and Horvath (2006) further draw attention towards the emissions released by construction equipment which constitute half of the total impact from construction processes, thus further suggesting that better control of emissions from construction operations is necessary.

Construction operations commonly utilize a large range of diesel-engines equipment that releases a considerable amount of greenhouse gas (GHG) emissions. For example, EPA (2005a) emphasizes that a bulldozer with a 175 HP engine produces 500 times more particle pollution compared to a new vehicle. Hence, it becomes a priority to determine the suitable methods that can improve operational management practice on site in order to reduce emissions. Recently, a considerable amount of research has been conducted in developing tools that are able to estimate and monitor emissions released by construction equipment (Abolhasani et al., 2008; Lewis, 2009; Ahn et al.,2010a, 2010b; Frey et al., 2010; Lewis et al., 2011, 2015; Rasdorf et al., 2012; González and Echaveguren, 2012; Ahn and Lee, 2013; Zhang et al., 2014). However, there is still limited attention given to emissions released by construction equipment in relation to field production (Carmichael et al., 2013).

Hence, this thesis has examined the construction industry's attitude towards emissions through quantitative measures in order to offer a different view of emissions in the construction industry. This thesis has also examined the operational management strategies for construction operations that have the potential to reduce emissions and cost while at the same time maximizing production. The purpose of this research is to provide useful information that could help in determining the most environmentally friendly and economical approach to design and manage earthmoving operations in accordance with sustainability practices.

1.2 Problem Statements

The following section discusses the three key issues that form the basis for this research.

1.2.1 Lack of quantitative measures on the attitude of construction industry towards emissions

The construction industry is a large contributor to global emissions despite its efforts of becoming more aligned with sustainability practices. Previously, the industry used to focus on cost, production and time, but now adds emissions to this list. Most of the established studies on construction emissions only focused on the causes of large emissions from the industry without considering the importance of instilling positive attitudes to reduce carbon emissions, although pointing to a required urgency to address this (Kulatunga et al., 2006). It is important to understand that attitudes can be formed and changed based on the influence of numerous underlying factors. These factors include behavioral norms, economics, individuals' environmental concerns, ease of implementation of processes and technology, culture of organizations, government attitudes and policies, and public contributions.

Most of the established studies on the construction industry's attitude towards emissions have been conducted qualitatively using surveys, questionnaires and reports, as demonstrated in Fujii (2006) and Giesekam et al. (2016). No publication has attempted to quantify or model industry attitudes to emissions, apart from some nominal statistics. The use of utility functions, as a way of determining people's preferences on emissions, has not been attempted before. Hence, this thesis addresses the existing gap in this field by establishing the quantitative measures and models of industry attitude for the first time using two elements, namely the medium of utility and utility functions. Specifically, utility functions offer the prospect of distinguishing between different people's attitudes, which will be directly incorporated into construction decisions. The implications of this research are demonstrated in terms of unit emissions and unit costs of earthmoving operations.

1.2.2 Alternative loading policies in earthmoving operations

It is important to identify effective methods to improve the operational efficiency of equipment for the purpose of reducing emissions from construction operations. However, most of the current efforts in reducing emissions have focused on technological strategies, with little attention given to operational strategies at site (Ahn et al., 2010c; Ahn and Lee, 2013). Introducing new emissions-improvement technologies which include adopting engine retrofits, replacing engines and using cleaner fuels has the potential to reduce emissions; however, these new technologies may come with an additional cost (Ahn et al., 2010c). In relation to this, EPA (2009) emphasizes that emissions can also be reduced by improving or changing operational practices at site. Apart from reducing emissions, the reconfigurations of operational practice also offer the opportunities to minimize the cost of operation (Ahn et al., 2010c). Avetisyan et al. (2012) draw attention towards the possible measures on emissions reduction in construction which includes reducing equipment idling time. The reduction of engine idling may offer a great opportunity to increase the productivity and minimize emissions caused by construction operations (Ahn and Lee, 2013).

The performance of earthmoving operations depends heavily on equipment utilization and the reduction in equipment idle time. Common practice uses single-sided loading of trucks by excavators or equivalent, where trucks get loaded fully in turn; such operations have been researched extensively in terms of their unit costs (cost/production) and unit emissions (emissions/production) (Ahn et al., 2009; Carmichael et al., 2012, 2014a; Kaboli and Carmichael, 2014a). However, there are other loading policies possible, including double-sided loading, fractional loading and zero waiting time loading. All such policies reduce equipment idle time and associated consumption of fuel and generation of emissions, but have different impacts on production. Using the common single-sided loading policy as a benchmark, this thesis explores the magnitude and nature of any penalties/bonuses in terms of unit emissions and unit costs associated with other loading policies.

It is important to note that the alternative loading policies may affect earthmoving parameters in terms of load, load time, cycle time, idle time and equipment utilization (percentage of time working). However, since these underlying parameters are interrelated with fuel use (and hence emissions), costs and operation production, it is unclear to what extent the alternative loading policies will change these underlying parameters on unit emissions and unit costs outcomes. Therefore, this thesis aims to explore the influence of the underlying parameters on unit emissions and unit costs.

1.2.3 Coincidence of unit emissions and unit cost in concreting operations

A considerable amount of research has focused on estimating production and determining the unit cost involved in earthmoving operations. Recent attention has turned to look at the optimization of fleet configurations based on emissions. Several established studies (e.g. Ahn et al., 2009; Carmichael et al., 2012; 2014a; Kaboli and Carmichael, 2012; 2014a) have demonstrated the coincidence of the optimum fleet size for unit emissions with unit costs for earthmoving operations. The findings of their studies reveal that undertaking earthmoving operations efficiently according to least unit cost tends to result in minimum unit emissions. However, previous studies have not dealt with the optima coincidence for other types of construction operations in terms of minimum unit cost and minimum unit emissions. It is not certain to what extent that managing equipment in terms of minimum unit cost may change the unit emissions of other operations. Therefore, this thesis aims to investigate the relationship between unit emissions and unit costs on concreting operations, including the influence of constraints and operation parameters on the optimum equipment configurations. This thesis seeks to indicate the most environmentally-conscious way to configure and manage concreting operations.

1.3 Research Aims

Three main objectives are developed for this thesis in order to address the research gap. The first objective is to examine the construction industry's attitudes towards emissions and to establish the quantitative measure in evaluating their risk attitude. The implications of this research are demonstrated in terms of unit emissions and unit costs of earthmoving operations. This thesis hopes to provide useful insights for the development of pragmatic measures in reducing construction emissions. The second objective of this thesis is to explore the loading influence as well as to demonstrate the implications associated with alternative loading policies on unit emissions and unit costs in earthmoving operations. The final objective is to investigate the optima coincidence in regard to minimum unit emissions and minimum unit costs and explore the influence of constraints and operation parameters on the optimum equipment configurations in concreting operations. The outcomes of this research are therefore intended to provide useful information in assessing the most environmentally aware and economical approach to design and manage construction operations.

The specific research objectives are described as follows:

1. To explore the attitude of the construction industry towards emissions.

2. To establish quantitative measures in evaluating the risk attitude of the construction industry towards emissions.

3. To explore the loading influence on production, unit emissions, unit costs, and the optimality with respect to fleet size in earthmoving operations.

4. To demonstrate the penalties or bonuses associated with non-standard earthmoving loading policies on unit emissions and unit costs.

5. To evaluate the influence of underlying parameters on production, unit emissions and unit costs with respect to alternative loading policies in earthmoving operations.

6. To examine the optima in terms of minimum unit emissions and minimum unit costs with respect to fleet size in concreting operations.

7. To compare the performance of concrete placement methods on production, unit emissions and unit costs with respect to optimum fleet size.

The research questions are postulated as follows:

1. What is the attitude of the construction industry towards emissions?
2. How can the attitude of the construction industry towards emissions be measured quantitatively?
3. To what extent do the alternative loading policies lead to different unit emissions and unit costs outcomes in earthmoving operations?
4. How much gain/loss in the production, and how much extra/less unit emissions and unit cost are involved in non-standard earthmoving loading policies?
5. To what extent do the different loading policies influence the earthmoving underlying parameters on production, unit emissions and unit costs?
6. To what extent does managing the concreting operations in terms of minimum unit cost change the unit emissions?
7. How can different configurations and operation parameters influence the optima in terms of unit emissions and unit costs in concreting operations?

The research framework and methodology adopted in this thesis are further elaborated in the next section.

1.4 Research Design

A case study approach has been adopted as the primary method for data collection in this research. The case study is used to acquire data and information from construction personnel and operations. A series of field studies on cut-and-fill operations and concreting operations were undertaken on residential construction sites. The field time measurements of equipment cycles were conducted and observed over an extensive period by recording the data both manually and by video. This thesis have adopted the estimating approach of Lewis (2009), Frey and Kim (2009), Hasan (2013) and Peralta et al. (2016) along with the field data to calculate idling and non-idling emissions of construction equipment, whereas DCCEE (2017) have been used to convert the fuel use and electricity usage into greenhouse gas emissions.

The analysis of this thesis has been conducted using several analysis methods which include utility function theory, Monte Carlo simulation and queuing theory. In the case of this thesis, different approaches are adopted in different chapters, depending on the specific purpose of the analysis carried out.

Specifically, utility function has been adopted in Chapter 3 to establish the quantitative measures of industry attitude on emissions. In a review of attitudes related to emissions, it is seen that all publications on the matter are qualitative, relying on surveys, questionnaires or opinions, but these necessarily only give qualitative information, apart from some nominal statistics. Surveys and questionnaires, as are currently used, have their flaws if not done rigorously. The use of utility functions, as a way of determining people's preferences on emissions, has not been attempted before. Utility functions offer the prospect of distinguishing between different people's attitudes, and attitudes being directly incorporated into construction decisions. Without such a measure, attitudes would be difficult to compare (except for extremes in attitude) in any meaningful way. Utility functions are seen as an effective supplement to these qualitative methods because they generate a different perspective on attitudes, namely in terms of categorizing attitude as either risk averse, risk neutral or risk seeking. And, because utility functions can be represented in both mathematical and graphical format, the functions also permit comparisons to be made between different groups of people. By establishing industry attitudes, it may then be possible to gauge any change in attitudes over time, and hopefully improve attitudes over time.

On another note, Monte Carlo simulation has been used to model cyclic construction operations in Chapters 4, 5 and 7. The typical construction operation such as earthmoving and concreting involves the cycling of trucks, repeatedly hauling between loading and unloading points. A queue of trucks may occur while trucks wait at the loading or unloading points, because of variability in the truck cycle component times. Monte Carlo simulation has been used in this thesis to provide the analysis for the cyclic queuing operation although, it is noted that discrete event-oriented simulation or modified finite source queuing theory could also be used. The original recursive relationships, that are amenable to Monte Carlo simulation, are derived to analyse different loading policies and to also include emissions, cost and production for these different policies. The consideration on the choice of computer simulation is reflected by its simple operational procedures, user-friendly and easy to introduce changes into the simulation model (Smith, 1998).

Meanwhile, queuing theory is an established tool for analysing construction operations, and has been used to analyse concreting operations in Chapter 6. The occurrence of queues in concreting operations is considered as common due to the nature of the operations. Concrete delivery and placement have variability due to many unplanned disruptions occurring both on site and in the trucks travelling, and this variability affects production, concreting duration, emissions and costs. Thus, the thesis uses, in particular, a finite source queuing analysis to calculate emissions, cost and production in concreting operations, because of its direct applicability to the operation at hand. Good fits to field data are obtained by averaging the constant (D/D/1)/K case and the exponential distribution (M/M/1)/K (Carmichael, 1989).

Overall, this thesis addresses operational emissions and costs for the existing field equipment set ups. It should be clearly noted that this thesis does not address the issues related to the introduction of new emissions-saving technology such as equipment modifications, utilization of newer equipment or adoption of operator training. Nevertheless, it is believed that the absolute results in terms of unit emissions and unit costs could be further decreased by adopting these possible solutions; however, the relative results presented in this thesis will not change, and the same conclusions will hold.

1.5 Thesis Structure

Figure 1.1 illustrates the overall thesis structure. A broad summary of the key contents of each chapter is highlighted below.

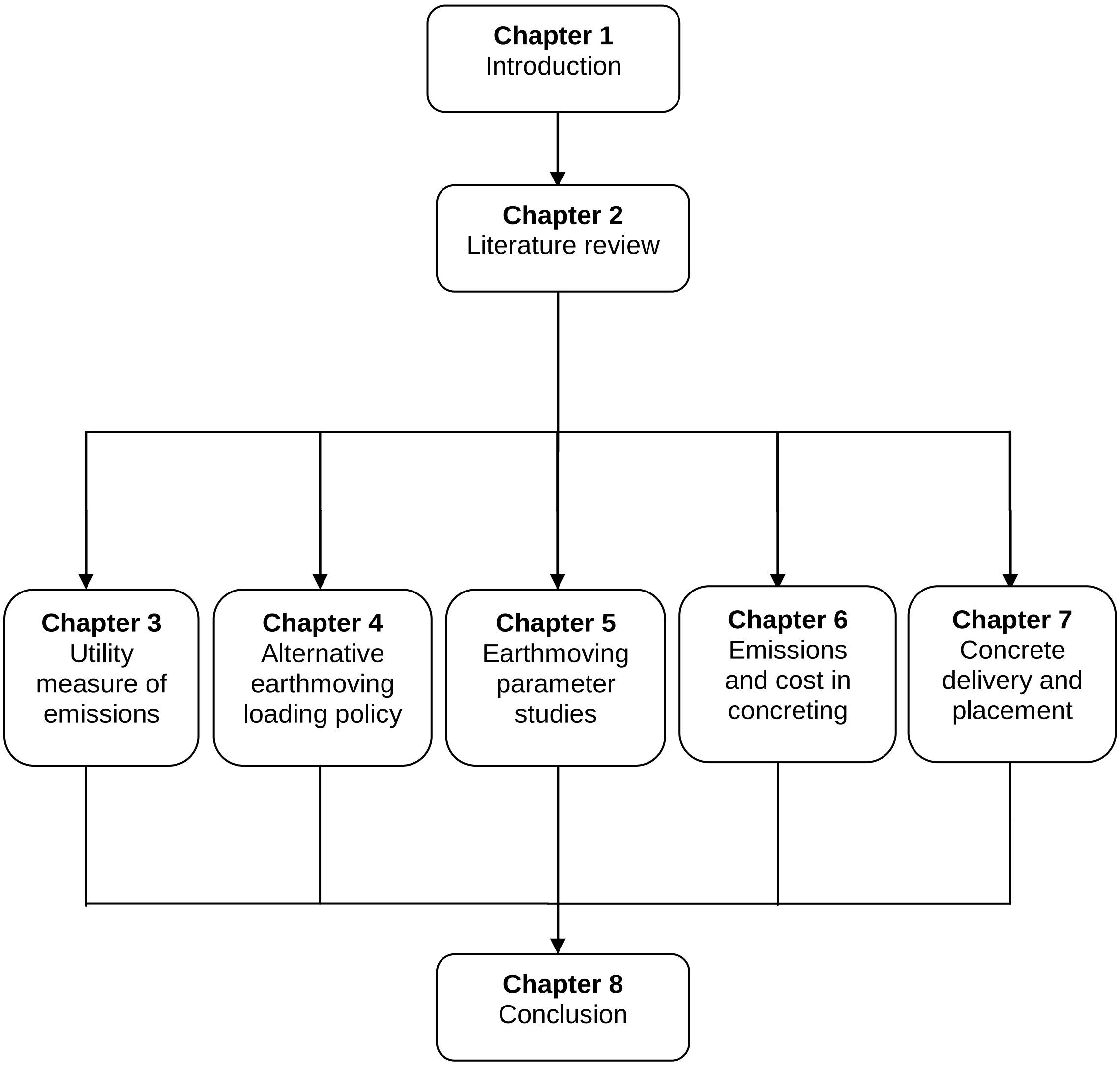


Figure 1.1. Structure of thesis.

Chapter 1 begins with the overview of the background study. The broad issues highlighted in the overview section help to develop the problem statements, research objectives, research questions and research design which are also presented in this chapter.

Chapter 2 initially provides a review on the attitudes of the construction industry towards emissions. The next section discusses the available methods and approaches for estimating emissions from construction equipment. The final section reviews the operational analysis in earthmoving and concreting operations, respectively. The gaps in the current literature are presented at the end of each section.

Chapter 3 starts by highlighting the need for quantitative measures and models of industry attitude with regard to emissions. This chapter presents the current perceptions of the construction industry towards emissions. Following that, the quantitative measures of the industry attitude are proposed to be performed through the medium of utility and utility functions. The implications of this measure are demonstrated in terms of unit emissions and unit costs in earthmoving operations, where the results for differing degrees of risk aversion are highlighted.

Chapter 4 explores the loading influence on unit emissions, emissions or production, unit cost and optimality with respect to the fleet size. This chapter examines the alternative loading policies of zero waiting time loading, fractional loading and double-sided loading in the case of excavator-truck earthmoving operations by comparing their performance with the standard single-sided loading. Original recursive relationships that are amenable to Monte Carlo simulation are derived. Case study data are used to demonstrate the penalties/bonuses associated with non-standard earthmoving loading policies on unit emissions and unit costs.

Chapter 5 examines the effect of varying operation parameters on unit emissions and unit costs for alternative loading policies in excavator-truck operations. This chapter extends the analysis performed in Chapter 4 by incorporating the examination on slight overloading and slight underloading cases. Using the queue simulation approach, this chapter explores the effect of underlying parameters of load, load time, cycle time, idle time and equipment utilization on emissions, cost and operation production. Following that, this chapter evaluates how the alternative loading policies will change the underlying parameters on unit emissions and unit costs outcomes.

Chapter 6 investigates the unit emissions for concreting operations and links it with unit costs and associated optimum equipment configurations. The effects of truck size, unloading policy, travel times, pumping rate, fuel type and fleet size on unit emissions and unit costs are examined. Case study data of concreting operations where trucks cycle between a batching plant and site are used. Queuing analysis is adopted for the computations of production, unit emissions and unit costs for varying operation parameters.

Chapter 7 compares the emissions, production and cost performance of different concrete placement methods in concreting operations. This chapter examines the relationship between production, unit emissions and unit costs with respect to optimum fleet size for placement methods, namely pump and crane. Furthermore, this chapter also compares the equipment utilizations of concrete placement methods. Monte Carlo simulation is used for the analysis in conjunction with the field data. Sensitivity-style analysis is performed by changing several underlying parameters such as server capacity, truck capacity, unloading policy and fuel type.

The purpose of Chapter 8 is to summarize the findings in each chapter and draw conclusions on the practical implications and major contribution of this research to the body of knowledge. Finally, this chapter provides limitations and recommendations for the purpose of future research.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

The first section of this chapter provides a review of the attitudes of the construction industry related to emissions. Section 2.3 discusses the available methods and approaches for estimating emissions from construction equipment. Section 2.4 reviews the operational analysis and operation parameters of earthmoving operations. Finally, Section 2.5 discusses the operational analysis and the influence of factors involved in concreting operations. The gaps in the current literature are presented at the end of each section.

2.2 Attitudes of Construction Industry on Emissions

In a review of attitudes related to emissions, it is seen that all publications on the matter are qualitative, relying on surveys, questionnaires or opinions. No publication has attempted to quantify or model these attitudes, apart from some nominal statistics. This thesis addresses this shortfall.

The following reviews articles where the construction industry's attitudes to emissions might be found directly or implied. These articles include published surveys, academic journals, industry magazines and reports. Attitudes themselves are formed and changed based on many underlying factors. These factors include behavioral norms, economics, individuals' environmental concerns, ease of implementation of processes and technology, the culture of organizations, government attitudes and policies, and public contributions. There is an extensive literature on this, and hence it is not possible to cite everything; rather, a selective, yet comprehensive, sample of articles is cited.

2.2.1 Emissions reduction

There are positive attitudes towards the reduction of industry emissions, but this comes with a reported lack of uniform effort (Kulatunga et al., 2006). Many suppliers are said to be engaged and working towards the mitigation of their emissions (with many having set reduction targets), investment in reduction initiatives, and reporting on cost savings (Ford, 2013). Parts of the construction industry are said to be demonstrating a strong commitment to reductions (Lu et al., 2016). Attitudes are found to be different between different professional groups (Kulatunga et al., 2006; Chong et al., 2009), and the willingness of industry to manage and report their emissions varies between different groups (Ford, 2013). Different countries have different perspectives, with Europe appearing to show stronger concern for the environment compared to other regions (Bigerna et al., 2017).

Many professionals believe that regional targets for emissions reductions are unlikely to be achieved; however, they see value in the setting of goals. People believe incremental change (rather than radical change), regulatory requirements, as well as appropriate processes and incentives, are effective and essential in enforcing the mitigation of emissions (Giesekam et al., 2016). An allocation of responsibility for quantities of carbon emissions is also believed to be required. The survey of Giesekam et al. highlights that architects, clients and civil engineers have the most control over the selection of materials and construction methods, and hence the quantity of carbon emissions. Despite this, it is difficult to directly assign one party to having direct responsibility, due to interaction between the parties. The survey highlights that participants believe that responsibility should be allocated as a collective group. The survey also suggests: people should select the more sustainable materials because they are morally obliged to or are driven by client demands; and people believe that the ‘regulation of limiting embodied carbon’ (Giesekam et al., 2016, p. 434) as well as the reduction in costs are important incentives towards the use of alternative materials in the future. Yet, it is considered a challenge to consider emissions in design and construction while simultaneously doing what society expects professionals to do, namely to design, build and operate safe and reliable infrastructure (Walpole, 2016).

Non-monetary or non-legal motivation for emissions reduction may come from improving the image of companies through the recognition of environmentally friendly procedures, the raising of awareness of emission-related issues to subcontractors, the 'standardization of environmental management procedures', as well as the gaining of confidence from clients (Zeng et al., 2003, p. 107). 'There are some indications that some short-term goals are adversely affecting long-term results' and as a result of this, long-term goals should have higher priority in order to deal with emissions reduction in the most effective manner (Trusson, quoted in Cardno, 2015a).

2.2.2 Monitoring and managing emissions

Most organizations appear not to monitor emissions of their suppliers, while acknowledging that managing their carbon emissions is going to become a 'bigger priority' (Achilles, 2015, p. 2). The monitoring and management of emissions, within companies, seems to be limited (Edeoja and Edeoja, 2015). The analysis of Edeoja and Edeoja implies that the general awareness of the impact of greenhouse gases can be deficient, with organizations still lacking people directly managing carbon emissions. The survey of Chong et al. (2009) highlights that the majority of construction stakeholders agree on the concept of sustainability, while admitting that their organizations' commitments toward sustainability are low. Contractors have been observed to be slow in implementing emission mitigation strategies (Wong et al., 2013). Walpole (2016) believes that the mindset of engineers has to change. Lupp et al. (2016) highlight that stakeholders only take action towards emissions reduction if there are positive stimuli and outcomes.

The quantity of emissions involved follows from the construction method employed. For example, how materials are manufactured and transported is different from on-site construction to off-site prefabrication (Mao et al., 2013). Contractors have the potential to influence the quantity of emissions released during processes occurring on site; however, they do not have much influence over other factors, such as the selection of materials, which is primarily decided by the architects and designers. EPA (2009, p. 2) believes that emissions could be substantially reduced 'if a large number of small GHG emissions sources within the construction industry were to adopt energy and climate-conscious practices'. Florez et al. (2013) argue that despite the increasing availability of information on sustainable materials, there is a lack of agreement between researchers on the suitability of this information.

Nevertheless, over time, there has been an increase in the usage of cleaner fuels, an increased usage of more efficient technology, driver training, as well as people developing higher environmental standards (Nejat et al., 2015; Jukic and Carmichael, 2016). There is significant momentum in providing environmental product declarations (verified documents that give information on life cycle environmental impacts of products), citing three reasons for this including: 'a growing demand for green construction projects, a growing demand for actual proof of environmental claims, and advancements in the technologies used to verify environmental product declarations' (Deitz, quoted in Witcher, 2013).

2.2.3 Cost

Generally, findings show that cost or perceived cost is the greatest barrier to the implementation of more sustainable materials and less emission intensive construction processes (Giesekam et al., 2016; Cardno, 2015a). Zeng et al. (2003) identify financial burden and poor rates of return as the major barriers. However, Giesekam et al. (2016) establish, through surveys, that people perceive, rather than know, that sustainable materials are more expensive than conventional materials. Clients and professionals tend to focus on the economics, quality, and functionality of projects, rather than environmental concerns because there are no clear short and medium term consequences (Giesekam et al., 2016). Marginal abatement cost curves (MACC) attempt to address this (Carmichael et al., 2014c). Although the introduction of sustainable technologies could bring long-term environmental benefits and cost savings, low demand is hindering technologies from becoming economically competitive (Chong et al., 2009). Related to cost is frugality, an individual's concern for the economical and reduced use of resources, rather than their concern for the environment, with a positive impact on the environment being an incidental by-product (Fujii, 2006).

If behavior (towards emissions) is perceived as being difficult to execute, or the cost associated with the behavior is perceived as high, the behavior may not be attempted even if the motivation to do so is present (Fujii, 2006).

2.2.4 The environment

A person's environmental concern or 'awareness of consequences' can 'induce a sense of responsibility' in a personal or moral manner, and enable them to behave in a pro-environmental way. Concern for the environment depends on a person's disposition and concern for consequences of their behavior. People may also feel guilt when contributing large amounts of greenhouse gases (Fujii, 2006, pp. 262, 266). Yip (2000) argues that another dimension of construction management, namely the environment, needs to be added to the conventional dimensions of time, quality and cost.

2.2.5 Organizational culture

The culture of an organization, representing its values, can dictate the practices and approaches a company utilizes with regards to emissions and emission-intensive methods, and such values may be difficult to change (Wong et al., 2013; Giesekam et al., 2016; Thompson, 2016).

2.2.6 Government policies

Government policies can impact industry attitudes and bring about behavioral change. For example, introducing a cost or tax for carbon emissions, environmental awards, or energy standards could be anticipated to influence organizations to pursue more environmentally friendly options and hence reduce their emissions (Wong et al., 2013; Anthonissen et al., 2015; Bigerna et al., 2017). Osmani et al. (2008), Bigerna et al. (2017), Cardno (2013) and UNEPSBCI (2009) argue that positive incentives (subsidies, awards, tax rebates, grants and loans), rather than penalties, are more effective in changing behavioral attitudes. Nejat et al. (2015), on the other hand, believe making something mandatory not only forces industry to reduce emissions, but also raises awareness and promotes the development of new technologies.

Regulations and standards are seen as effective motivators for companies to look at carbon emissions (Wong et al., 2013; Giesekam et al., 2016; Zeng et al., 2003). Lu et al. (2016), however, believe that there is still a lot of investigation required on construction industry emissions in order to develop relevant and appropriate regulations.

Governments also contribute to industry attitudes through funding and uncertainty in funding of emissions mitigation practices, and also through fragmentation of political interests on the subject (Shen, 2015).

2.2.7 The public contribution

A number of not-for-profit and government and semi-governmental organizations and committees exist, along with international efforts, promoting carbon emissions reduction, and developing standards, data bases and reporting mechanisms (Ford, 2013; Jones, 2014; Wilcox, 2015; Cardno, 2015b; Walpole, 2016; Pascall, 2016).

2.2.8 Gaps in current research

The survey papers mentioned above result from an attempt to determine the construction industry's attitudes towards emissions. Generally, they only give a qualitative impression of attitudes, apart from some nominal statistics. No quantitative view or model of industry attitudes to emissions exists. The use of utility functions, as a way of determining people's preferences on emissions, has not been attempted before. Utility functions offer the prospect of distinguishing between different people's attitudes, and attitudes being directly incorporated into construction decisions.

2.3 Emissions Estimation

Recent attention in the construction industry has shifted to emissions because of the industry's large energy consumption, associated greenhouse gas (GHG) emissions, and society's desire to reduce environmental impacts. Hence, there has been a constant demand that urges environmental impact resulting from the construction operations to be strictly minimized. As a result, a wide range of relevant extensive rules, regulations and guidelines have been introduced to monitor and measure the emissions. For instance, the Environmental Protection Agency (EPA, 2008b) and the California Air Resources Board (CARB, 2009) have introduced emission inventory models respectively known as NONROAD and OFFROAD with the purpose of providing a database to estimate the emissions for various types of construction equipment.

There are a number of published studies on estimating emissions from earthmoving operations using real-world emissions measurement. The field-based studies include those conducted by Frey, Rasdorf, Lewis, Abolhasani, Kim, Pang, Marshall, and Hajji (see Lewis et al., 2009, 2012, 2015). Additionally, construction emissions have been incorporated into earthmoving calculations through several means which include typically discrete-event oriented simulation (Peña-Mora et al., 2009; Ahn et al., 2009, 2010a, 2010b; González and Echaveguren, 2012; Ahn and Lee, 2013; Zhang et al., 2014), equipment tracking system (Heydarian and Golparvar-Fard, 2011; Ahn et al., 2013b), carbon calculator (Sihabuddin and Ariaratnam, 2009; Hughes et al., 2011), multilinear regression (Lewis and Hajji, 2012; Hajji and Lewis, 2013) or queuing analysis (Carmichael et al., 2012, 2014a; Kaboli and Carmichael, 2012, 2014b).

Several attempts have also been made in developing a model that could estimate the fuel consumption of construction equipment. According to Klanfar et al. (2016), alternatively, equipment fuel consumption can be estimated according to the specific fuel consumption, rated engine power and engine load factor despite relying on actual field measurement. Kecojevic and Komljenovic (2010) establish a relationship between fuel consumption, power and engine load factors of the earthmoving trucks. The findings reveal that the fuel consumption of the truck is very dependent on two elements, namely power and engine load factor. Baucom (2008) also suggest that the fuel consumption rate for the truck is directly related to power utilization. Lewis (2009) performs field measurement to develop a model for estimating emissions of construction equipment. In this approach, the engine load is divided into different modes to determine the fuel use and emissions for different work cycles. The fuel use and emissions values for various engine power and engine tiers can be calculated using the developed equations. Several studies have adopted Lewis's approach in determining the emissions of earthmoving equipment (Ahn et al., 2009; Ahn and Lee, 2013; Kaboli and Carmichael, 2012).

However, the focus of all these publications is limited to earthmoving and does not consider concreting equipment. A significant study, related to emissions associated with concreting equipment, is given by Frey and Kim (2009). Fuel used in two different blends and emissions generated from the work cycle of the trucks (loading, hauling, unloading and idling) are measured using a portable emission monitoring system. Trucks at the unloading point generate more emissions than at the batching plant.

Cranes traditionally have been used for placing concrete in high-rise buildings. In this context, the operation of cranes is generated using electricity power which in turn may come from burning fossil fuels. A process of burning these primary energy sources to generate electricity in operating cranes indirectly produces a large amount of greenhouse gas emissions. Hasan (2013) establishes a method to estimate the emissions of cranes based on idling and non-idling time field use data. In concrete placement, a crane is considered non-idling when the engine is in full-throttle during uplifting, holding and down-lifting the bucket. The time spent by a crane during bucket loading is regarded as idling.

DCCEE (2017) develops a framework for estimating the emissions associated with equipment fuel use. The amount of emissions is calculated by multiplying the actual fuel use with a fuel-specific energy content factor and a fuel-specific emissions factor. The total greenhouse gas emissions in carbon dioxide equivalents (CO_2-e) are determined by summing the greenhouse gases contributions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). For electricity generation, the consumption of electricity is obtained from the main electricity grid. The emission factor is given in kgCO_2-e per kilowatt hour to convert electricity usage into total greenhouse gas emissions.

This thesis adopts the estimating approach of Lewis (2009), Frey and Kim (2009), Hasan (2013) and Peralta et al. (2016) along with the field data to calculate idling and non-idling emissions of construction equipment, whereas DCCEE (2017) is used to convert the fuel use and electricity usage into greenhouse gas emissions. It is worth to note that different estimation approaches are adopted in different chapters, depending on the purposes.

2.4 Earthmoving Operations

This section attempts to provide a brief overview covering earthmoving operational analysis, earthmoving underlying parameters and finally draws attention to the gaps in current research.

2.4.1 Operational analysis

Most studies on truck-excavator operation to-date have focused on maximum production and minimum cost criteria. Most approaches adopt deterministic thinking, while acknowledging the presence of variability or uncertainty. A range of quantitative techniques have been used. Table 2.1 provides a summary of various techniques that have been adopted in earthmoving analysis. Different approaches are adopted in different studies, depending on the personal preference and analysis purposes (Blackwell, 1999; Hardy, 2007; Chanda and Gardiner, 2010). Burt and Caccetta (2014) review the advantages and disadvantages of some of these approaches.

Authors	Techniques/tools
Alkass and Harris, 1988; Amirkhanian and Baker, 1992; Kirmanli and Ercelebi, 2009	knowledge-based expert systems
Smith et al., 1995; Morley et al., 2013b; Shawki et al., 2015	discrete event simulation
Cheng et al., 2010; Alshibani and Moselhi, 2012a	simulation and optimization
Easa, 1987	linear programming
Marzouk and Moselhi, 2004; Shawki et al., 2009; Hsiao et al., 2012	combined genetic algorithms with simulation
Burt and Caccetta, 2007	match factor
Carmichael, 1987; Alkass et al., 2003	queuing theory
Shi, 1999; Chao, 2001	neural networks
Smith, 1999a; Han et al., 2008	linear regression analysis

Table 2.1 Techniques/tools adopted in earthmoving analysis.

Recent attention has shifted to also include a minimum emissions criterion, in attempting to address the construction industry's large energy consumption and associated greenhouse gases (GHG) generation, and a call from society to reduce the environmental impact of construction operations. Carmichael et al. (2014a) show that the traditional practice of managing an operation at minimum unit cost also results in minimum unit emissions. Jukic and Carmichael (2016) demonstrate the benefits of a driver-training program in reducing emissions and cost.

2.4.2 Earthmoving underlying parameters

The section draws on literature covering the underlying components, namely payload, load time, travel time and fleet size of earthmoving operations.

Payload

Several studies have supported slightly overloading a truck. Chironis (1991) claims that an overloading of a truck might increase the production as well as reduce the unit cost of operation, despite the slight increase in truck cycle time and fuel use. According to Smith et al. (1995), an overloaded truck with an extra bucket can be beneficial in terms of production when the backcycle time is larger and the increased payload never exceeds the truck limit. Similarly, a study on the effect of payload on production conducted by Schexnayder et al. (1999) suggests that the increased payload leads to the increase in production; but it must not exceed the truck's capacity. However, Hardy (2007) argues that the overloading of trucks at some moderate degree will increase the production but with penalties of increased unit cost due to the accelerated rate of truck wear-and-tear. Meanwhile, Ibrahim and Moselhi (2014) suggest that the trucks must be loaded close to their rated capacity to achieve maximum efficiency of the operation. An overloaded truck will result in higher fuel consumption, shorter tire life and increase component failures. Kaboli and Carmichael (2016) appear to be the only commentary on benefits from overloading trucks to fuel use and emissions. They compare the estimation model with the observed data of DRET (2011), with the result showing that a slight overloading of trucks tends to produce better emissions outcomes compared to the fully loaded trucks, but subject to the concerns of maintenance and equipment reliability.

Caterpillar Inc. (2011) establishes a payload management guideline known as '10/10/20 policy' that 'distributes truck payload over a set period of time to address risks associated with overloading' (Humphrey and Wagner, 2011, p.144). Furthermore, this policy also emphasizes the underlying risk caused by the overloading that exceeds the 120% target payload. On another note, Humphrey and Wagner (2011) suggest that the increase of load is considered acceptable if the performance of the trucks remains consistent on average and within the rated levels. They also refer to two particular standards in regard to payload management, listed as follows: (1) ISO 3450 (1996) subject to braking certification, and (2) ISO 5010 (1992) subject to steering certification. In this case, both certifications require a truck to only be loaded to its maximum payload to prevent any damage to the truck and for safety purposes. The advantages of the latest technologies for payload measurement devices, developed to determine the accurate payload weight on site, are further discussed in Vickers and Boyle (2008) and Ibrahim and Moselhi (2014).

From an underloading perspective, Smith et al. (1995) discuss the implication of underloading practice with the purpose of compensating truck waiting and that loader operators will do this instinctively in such cases. Hardy (2007) argues that the underloading of trucks produces better value in unit costs compared to overloading. He further added that reducing the truck length queue by sacrificing bucket pass will enhance the productivity and provide more cost benefits.

Load time

Several published studies highlight the increased significant of the loading influence. Smith et al. (1995, p. 395) analyze the influential factors in earthmoving operations. Interestingly, the findings reveal that '… reductions of 3 seconds per load pass time tend to reduce 9% of the unit cost and increase the production by 11%.' Hence, this further indicates the significant influence of the load pass time on the earthmoving production as well as the unit cost. Gransbergh (1996) concludes that the maximum productivity of earthmoving operation is highly dependent on load and load time. Kannan et al. (1999) propose a simulation model to calculate the load time and load; however, they are not certain about the ability of load-growth curves in acknowledging the variability of the loading activity.

The consideration on both truck maneuver time and load time is important because it is able to reduce the service time, which in turn will increase the production. Hardy (2007) 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. 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 (Smith et al., 1995; Nunally, 2000; Soofastaei et al., 2016a).

Travel time

Travel time is considered as variable time involved in the truck cycle time, which includes the hauling load and the returning of an empty truck. Travel time is dependent on many factors which include haul grades, engine power, gross weight, truck speed, length of haul and haul road design (Dinovitser and Taylor, 1997; Nunally, 2000). In the case of truck payload, the travel time is affected when the average of hauling speed decreases with an increase of payload weight. Soofastaei et al. (2015) stress the effect of truck bunching caused by payload variance, in which the overloaded truck will move slower and delay the faster truck. Moreover, truck bunching may negatively affect the production by increasing the idle time of trucks and loader at the loading facility (Smith et al., 2000).

On top of that, performance handbooks published by manufacturers such as Caterpillar Inc. (2011) and Komatsu Ltd. (2007) provide a guideline that can assist engineers in estimating the travel time of their haul trucks in earthmoving operations. Travel time for both rated and empty load conditions can be determined based on the travel time curves or rimpull curves provided by the manufacturers. However, it is worth noting that the above methods are given for a truck moving uphill. Meanwhile, the retarding curves are used for downhill travel to determine the allowed speed when a truck is descending a grade with a retarder. These manual methods are dependent on the model of the trucks, particularly considering their equipment performance specifications and the average values. Alternatively, Gransbergh et al. (2006) suggest the equation developed by Phelps (1977) in calculating the speeds for the haul and return directions. On another note, Nunally (2000) proposes average speed factor to obtain average truck speed with the purpose of incorporating the acceleration and deceleration factors.

Travel time becomes a determinant factor in earthmoving operations, especially on long hauls. In general, longer haul translates to higher fuel consumption of the truck. Peralta et al. (2016) present an approach to estimate the fuel consumption and emissions of a haul truck. The fuel consumption and emissions for truck cycle times are determined according to truck speed, power requirement, truck load, engine load factor and haul characteristic by incorporating the formulations provided by past studies (Catterpillar Inc., 2015; Runge, 1998; Soofastaei et al., 2008; Kecojevic and Komljenovic, 2010; EPA, 2005b).

Truck fleet size

Harmonizing excavator and truck choice is acknowledged to be necessary for maximum production. Excavator utilization determines production for over-trucked operations (Gransberg, 1996), while truck numbers determine production for under-trucked operations. Morley et al. (2013a) argue that the selection of the truck just to keep the excavator fully utilized may increase costs and reduce operational efficiency.

The optimum fleet selection depends upon a number of characteristics including load, load time, travel time, equipment performance and operating conditions. A substantial amount of research has been conducted in developing computer models in the fleet selection with the purpose of maximizing production and minimizing cost. Farid and Koning (1994), El-Moslmani et al. (2002) and Marzouk and Moselhi (2003) present a simulation package that is capable of automating the selection of earthmoving fleet. Schabowicz and Hola (2007) adopt an artificial neural network for predicting productivity in the earthmoving fleet. Eldrandaly and Eldin (2006) utilize the knowledge-based expert systems for cost estimations. Fu (2013) and Zhang (2008) incorporate the simulation and optimization techniques to generate appropriate truck fleets. Cheng et al. (2011) develop a Petri net model to simulate the factors influencing earthmoving operations. On the other hand, Alshibani and Moselhi (2012b) integrate linear programming (LP), genetic algorithm (GA) and geographic information system (GIS) in solving the fleet optimization problem.

Nevertheless, there are other computer-based methods that could help assist the management of haul truck operation, which include the Fleet Production and Cost

Analysis (FPC) and Truck and Loader Productivity and Costing (TALPAC). It can be summarized that the purpose of developing these commercial software programs is to assist the estimator in selecting the optimum fleets for productivity planning.

Recent attention has turned to also looking at the optimizing fleet configurations based on emissions. Several established studies by Ahn et al. (2009), Carmichael et al. (2012, 2014a) and Kaboli and Carmichael (2014a) demonstrate the coincidence of the optimum fleet size for unit emissions with unit costs for excavator-truck operations.

2.4.3 Gaps in current research

A large number of studies have found that the emissions, production, and cost performance of earthmoving operations are influenced by numerous variables. However, to date, there has been no reliable evidence that has explored loading influence on unit emissions, emissions or production, or optimality with respect to fleet size in a unit emissions or unit cost sense. Moreover, the change in equipment waiting time, equipment utilization, cycle time, production, fuel consumption, emission, and costs differ for each loading policy; hence, different loading policies may lead to different outcomes for unit emissions and unit costs. However, there have been no publications that have examined the influence of these underlying variables in alternative loading policies. This knowledge gap is the basis of this thesis.

2.5 Concreting Operations

The literature of this section is discussed according to concreting operational analysis and concrete placement.

2.5.1 Operational analysis

The foci of most previous concreting operation studies have been that of production and truck dispatching. Specifically, the underlying methods used are mostly in developing simulation modelling. This includes adopting simulation computer programs known as HKCONSIM (Lu et al., 2003; Lu and Lam, 2009), RMCSIM (Tang et al., 2005; Ying et al., 2005), MicroCYCLONE (Alkoc and Erbatur, 1998; Zayed and Halpin, 2001), RISim (Chua and Li, 2002), and Petri Nets (Sawhney et al., 1999) for modelling concrete production and delivery. Other available methods in the study of the management of batching plant operation and truck dispatching are presented in Table 2.2. Generally, these studies are concerned with maximizing performance associated with concrete supply and plant utilization from the point of view of the concrete batching plant.

Authors	**Techniques/tools**
Cao et al., (2004); Hegazy and Kassab (2003); Feng and Wu (2006)	combined simulation with optimization
Feng et al., 2004; Naso et al., 2007	genetic algorithm
Zhang and Zeng, 2013; Maghrebi et al., 2015; Liu et al., 2017	heuristic algorithm
Srichandum and Rujirayanyong, 2010; Wongthatsanekorn and Matheekrieangkrai, 2014; Mayteekrieangkrai and Wongthatsanekorn, 2015; Zhang et al., 2016	hybrid algorithm
Alkass et al., 1993	knowledge-based expert systems
Zayed et al., 2005; Graham et al., 2006; Maghrebi et al., 2014a	neural networks
Baxendale, 1984	Monte Carlo simulation
Kinable et al., 2014; Maghrebi et al., 2014b	integer programming
Zayed and Minkarah, 2004; Hashemi and Yuksel, 2014	linear programming
Yan et al., 2012, 2016; Liu et al., 2014; Galić and Kraus, 2016	network flow

Table 2.2 Techniques/tools adopted in concreting analysis

So far, there are a few studies that focus on the relationship between trucks and concrete placement on site. While Carmichael (1985, 1987) adopts a queuing analysis, Smith (1998) and Dunlop and Smith (2000) prefer a simulation method to determine the truck inter-arrival times and pumping times that maximize pump utilization and minimize total operation time, and minimum truck fleet size. Based on field data, Anson and Shou-qing (1994, 1998) establish benchmarking studies to compare the productivity performance of concrete placement methods. Dunlop and Smith (2002, 2003) examine the influencing factors on the production of concreting operations using simulation analysis, with the latter paper using multiple linear regression analysis.

2.5.2 Concrete placement

The selection of different concrete placement methods may result in placing rates, durations of pour, number of placing crew required and production. Most studies on concrete placement acknowledge that selected methods with higher placing rates offer advantages in productivity and cost. However, there are other factors that are equally important in the selection of placement method. For instance, Alkass et al. (1993) claim that the consideration of temporary work on a site plays an important role in selecting the placement method. Besides, they identify the need to prepare temporary access depends on the selection of the placement equipment. In addition, Anson and Shou-qing (1994) suggest that the utilization of existing concrete placement equipment on site contributes to the total cost savings for the project. Later on, Anson and Shou-qing (1998) study the link between shape and size of pour on productivity and cost.

The placement method also influences the level of equipment utilization on site. The pump or crane becomes idle while waiting to serve the trucks. The trucks become idle when they are queuing at the construction site prior to being loaded. Alkoc and Erbatur (1997) compare the idle time of placement methods and discover that the idle time of the crane is considerably higher than the pump. Anson et al. (2002) examine the influence of pouring size on the equipment idle time, where a smaller pour results in a lower number of trucks queuing while a larger pour leads to a long queue of trucks on site. In this context, the idle time of equipment can be minimized by effectively matching trucks relative to the placement equipment (Dunlop and Smith, 2004). However, based on field observation, Anson et al. (2002) state that only 17% of the sites have achieved a good balance of truck matching performance.

The consideration of both truck maneuver time and load time in concrete placement is important as they have been anticipated to increase production. Although, the lost time is considered insignificant for each pour, it appears to be significant to increase productivity and cost for the total pour (Dunlop and Smith, 2000). Kieffer and Selby (1983) discuss the importance of positioning trucks relative to the placement equipment to minimize maneuver time and maximize haul unit production. In particular, maneuver time can be reduced by having two trucks in position at the same time, which is almost similar to having double-sided loading (Nunnally, 2000). This situation reduces truck waiting time and leads to a reduction in the service time. Consequently, this leads to an increase in production. A similar approach has been examined in another construction operation: earthmoving (Soofastaei et al., 2016a). However, the implications of this loading practice on optimum unit emissions and optimum unit costs in concreting operations have not been previously explored and therefore, will be covered in this thesis.

A timely supply of concrete is a key factor in increasing the productivity of placing concrete. However, the achieved rate of concrete placement can be disrupted due to the uncertainty and variability that occurs both on site and in the trucks travelling. In this context, uncertainty implies probability, likelihood or frequency of occurrence, in contrast with determinism. Concrete delivery and placement have variability due to many factors including haul route condition, traffic, and site layout, and this variability affects production, concreting duration, emissions and costs. The importance of acknowledging uncertainty and variability in concreting operations is discussed by Carmichael (1985, 1987) and Smith (1998). Smith (1999b) demonstrates how the disruption of the continuous production of concrete placement may affect productivity and cost for both the contractor and concrete supplier. In this situation, the concrete supplier has to bear additional cost due to possible wasted concrete. Similarly, Feng et al. (2004) discuss how the disruption during placing process can affect the concrete supply at the batching plant. Chou and Ongkowijoyo (2015) develop a multi-expert decision aiding system to evaluate uncertainty involved in concreting operations.

2.5.3 Gaps in current research

In summary, previous studies have primarily been concerned with maximizing performance in terms of production, cost and duration in concreting operations. No studies examine the configurations of concreting operations in terms of least unit emissions or provide the link with minimum unit cost as performed in this thesis. Moreover, no publications have examined the influence of the placement method on unit emissions and the relationship between unit costs and unit emissions with respect to optimum fleet size. Therefore, this thesis aims to look into this matter and provide reliable evidence.

CHAPTER 3 - A UTILITY MEASURE OF CONSTRUCTION EMISSIONS ATTITUDES

3.1 Introduction

The construction industry is a large contributor to greenhouse gas (GHG) emissions (EPA, 2009). The sources of emissions include energy and power use, materials consumption, transport, demolition and waste. Chong et al. (2009, p. 143) state that attitudes within the construction industry ‘towards sustainable construction vary widely’, but are becoming more attuned to sustainability. Traditionally, the construction industry aims for minimal costs and durations, and maximum production. Higher costs are commonly perceived to be associated with adopting sustainable practices. However, there is a general public, political and industry acknowledgement that emissions need to be addressed, though it is felt that appropriate incentives or attitude change need to be put in place before widespread lowering of emissions will occur (Golob and Hensher, 1998; Fujii, 2006). The literature on construction emissions emphasizes the industry’s large emissions and their causes, and a lack of a universally positive attitude towards reducing emissions while pointing to a required urgency to address this (Kulatunga et al., 2006).

Commonly, information on the construction industry’s attitude towards emissions has been extracted using surveys, questionnaires and reports, as demonstrated in Fujii (2006) and Giesekam et al. (2016), but these necessarily only give qualitative information, apart from some nominal statistics. This chapter takes a quite different tack and establishes, for the first time, quantitative measures and models of industry attitude. It does this through the medium of utility and utility functions.

Utility functions are seen as an effective supplement to these qualitative methods because they generate a different perspective on attitudes, namely in terms of categorizing attitude as either risk averse, risk neutral or risk seeking. The term risk here is used in the sense of the magnitude and likelihood of an outcome involving emissions (Carmichael, 2016). And, because utility functions can be represented in both mathematical and graphical format, the functions also permit comparisons to be made between different groups of people. The chapter is original in terms of offering this different view of emissions in the construction industry. Utility functions can be generated through designed ‘lotteries’, whereby certain actions of individuals and probabilities associated with these actions establish attitudes (Carmichael, 2013). Utility functions, while not being without their critics, have reasonably wide acceptance (de Neufville, 1990). By analyzing the utility functions obtained, the construction industry’s attitude toward carbon emissions can be better understood. And flowing from this, more effective and efficient methods for reducing carbon emissions might be able to be created.

Within construction projects, designers, planners and managers have multiple dependent concerns such as cost, production and time, in addition to emissions. These concerns or criteria generally have to be considered together and not in isolation. Such multi-criteria (multi-objective, multi-attribute) thinking (Ang and Tang, 1984; de Neufville, 1990) naturally introduces subjectivity and different people will weight criteria differently, leading to different outcomes. To avoid this subjectivity, and to avoid looking at emissions out of context (where presumably everyone would support a zero emissions scenario), this chapter looks at combining the criteria in a natural way, for example through emissions per production (unit emissions), and emissions per time, and developing utility functions in these measurement scales. Emissions per dollar as a measurement scale is not considered, because generally carbon is given a dollar value through various countries’ uses of carbon markets or carbon taxes.

The research considers a range of construction-related scenarios where emissions are involved, and utility functions established for each of these. From these, the industry’s risk attitude is established. A range of construction industry personnel is used in obtaining the data. The implications of this are demonstrated through an earthmoving operation, where the results for differing degrees of risk aversion are highlighted. The findings will be of interest to those looking to reduce or manage construction emissions.

The organization of the chapter is as follows. The utility method is first presented. This is followed by case studies examining emissions attitudes via utility functions. Such utility functions are applied to understanding an earthmoving operation. Discussion and conclusions follow.

The related background to this chapter is given in Section 2.2.

3.2 Utility

3.2.1 Outline

Utility has been used in many application areas, for example, economic, financial, actuarial, water management, energy management, engineering and agricultural (Velasquez and Hester, 2013). Keeney (1973), Keeney and Wood (1977) and Brinck et al. (1979), among others, have shown utility to be a useful measure in assisting decisions involving uncertainty. Uncertainty, here, is used to imply probability, likelihood or frequency of occurrence, in contrast to determinism, and is distinguished from risk which requires an outcome and the likelihood of that outcome (Carmichael, 2013, 2016). Utility 'provides a framework whereby values may be measured, combined and compared consistently with respect to a decision maker' (Ang and Tang, 1984, p. 56). An associated utility function is used to weight preferences nonlinearly (Ang and Tang, 1984). Utility is considered a preferred descriptor of risk attitudes (Velasquez and Hester, 2013).

Utility and expected utility have been scrutinized quite extensively, and they have their critics, but also have wide acceptance (de Neufville, 1990). Common issues involved whilst developing utility functions relate to: the Hawthorne effect (Schwartz et al., 2013); the use of structured scenarios; and interviewees giving perceived-wanted answers, believed-correct answers, manipulated answers or averaged answers (de Neufville, 1990). For these reasons, the underlying interview needs to be designed carefully.

de Neufville (1990), among others, gives commentary on the theoretical basis for utility and utility functions. The method of getting to utility functions is well established through the use of designed alternative choices and the Certainty Equivalent Method (Ang and Tang, 1984), and is not repeated here. In assigning utility, the most favorable outcome is given a utility value of 1 and the least favorable outcome a value of 0. One criticism of the Certainty Equivalent Method is that it works on scenarios that, although realistic, may be disconnected from the intended application. Results obtained might then be queried as to whether they can be applied to scenarios different to that used in the data gathering. However, the method is still useful for establishing attitudes and how people behave (Carmichael, 2013). Hypothetical scenarios are avoided in this thesis.

Characterizing the shape of utility functions may be according to any suitable mathematical form (Ang and Tang, 1984; de Neufville, 1990). In this thesis, quadratic functions are used of the form,

$$u(X) = \alpha X^2 + \beta X + \gamma \qquad (3.1)$$

where u is utility, and α, β and γ are constants, different for each person or organization and situation. X, below, refers to the independent variable or attribute being examined, for example unit emissions.

The second derivative of u gives an indication of risk aversion. The degree or level of risk aversion, RA, is sometimes measured by,

$$RA(X) = -\frac{u''(X)}{u'(X)} \qquad (3.2)$$

From Equation (3.1) and using a Taylor series expansion of u about E[X], expected utility becomes,

$$E[U] \cong \alpha E^2[X] + \beta E[X] + \gamma + \alpha \mathrm{Var}[X] \qquad (3.3)$$

where E[ ] and Var[ ] denote expected value and variance respectively. The more general version of this can be found in Benjamin and Cornell (1970), Ang and Tang (1984) and Carmichael (2014). Such an expansion is valid for usual utility function shapes.

Ang and Tang (1984, p. 74) note that *the expected utility is relatively insensitive to the form of the utility function at a given level of risk-aversion, and that the expected utility does not change significantly over a wide range of risk-aversion coefficients. Hence, the exact form of the utility function may not be a crucial factor in the computation of an expected utility. Moreover, the risk-aversiveness coefficient in the utility function need not be very precise; that is, any error in the specification of the risk-aversiveness coefficient may not result in a significant difference in the calculated expected utility.*

3.2.2 Risk attitudes

Risk attitudes are commonly classified as being risk averse, risk neutral or risk seeking.

A risk averse attitude shows a nonlinear preference characterized by a marginal decrease in utility with improving value of the attribute (de Neufville, 1990). The utility function of a risk averse person is concave downwards. Most people tend to show varying degrees of risk-averseness (Ang and Tang, 1984). The utility function of a risk seeking person is concave upwards (Ang and Tang, 1984, de Neufville, 1990).

3.2.3 Utility functions for variables other than money

By far, the overwhelming majority of utility function usages have involved money as the main independent variable. However, utility functions have applications beyond this. Examples include: de Neufville and Keeney (1972) on travel time; Keeney and Wood (1977) on environment, international cooperation, development possibility, and flexibility in water resource planning; Brinck et al. (1979) on animal carrying capacity, animal count, and ground water quality in strip-mining; and Kailiponi (2010) on loss of life and economic disruption in emergency evacuations.

3.3 Case Studies

The following case studies give utility function results. Different scenarios, involving different levels of emissions, were outlined to people with different construction industry backgrounds – clients, consultants, contractors and suppliers. The following figures give average results based on a total sample of 35 persons - 12 consultants, 10 contractors, 8 clients and 5 suppliers – and agree with similar results obtained less formally and previously by the authors. The structured questions were designed to assess the decision maker's preference by simply requiring a comparison of probabilistic variables against a deterministic outcome. The opening question in each case study sets the favourable outcome against the least favourable outcome as 'choice 1', while 'choice 2' consists of the next most desirable outcome as a guarantee. Respondents were asked to choose a probabilistic value for a given scenario involving these two different choices. A utility value can be calculated based on the probability value that is obtained from each scenario. The utility functions were then determined through the use of a quadratic function as described in Section 3.2.1. The utility functions are presented as being indicative but not definitive. The shapes of the utility functions could be anticipated to change slightly across different situations and people, and hence large samples and a statistical analysis would not better inform. The structured questions and details of utility function results for case studies are given in Appendix A and B, respectively.

3.3.1 Earthmoving operations

The scenario tested involved moving earth between cut and fill locations using trucks. The certain outcome has trucks hauling and returning along an un-trafficked road, where travel time, fuel use and emissions generated are assumed to be always the same on every cycle. That is, the emissions per production ($kgCO_2$-e/m^3) are known. The uncertain outcomes involve selecting an alternative shorter route, but this comes with unpredictable (differing probabilities) and variable amounts of traffic. Where the traffic is denser, this leads to greater travel times, greater fuel use, and greater emissions. Conversely, lesser traffic leads to shorter travel times, lower fuel use, and lower emissions. Figure 3.1 shows the average utility functions developed for a specific situation.

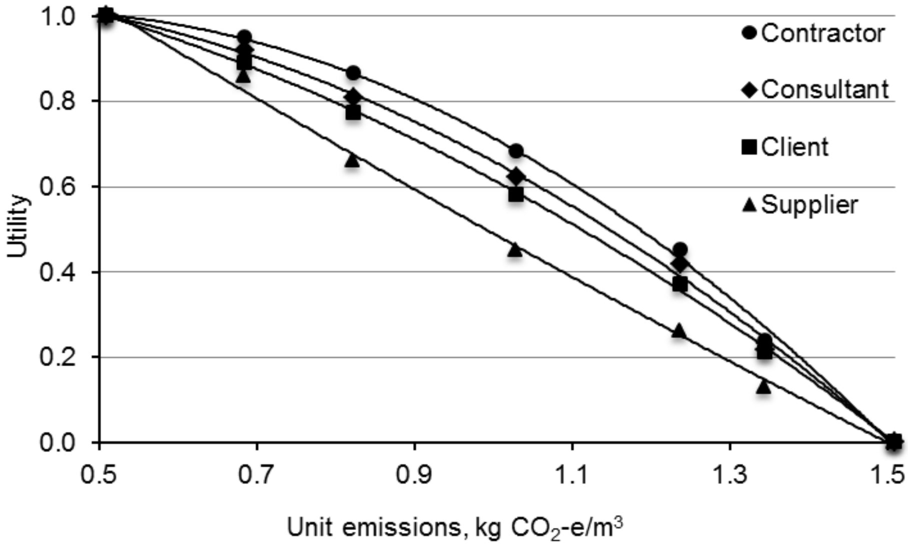


Figure 3.1. Earthmoving scenario; average utility functions for unit emissions (kgCO_2-e/m^3).

3.3.2 Tender submissions

The scenario tested involved evaluating non-conforming (alternative) tenders based on submitted prices and submitted technology. The certain outcome uses existing technology (conforming tender), where the price (cost) is known, and the technology and hence emissions are known (from past measurement). That is, emissions per cost (kgCO_2-e/$) is known. The uncertain outcomes result because other tenders use alternative, non-conforming technology. For each tender, the price (cost) is known (as tendered), however the emissions are unpredictable because of the alternative technologies proposed. Some alternative tenders are cheaper and some are more expensive, while for each alternative tender, the actual emissions are uncertain. Figure 3.2 shows the average utility functions developed for a specific situation.

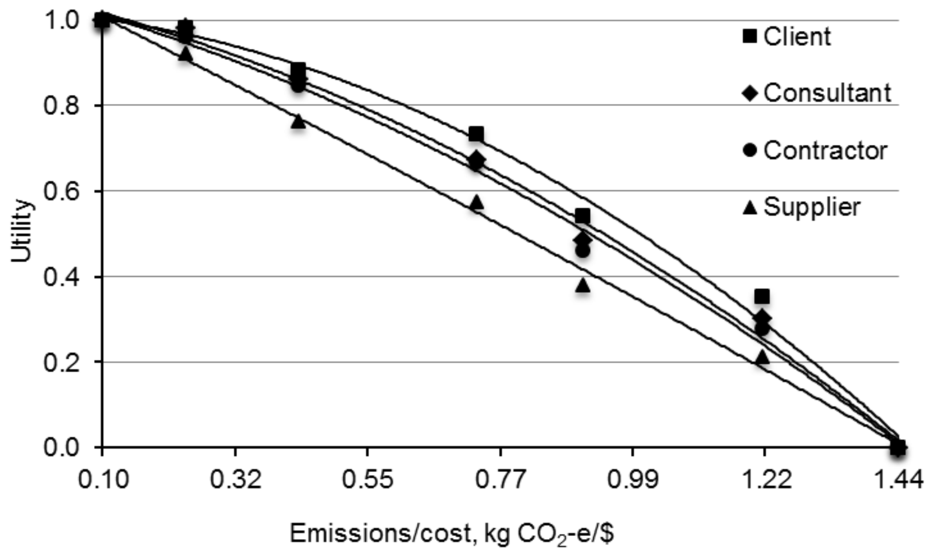


Figure 3.2. Tender submission scenario; average utility functions for emissions per tender cost (kgCO_2-e/$).

3.3.3 Service life of materials

The scenario tested involved the use of different materials within infrastructure, where the materials have different embodied carbon and different lifetimes. The different materials are assumed to be able to perform in the same desired way, and have equivalent appearance. The certain outcome uses an established material. This material has known embodied carbon, a known lifetime (in years, established from past knowledge), and hence known emissions per year (kgCO_2-e/year). The uncertain outcomes use alternative, newly available materials. Each new material has known embodied carbon, but the lifetimes of each of the new materials is indefinite (until the materials are used till the ends of their lifetimes, at which point their lifetimes can be established). Figure 3.3 shows the average utility functions developed for a specific situation.

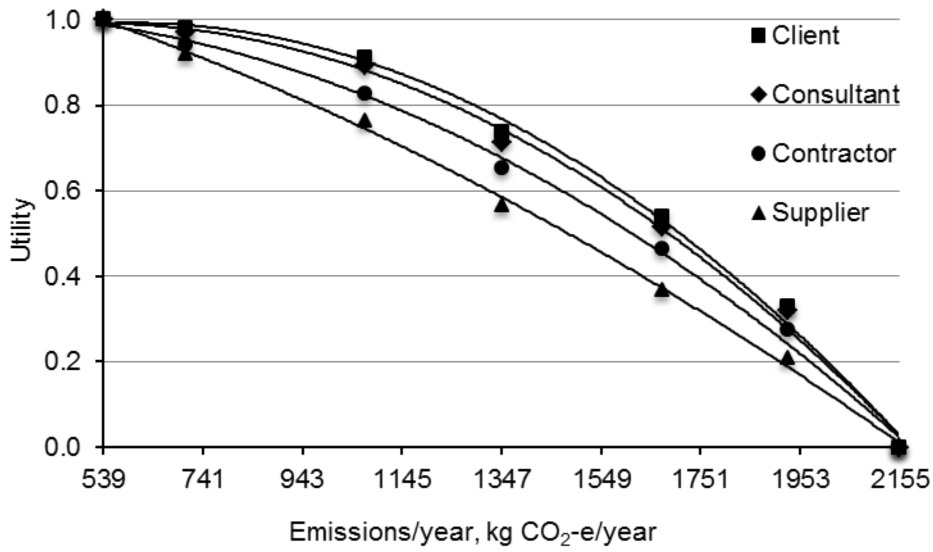


Figure 3.3. Service life of materials scenario; average utility functions for emissions per year (kgCO_2-e/year).

3.3.4 Management of construction equipment

The scenario tested involved the use of multiple pieces of mixed equipment as occurs in road construction – scrapers, graders, compactors, water carts. Different managers organize the usage and interaction of equipment differently. The certain outcome uses an experienced manager with known practices, which may not be the optimum, but nevertheless are accepted by and familiar to the equipment operators. This leads to known production and known emissions (based on past performance). That is, the emissions per production (kgCO_2-e/m^3) are known. The uncertain outcomes involve employing alternative managers. These managers are offering new, but untried, ways to do and organize the work. The same production results, but emissions will vary depending on the efficiency with which the work is done. Figure 3.4 shows the average utility functions developed for a specific situation.

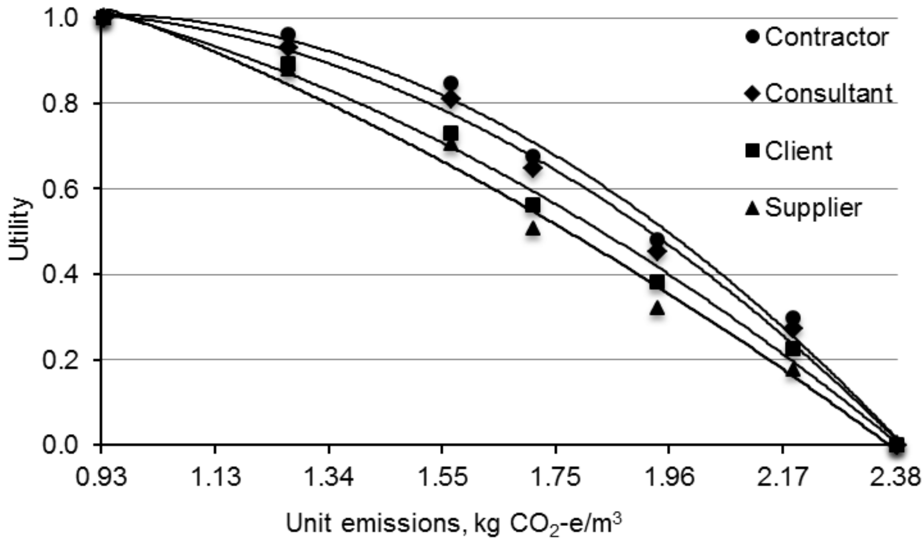


Figure 3.4. Equipment management scenario; average utility function for emissions per production (kgCO_2-e/m^3).

3.4 Discussion

The results show that people in the construction industry are generally risk averse but to varying degrees. Other studies done by the authors confirm this risk averse nature (Carmichael and Mustaffa, 2018). It is emphasized, however, that the levels of risk aversion shown are indicative only; any individual across different situations could be anticipated to have different levels of risk aversion, albeit not greatly different. And individuals will also differ among themselves.

The results show the attitudes of construction industry people to emissions, and also emissions reduction. The quantity of emissions influences attitudes and behavior. In line with the observed risk aversion, people tolerate some emissions, but start to show concern when the quantity of emissions is large. This is consistent with risk aversion in money utility.

3.4.1 Group differences

The different groups of construction people show different levels of risk aversion, possibly reflecting their different levels of understanding, knowledge, experience, roles, and involvement in different construction operations. Consultants and contractors, who are directly involved in designing, planning and management of construction operations, show an overall higher level of risk aversion compared to clients. This might be attributed to having greater awareness of the growing number of rules, regulations and policies introduced by governments to minimize environmental impacts, and the shift in construction emphasis to emissions mitigation practices, along with traditional cost and time. This in turn, possibly leads to an increased consciousness regarding the importance of excessive emissions. Clients differed in their attitudes across the different scenarios, dependent on the nature of each scenario, while suppliers were consistently closest to being risk neutral across all scenarios. Table 3.1 shows this quantitatively. Table 3.1 shows the risk aversion coefficients, RA, for each group of people for each scenario, using Equation (3.2) evaluated at the mid-point of each of the independent variables.

Scenario	**Contractor**	**Consultant**	**Client**	**Supplier**	**Average**
Earthmoving	1.66	1.22	0.86	-0.19	0.89
Tender submission	0.64	0.73	1.12	0.08	0.64
Service life of materials	1.13	1.36	1.45	0.81	1.19
Equipment management	1.36	1.17	0.7	0.45	0.92
Average	1.20	1.12	1.03	0.29	0.91

Table 3.1. Risk aversion coefficients (RA) for scenarios studied.

3.4.2 Scenario differences

The different scenarios lead to different levels of risk aversion (Table 3.1). This may be influenced by the different measurements used for the independent variable in each scenario. The extent to which people respond to each scenario depends on their own roles. Each group has a different role and expertise in construction, and the responses to each scenario would be influenced by their familiarity, experience, knowledge and the level of involvement in dealing with such scenarios.

By using combined measures, for example, emissions per production, subjectivity issues to do with measures treated singly, and then combined, are avoided. Emissions in isolation were not considered because, out of context, everyone presumably would want zero emissions.

Some issues to do with obtaining the utility data are as follows. (i) The sample sizes used were sufficient for understanding purposes. Rather than adopting a statistical-significance type mentality, which would not assist the understanding of the results here, the paper emphasizes that the results are indicative, not definitive. Clearly, future development could look to expand the sample size and sample subdivision, and provide more robustness to the conclusions. Of interest might be a comparison between people who work for companies committed to sustainability and people who work for companies that ignore sustainability. (ii) Generally, the interviewees were enthusiastic about the idea of measuring people's attitudes to emissions. However, over time, this may change, and this in turn may affect interviewees' responses. To get sensible responses, the interviewees need to have some motivation for showing respect to the data gathering. Offering incentives and rewards to interviewees may distort the responses. Because the reduction of emissions is publicly perceived as being desirable, some individuals may skew their responses accordingly. (iii) The Hawthorne effect was not believed to impact the results. (iv) The number of data points used to establish each utility function is not considered to be a concern (Accorsi et al., 1999).

3.5 Implications of the Study's Approach

By quantitatively modeling people's attitudes to emissions, it is then possible to better inform on construction operation performance, and assist in operation design and management. The following example on an earthmoving operation shows this.

Consider an earthmoving operation, schematically shown in Figure 3.5. Trucks cycle repeatedly between loading and dumping points. The component times all comprise variability or uncertainty. Table 3.2 shows the component times from one observed earthmoving operation. The excavator used was 140HP, engine tier 3, with 1 m^3 bucket. The trucks were 168 HP, engine tier 2 with 6 m^3 trays. The ratio of hourly (total) costs of a truck to excavator was 0.44.

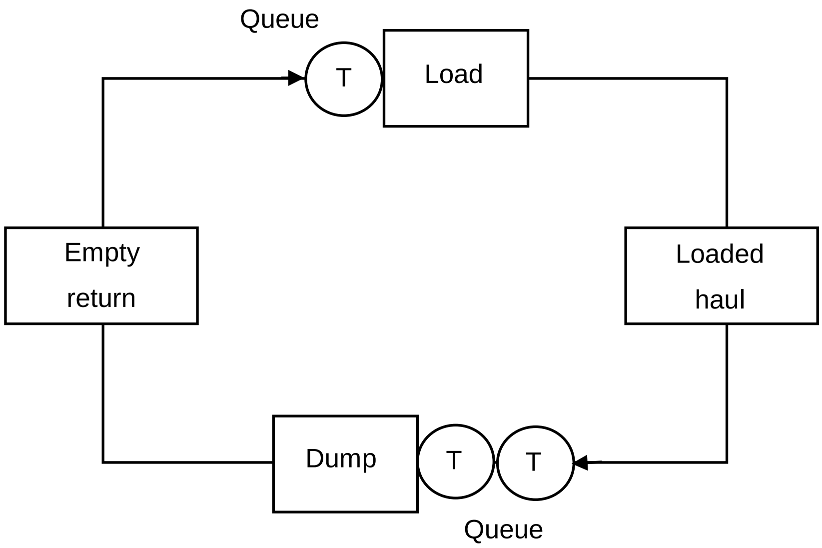


Figure 3.5. Schematic of earthmoving operation studied. Truck denoted as T.

Truck cycle component	**Mean** (min)	**Standard deviation** (min)
Maneuver at excavator	0.504	0.220
Load	1.709	0.214
Loaded haul	1.440	0.382
Maneuver at dump area	0.443	0.282
Dump	0.394	0.046
Return	1.926	0.771

Table 3.2. Example earthmoving operation observed data.

Emissions are estimated based on Lewis (2009). Of the CO_2-e emissions generated by the combustion of diesel fuel, carbon dioxide (CO_2) is the major greenhouse gas and usually ranges between 98% and 99.5% of the total, with the remaining of 0.5% to 2% coming from a production of small quantities of methane (CH_4) and nitrous oxide (N_2O) (DCCEE, 2017).

The utility function (that of a contractor) used for unit emissions is Figure 3.6, while for unit cost (cost per production), Figure 3.7 was obtained through a similar process, and with the same contractor. The operation analysis was done using Monte Carlo simulation (Appendix C).

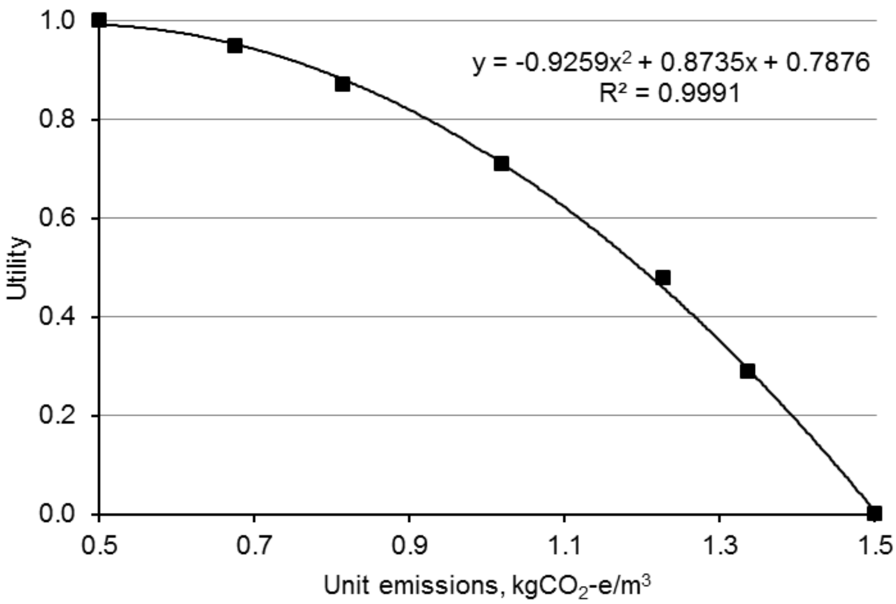


Figure 3.6. Example contractor utility function for unit emissions (kgCO_2-e/m^3) used in the analysis.

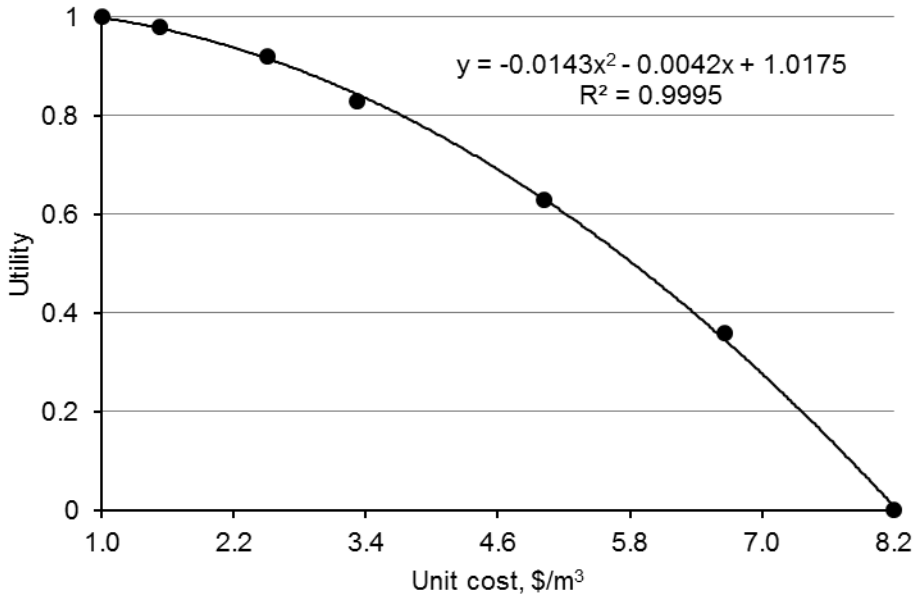


Figure 3.7. Example contractor utility function for unit cost ($\$/m^3$) used in the analysis.

Figure 3.8 shows the plots of expected utility for unit emissions ($E[U]_{EP}$) and expected utility for unit costs ($E[U]_{CP}$) versus fleet size. It is seen that the optimum fleet size for unit emissions and unit costs coincide, a result consistent with non-utility thinking (Carmichael et al., 2012, 2014).

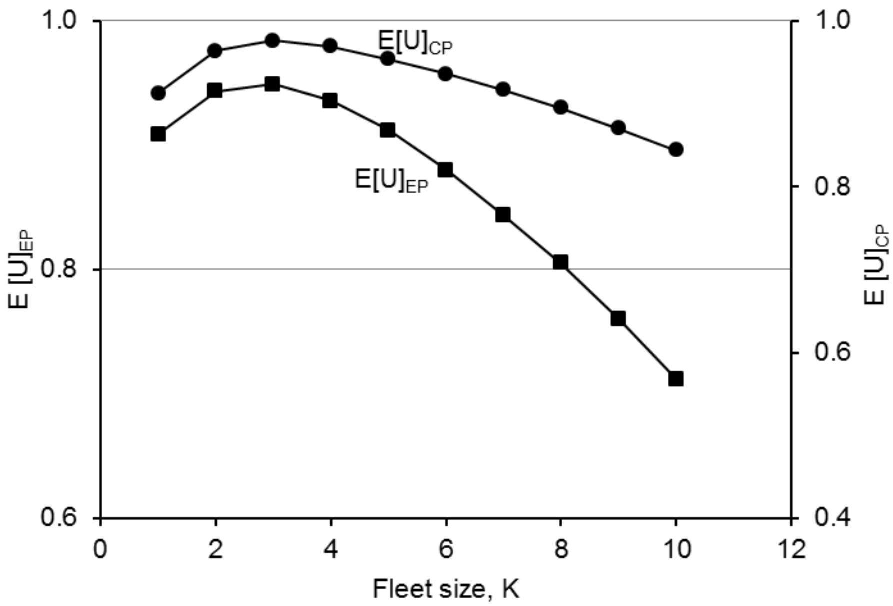


Figure 3.8. Expected utility of unit emissions, $E[U]_{EP}$, and expected utility of unit cost, $E[U]_{CP}$, versus truck fleet size, K.

Figures 3.9 and 3.10 show the sensitivity of expected utility of unit emissions and expected utility of unit costs, respectively, to changes in levels of risk aversion (evaluated at the middle of the utility functions). RA = 1.89 in Figure 3.9 corresponds with Figure 3.6. RA = 0.21 in Figure 3.10 corresponds with Figure 3.7.

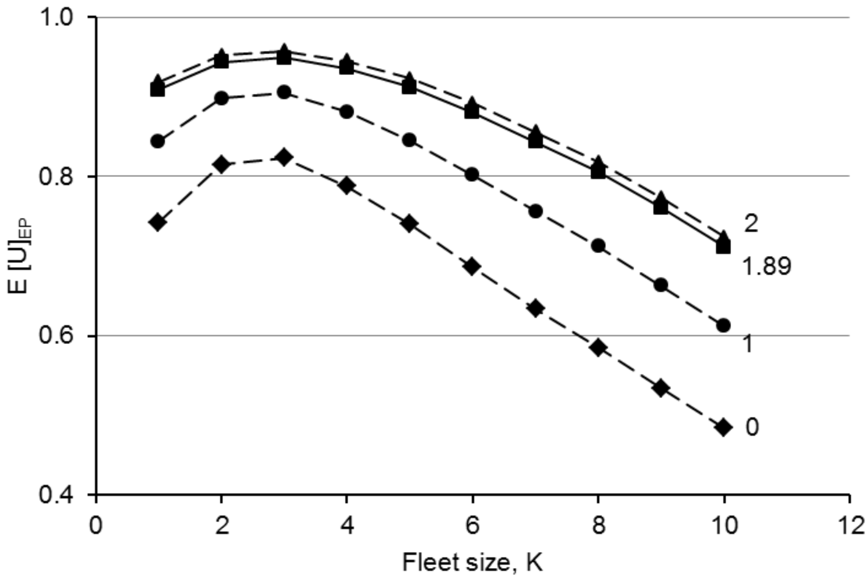


Figure 3.9. Expected utility of unit emissions, $E[U]_{EP}$ versus truck fleet size (K), for different levels of risk aversion (RA).

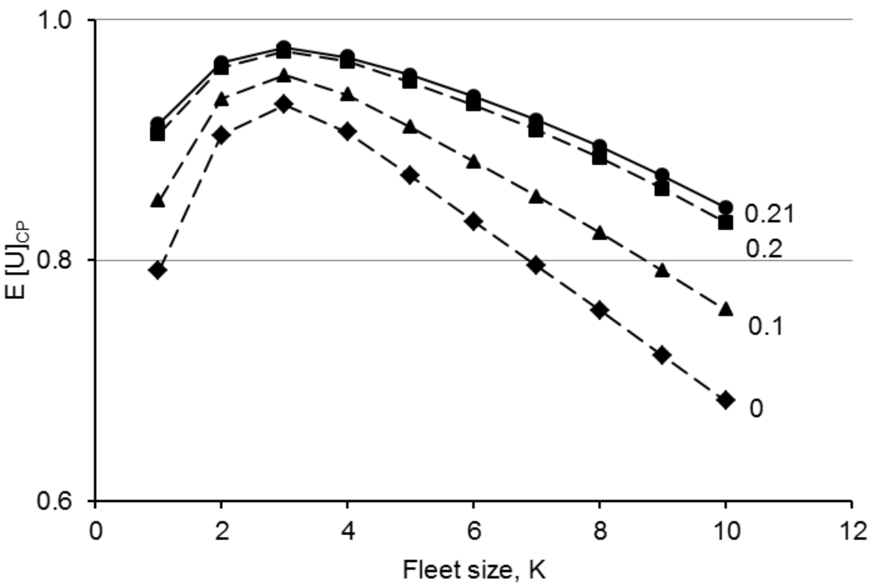


Figure 3.10. Expected utility of unit cost, $E[U]_{CP}$ versus truck fleet size (K), for different levels of risk aversion (RA).

Generally, as the level of risk aversion increases, the ‘theoretical’ (assuming fleet size as a continuous variable) optimum occurs at slightly higher optimal fleet sizes, but when viewed in terms of integer trucks, there is no difference in the optima. That is, as operation designers and managers become more risk averse to unit emissions, then so the fleet size could be anticipated to grow. The case study outlined in Table 3.2 had very short hauls, and the haul time was comparable to the load time; it is anticipated that as the ratio of haul time to load time increases, that there will be a jump in the optimum integer number of trucks between different levels of risk aversion. Similar conclusions follow for unit costs as the level of risk aversion increases.

3.6 Conclusion

The chapter established, for the first time, quantitative measures of industry attitude to emissions. The chapter is original in terms of offering a different view of emissions in the construction industry.

Utility is seen as a useful way of measuring and comparing attitudes towards emissions. Without such a measure, attitudes would be difficult to compare (except for extremes in attitude) in any meaningful way. Surveys and questionnaires, as are currently used, have their flaws if not done rigorously. By establishing industry attitudes, it may then be possible to gauge any change in attitudes over time, and hopefully improved attitudes over time.

The chapter’s findings indicate that individuals display risk averse tendencies with respect to emissions, and that much of industry has an emissions attitude in tune with its attitude to costs. The term risk here is used in the sense of the magnitude and likelihood of an outcome involving emissions. Small emissions are seen as tolerable, while large emissions are not. The results also highlight that attitudes towards emissions vary between people occupying different positions within the industry. The results obtained are indicative, but not definitive because different people display different utility in different circumstances.

Attitudes to emissions impact the design and management of construction operations. How this will happen was demonstrated through a case example on earthmoving.

CHAPTER 4 - EMISSIONS AND PRODUCTION PENALTIES/BONUSES ASSOCIATED WITH NON-STANDARD EARTHMOVING LOADING POLICIES

4.1 Introduction

Production and cost, and more recently also emissions, are central to earthmoving operations. The performance of such operations depends heavily on equipment utilization and the reduction in equipment idle time. Common practice uses single-sided loading of trucks by excavators or equivalent, where trucks get loaded fully in turn; such operations have been researched extensively in terms of their unit costs (cost/production) and unit emissions (emissions/production) (Ahn et al., 2009; Carmichael et al., 2012, 2014a; Kaboli and Carmichael, 2014a). However, there are other loading policies possible, including double-sided loading, fractional loading and zero waiting time loading. All such policies reduce equipment idle time and associated consumption of fuel and generation of emissions, but have different impacts on production. Using the common single-sided loading policy as a benchmark, this chapter explores the magnitude and nature of any penalties or bonuses in terms of unit emissions and unit costs associated with other loading policies.

As impetus for this thesis, Smith et al. (1995, p. 395) remark that '… the state of the truck queue will influence the value of an extra bucket: if there are trucks waiting, then it may be better to have fewer passes and increase truck use. Indeed, observations made on real sites have shown that if an operation is over-resourced, loader operators will tend to underload a truck to reduce the queue length.' Along with this, a large number of practitioners were informally interviewed as to what they thought would be the unit emissions and unit cost impacts and the magnitude and nature of these impacts due to different loading policies, and no one was able state with any confidence what these would be. The chapter enlightens on the magnitude and nature of loading policy impact.

Idle time exists whenever the excavator waits for a truck or when a truck queues prior to being loaded. Reconfiguring loading policies is a potential way of minimizing equipment idle time associated with loading or waiting to be loaded. It also potentially offers reduced emissions even though ‘non-idle fuel use and CO_2 emission rates are approximately three to five times higher than idle rates’ (Lewis et al., 2012, p. 36). However, since equipment idle time, equipment utilization (percentage of time working), fuel use (and hence emissions), and costs and operation production are interrelated, different loading policies will lead to different unit cost and unit emissions outcomes. These outcomes, the link between idle time, utilization, emissions, costs and production, and optimum equipment configurations, are explored in this chapter. While many publications look at earthmoving, this chapter is original in addressing the emissions and production penalties and bonuses associated with alternative loading policies.

Monte Carlo simulation is used in this chapter to provide the analysis for the different loading policies. However, it is noted that discrete event-oriented simulation or modified finite source queuing theory could also be used. The term excavator is used in a generic sense to describe loading equipment. A cut-and-fill operation on a residential construction site provides case study data.

This chapter is organized as follows. Publications forming the background to the study and a discussion on different loading policies are given, respectively, in the next two sections. The computational approach is then given, followed by a study using field data, and discussion on unit emissions and unit costs for the different loading policies. The final section presents the conclusions.

This chapter will be of interest to those who design and manage earthmoving operations. Several loading policies studied may only be seen intermittently in practice. However, there is no publication which tells how they perform relative to one another, how much gain/loss in production occurs, and how much extra/less unit emissions and unit cost are involved. This chapter quantifies these and provides useful information for assessing the most environmentally aware and economical way to design and manage earthmoving operations.

4.2 Background

This section discusses on earthmoving loading influence. The related background to the present study is also given in Section 2.3.

4.2.1 Loading influence

Peurifoy and Ledbetter (1985) suggest, based on experience, that the selection of the truck and excavator capacities be based on a rule of thumb of 4 to 5 buckets or passes per truck. By contrast, Morley et al. (2013a) suggest selecting trucks and the excavator in combination rather than by any predefined rule on buckets per truck, and Karshenas (1989) suggests different excavator to truck ratios greater than 5 can lead to lower unit cost.

Where truck capacity is not an integer multiple of excavator bucket capacities, Marinelli and Lambropoulos (2012) suggest that completing a partial last bucket (an incompletely loaded last bucket) can lead to cost reductions, compared with no partial last bucket. Burt and Caccetta (2007) allow, but without argument, up to an extra possible last one-third of a bucket in their calculations of matched or balanced truck fleet sizes. Gransberg (1996) and Nunnally (2000) disapprove the use of partially filled buckets, considering it an inefficient practice.

Smith et al. (1995) appears to be the only commentary on benefits from loading trucks to less than full capacity. They argue that there is value in under-loading when trucks are waiting, and that loader operators will do this instinctively in such cases.

Smith et al. (1995) also remark that in the design of operations, forethought of both maneuver time and load time is important in order to achieve maximum output.

Peurifoy and Ledbetter (1985) highlight the relationship between truck and fleet size and maneuver time, where a large fleet of small trucks has a higher total maneuver time than a production-equivalent small fleet of large trucks. Stubbs (1959) and Caterpillar (2011) discuss the importance of positioning trucks relative to the loader in order to minimize maneuver time and maximize production. Maneuver time can be reduced if the loading area facilitates desirable following truck location and positioning, with the extreme being double-sided loading (Nunnally, 2000; Soofastaei et al., 2016a), which has the added benefit of eliminating most truck waiting time. Any reduction in the maneuver time leads to a reduction in the service time, with a consequent increase in production.

Some overloading of a truck is supported by a number of authors. Smith et al. (1995) suggest that an extra bucketful per loading can be beneficial for operations with large backcycles, but increasing the load time may not be beneficial for operations with short backcycles where the ratio of the service time to the backcycle time is larger. (Backcycle time refers to the time between finishing loading and returning to the load site). Smith et al. (1995, p. 395) add the condition that '… an extra bucket should never cause the truck payload to exceed its limit.' This condition is based on preventing damage to trucks, and safety considerations. Kaboli and Carmichael (2016) suggest that slightly overloading trucks leads to better emissions outcomes than fully loaded trucks, subject to maintenance and equipment reliability concerns. Chironis (1991) and Schexnayder et al. (1999) argue similarly for production.

No publications explore loading influence on unit emissions, emissions or production, or optimality with respect to fleet size in a unit emissions or unit cost sense. This knowledge gap is the basis of this chapter.

4.3 Alternative Loading Policies

The typical earthmoving operation studied here involves the cycling of trucks, repeatedly hauling between loading (at excavator) and dumping points. Figure 4.1

shows a schematic of such an operation. A queue of trucks may occur while trucks wait at the loading or dumping points, because of variability in the truck cycle component times.

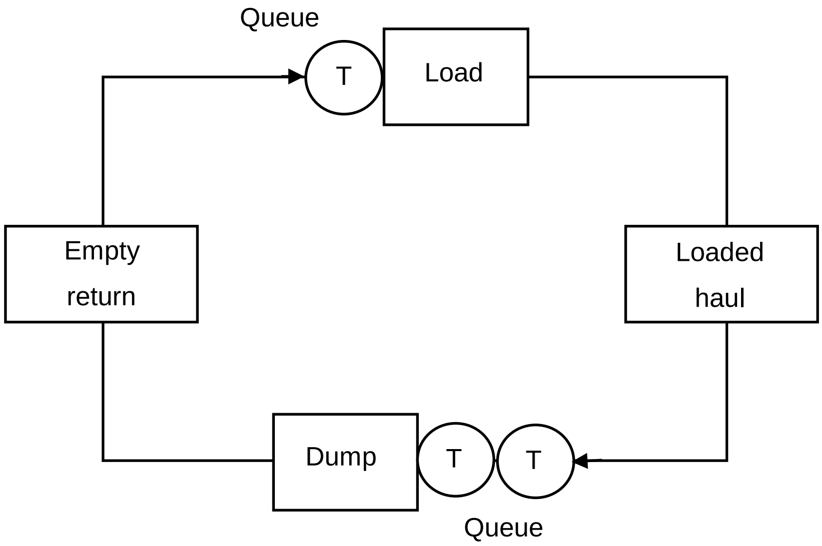


Figure 4.1. Schematic of earthmoving operation studied. Truck denoted as T.

Larger truck fleet sizes lead to more truck waiting, reduced truck utilization and production more influenced by the excavator, while smaller truck fleet sizes lead to higher excavator idle times, reduced excavator utilization and production more influenced by the trucks. Studies show that an increase in equipment waiting times translates to an increase in total fuel use, with a consequent increase in emissions (Lewis et al., 2012) and costs (Ercelebi and Bascetin, 2009). Different loading policies lead to different waiting times, as well as different equipment utilizations, production, costs, fuel use and emissions. Four alternative loading policies are discussed here.

4.3.1 Single-sided loading policy

Single-sided loading is a common loading policy where the following truck waits for the preceding truck to complete loading, and the excavator is idle or loading while waiting for the following truck to maneuver into a loading position, and idle (apart from some housekeeping) when no trucks are present. Trucks are loaded on one side of the excavator. The case study data and the single-sided loading benchmark used in the studies below refers to such loading, however single-sided loading also includes ‘continuous in-line spotting’ (Nunnally, 2000, p. 123) where site layout permits. Carmichael et al. (2012, 2014a) demonstrate the fleet size coincidence of the optimum unit emissions and optimum unit cost for such loading.

4.3.2 Double-sided loading policy

Double-sided loading means that trucks can be loaded on either side of the excavator. Nunnally (2000, p. 123) refers to this as ‘two spotting positions’. For the following truck, its maneuver can be started (and possibly completed) without waiting for the preceding truck to complete loading. Trucks more usually reverse into a loading position but, more rarely where the site permits, might drive directly in to be loaded as in the ‘in-line’ single-sided loading case. When the excavator finishes loading the preceding truck, it starts directly to load any following truck present. This leads to a lower service time at the excavator, lower cycle times for the trucks, and potentially higher production.

Previous studies have highlighted the advantages of double-sided loading from a production viewpoint (Smith et al., 1995, Nunnally, 2000 and Soofastaei et al., 2016a). However, the implication of this loading practice on the optimum unit emissions and optimum unit cost fleet configurations has not been previously explored. This is treated in this chapter.

4.3.3 Fractional loading policy

Fractional loading refers to a truck load being less than or equal to a full load depending on the arrival time of the following truck. Smith et al. (1995) comments that loader operators will do this instinctively when trucks are waiting. The fraction is preset, and if for example each truck holds 5 excavator buckets, the fraction could be preset at 0.2, 0.4, 0.6, or 0.8, where for example a fraction of 0.8 means that each truck is filled to at least 80% capacity, that is 4 excavator buckets minimum are used, but could be 5 buckets dependent on extra time being available for the fifth bucket before the arrival of the following truck. A fraction of 0 corresponds to the zero waiting time policy (Section 4.3.4), while a fraction of 1 corresponds to the single-sided loading policy (Section 4.3.1). With the arrival of a following truck at the loading point, the preceding truck fills to at least the preset fraction before then moving away from the loading point, while the preceding truck loads fully if this can be done before the arrival of the following truck. Each truck is loaded to between a fraction of full load and full load. This leads to, on average, smaller truck waiting times, truck under-loading and reduced production per truck, and some reduction in fuel used because of lighter loads, while non-fuel costs remain largely unchanged. The implication of this loading practice on operation performance, whether unit emissions or unit costs, has not been previously explored. This is treated in this chapter. Carmichael et al. (2014a) show that the optimum truck fleet sizes for unit emissions and unit cost coincide regardless of the truck capacity. However that result assumes that all trucks are of the same capacity and not with variable capacity dependent on the following truck arrival time, as with the fractional loading policy.

Fractional loading in this chapter refers to using full excavator buckets, but loading trucks to less than full capacity. This could be extended to using partially filled excavator buckets, but this is not considered here.

4.3.4 Zero waiting time policy

Truck waiting time can be eliminated or almost eliminated by adopting a practice whereby the preceding truck (if loading) moves away from the loading point when the following truck arrives to be loaded. The following truck arrival triggers the end of the preceding truck loading, while the preceding truck loads fully if this can be done before the arrival of the following truck. Trucks are accordingly loaded to amounts up to and including full load. The consequences in terms of truck waiting time, truck under-loading and reduced fuel use are similar to that outlined for fractional loading. The implication of this loading practice on operation performance, whether unit emissions or unit costs, has not been previously explored. This is treated in this chapter.

4.4 Underlying Modeling and Calculations

The Appendix D gives the notation and underlying models used in the chapter's analysis for all loading cases considered. A broad summary is given here of the underlying modeling.

Truck cycle component times can be related through recursive relationships. The queue simulation approach of Carmichael (1988) is extended in this chapter, to different loading policies and to also include emissions, cost and production for these different policies. The sole server or sole excavator case is described here. Trucks are the customers.

For each truck cycle n, n = 1, 2,…, ζ, a service time, S(n), backcycle time, B(n), maneuver time, M(n), and load time, LT(n), are variously generated by sampling from field data distributions for S, B, M and LT respectively, as in usual Monte Carlo simulation. ζ, the total number of truck cycles, is chosen reasonably large.

To start the recursive calculations, introduced cumulative time measures for the first set of cycles, CUM(n), n = 1, 2,…, K+1, are set to some reasonable values. Here, K is the truck fleet size. Then, for the remaining cycles, n = K+2, K+3, …, ζ, waiting times, W(n), and the cumulative time measures, CUM(n), are calculated recursively based on previous cycles' values. Emissions, E(n), and production, PROD(n), are calculated for each cycle, and cost is included to get a total picture of the operation.

Information collected during the calculations is: number of truck cycles (NC), total duration (TD), server utilization, truck utilization, total emissions, total cost, total production, emissions/production and cost/production.

The server (excavator) utilization (the proportion of time that the server is busy), η, is calculated from,

$$\text{Server utilization, } \eta = \frac{\sum_{NC} S(n)}{TD} \tag{4.1}$$

The truck utilization, u, is the proportion of time that trucks are either in service or travelling with respect to total truck cycle time. It excludes truck waiting time. It is calculated from,

$$\text{Truck utilization, } u = \frac{\sum_{NC} B(n) + \sum_{NC} S(n)}{K \times TD} \tag{4.2}$$

The service time S(n) is adjusted to a value $S_s(n)$, where $S_s(n) \le S(n)$, in these last two expressions in line with fractional loading and zero waiting time loading. η and 1 - η are the proportion of time that the excavator is idling and the proportion of time non-idling, respectively, while $\mu\eta / K\lambda$ and (1 - $\mu\eta / K\lambda$) are the proportion of time that the trucks are idling and the proportion of time non-idling, respectively. Here, for emission calculation purposes, excavator utilization is taken to be the same as the server utilization where the excavator is assumed to start working when the truck starts maneuvering; for trucks, the time for loading and queuing at load is regarded as idling time while backcycle time is considered as non-idling time. For the calculations below, the approach of Lewis (2009) along with the field data are used to establish the idling and non-idling emissions.

4.5 Case Study Data

4.5.1 Outline

A field study on a cut-and-fill operation was undertaken on a residential development construction site. The operation used a 1 m^3 bucket capacity excavator, and five trucks each of 6 m^3 capacity hauling approximately 300 m from loading to fill area. The rolling resistance was estimated at 5%, with loaded and return hauls having grade resistances the same in magnitude, namely -5% and +5% respectively. Field equipment time measurements were supplemented with data on fuel use, owning and operating costs, equipment capacities, distances, equipment engine power (HP), engine load and engine tier. The hourly owning and operating cost ratio of a truck to that of the excavator was 0.44. The equipment details are shown in Table 4.1.

Equipment	Engine power (HP)	Engine tier
Excavator (1 m^3)	140	3
Truck (6 m^3)	168	2

Table 4.1. Field study equipment characteristics.

4.5.2 Cycle data

Truck cycles were observed over an extensive period and data were recorded both manually and by video, giving the following truck event times: arrival at the excavator; start maneuver to load; start loading; end loading; arrival at the dump; start maneuver at dump; start dumping; and end dumping. From the data, queue waiting times and maneuver times at both the excavator and the dump, loading times, dumping times and travel times were obtained. Table 4.2 shows the resulting average truck cycle component times, giving a servicing factor (S/B), for the excavator as the server, of 0.51. Table 4.2 also gives the best fit Erlang distributions used in the chapter's simulations.

A summarised event time data for the truck cycles and cumulative distributions for each of the cycle component times are given in Appendix E.

Truck cycle component	**Mean** (min)	**Standard deviation** (min)	**Erlang shape parameter**
Queue at load area	4.227	1.505	3
Maneuver at excavator	0.504	0.220	109
Load	1.709	0.214	1404
Loaded haul	1.440	0.382	97
Maneuver at dump area	0.443	0.282	31
Dump	0.394	0.046	33413
Return	1.926	0.771	11
Backcycle	4.203	0.921	25
Service (at excavator)	2.213	0.330	413

Table 4.2. Field-observed truck cycle component times, and best fit Erlang distribution shape parameters.

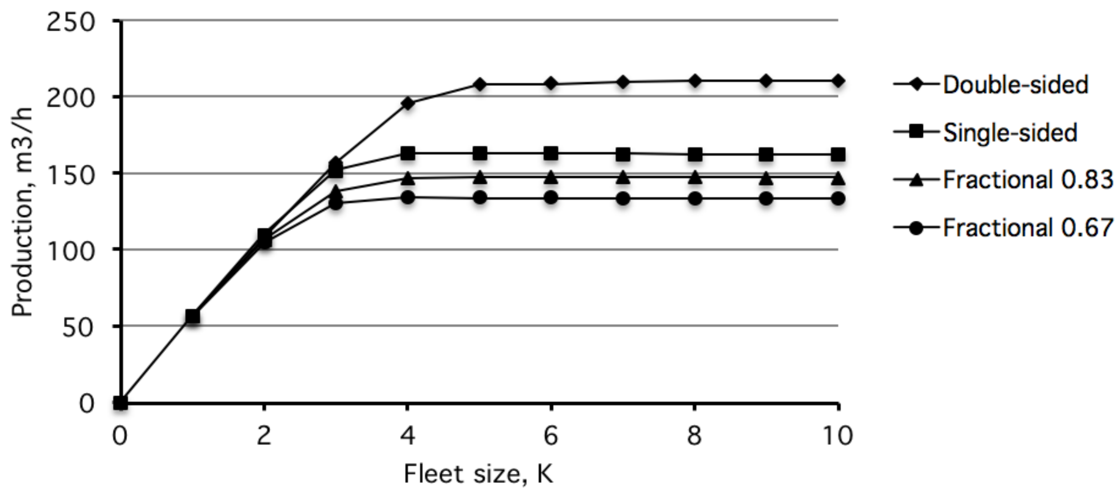
4.6 Results and Analysis

Based on the outlined modeling, calculations and case study data of the previous sections, production, unit emissions, unit costs and optimal fleet sizes for different loading policies can be established and compared.

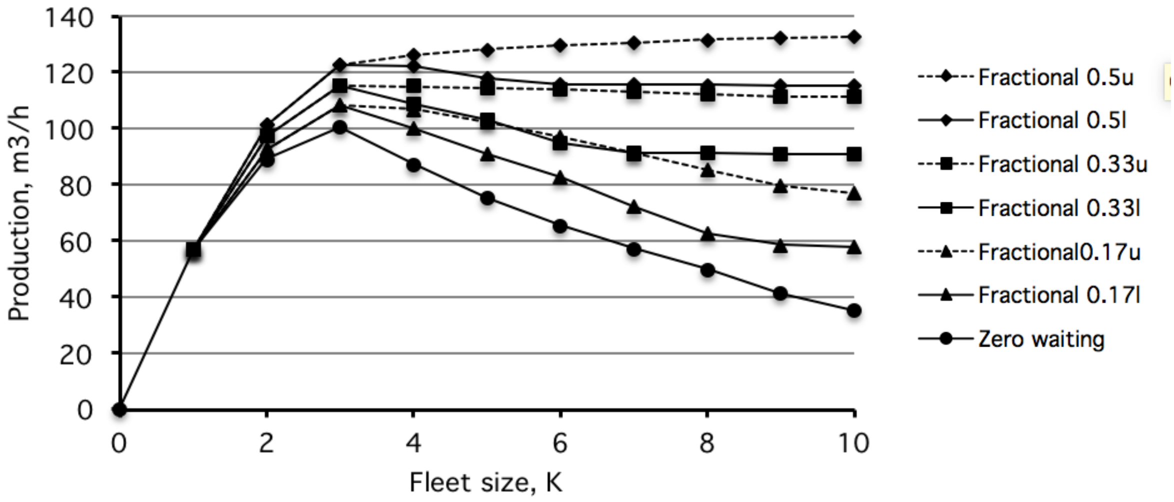
Comments common to all results given below are as follows. For K = 1, loading policies other than single-sided strictly don't exist, but have been included in all results presented as a check on the values calculated by the recursive relationships. For the particular case study, the backcycle time, loaded haul speed, fuel use and hence fuel cost and emissions were assumed to change little for all fractional loading cases because the loaded haul was downhill (negative grade resistance), narrow in places, and short in distance with a sharp bend and road speed limits restricting loaded travel speeds; the empty return speed, being the largest contributor to the backcycle time, and associated emissions and fuel cost are independent of the load. In other studies, these assumptions may not apply, in which case the backcycle time, truck speed and fuel cost would be adjusted in line with the lesser load being carried (Soofastaei et al., 2016b; Peralta et al., 2016).

4.6.1 Production

Figures 4.2a and 4.2b show production (expressed as m^3/h) plotted against truck fleet size for different loading policies. Double-sided loading, as anticipated through reducing idle time and maximizing equipment utilization, gives the highest production. This is followed by single-sided loading, equivalently fractional loading where the fraction is set as 1. For fractional loading, most noticeable below fractions of about 0.67 and for large fleet sizes, the plots can take different shapes depending on the assumptions adopted at loading. The envelopes of shapes are demonstrated in Figure 4.2b. As the fraction nominated decreases, average truck waiting time reduces, but average service time (related to the number of excavator buckets) also reduces leading to lower average truck payloads and lower production. The zero waiting time case behaves similarly to fractional loading, and is equivalent to fractional loading where the fraction is set as 0; it leads to the lowest production of all loading policies.



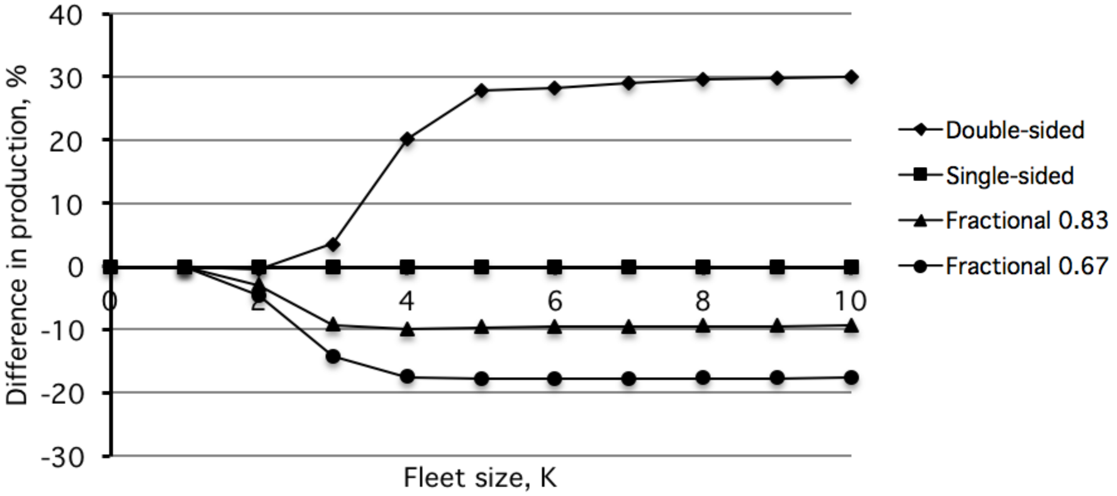
(a)



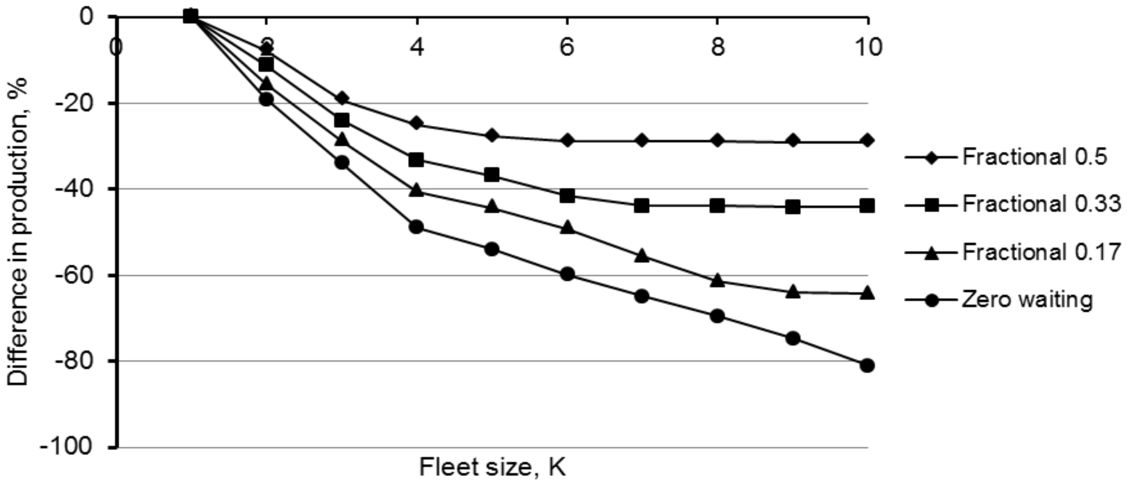
(b)

Figure 4.2. Production versus truck fleet size for different loading policies. (u – upper, l – lower).

For the fractional loading cases, production reaches maximum values near the single-sided loading match or balance point (approximately 3 trucks). As a percentage change in production relative to single-sided loading, double-sided loading gives increases in production up to about 30%, because of decreased service times of up to 30 seconds, while the worst case (zero waiting time) decreases production by much greater amounts. Loading with one bucket less than full load only leads to a loss in production up to 10%. The difference in production compared to single-sided loading changes with fleet size, K. Figures 4.3a and 4.3b show the percentage difference in production for all the different loading policies, where a positive (negative) percentage denotes an increase (decrease) in production relative to the single-sided loading case. In getting to Figures 4.3a and 4.3b, the plots giving lowest production in Figure 4.2 are used.



(a)

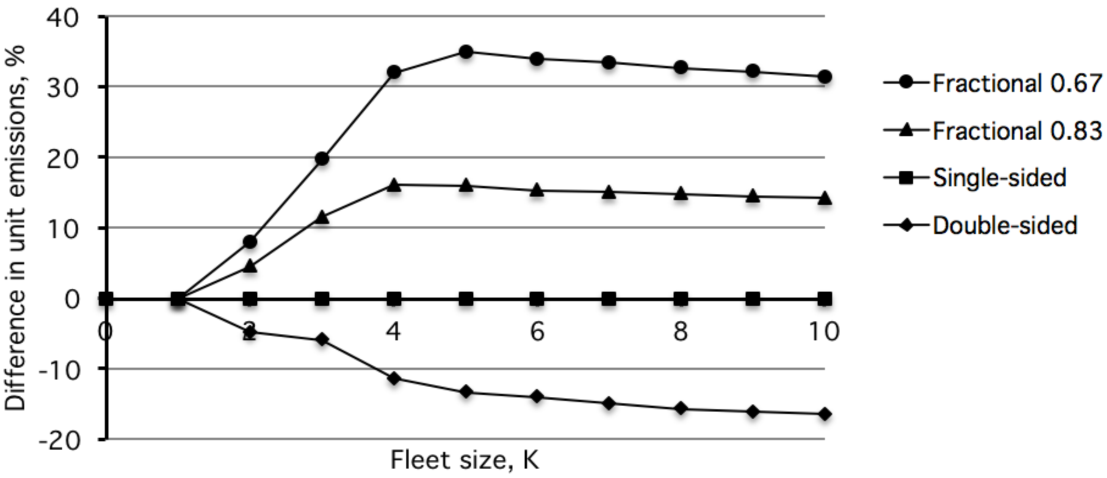


(b)

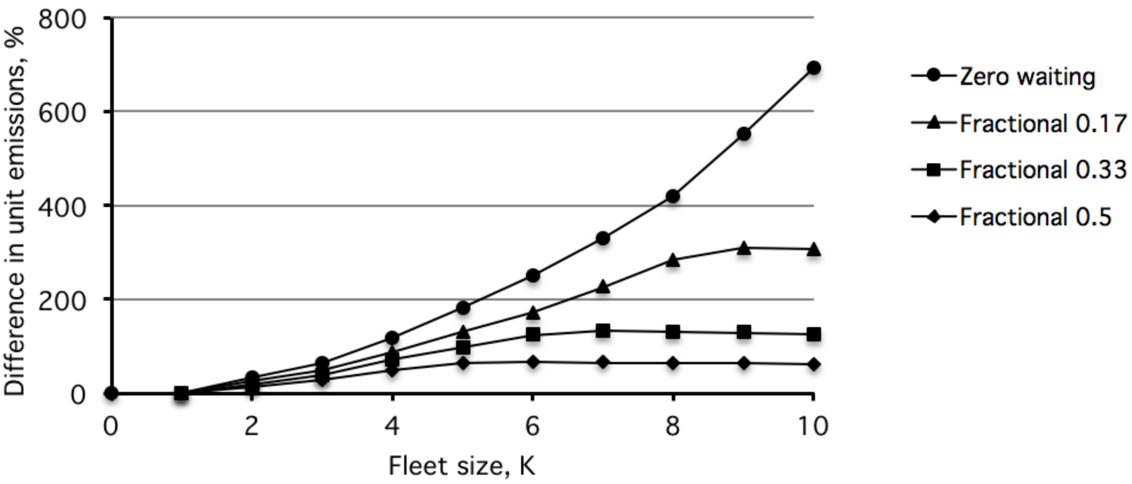
Figure 4.3. Percentage difference in production (compared with single-sided loading) versus truck fleet size for different loading policies.

4.6.2 Unit emissions

Figures 4.4a and 4.4b shows the percentage difference in unit emissions compared with single-sided loading for all the loading policies. In getting to Figures 4.4a and 4.4b, the plots giving lowest production in Figure 4.2 are used. The unit emissions are least for double-sided loading, while they increase as the fraction in fractional loading is reduced, with the greatest unit emissions being for zero waiting time loading. Double-sided loading reduces unit emissions by up to about 15%, while the fractional loadings for low fractions and zero waiting time loading increase unit emissions considerably, but dependent on the fleet size. Fractional loading leads to, for a given fleet size, an increased ratio of non-idle fuel use to idle fuel use, while with increasing truck numbers, the ratio of non-idle time fuel use to idle time fuel use of the excavator increases.



(a)



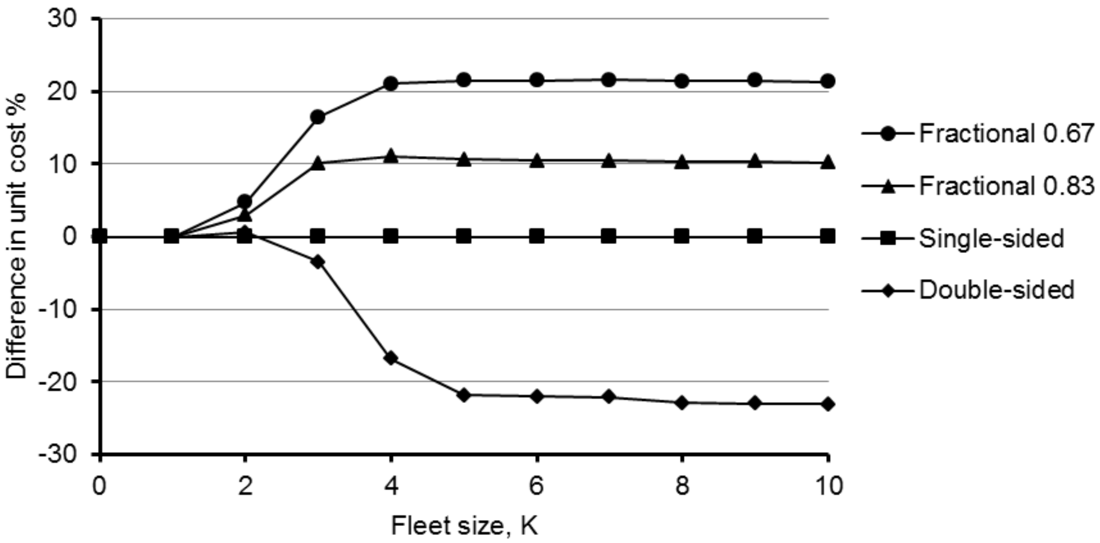
(b)

Figure 4.4. Percentage difference in unit emissions (compared with single-sided loading) versus truck fleet size for different loading policies.

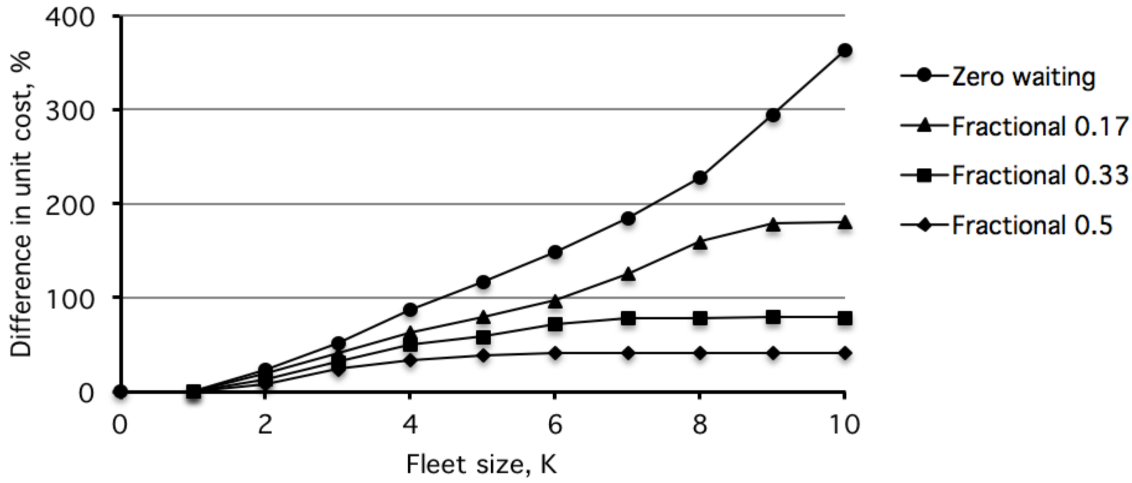
For fractional loading, the results show that loading to one bucket less than full load has an impact of about 15% on unit emissions for large truck fleets, while for two buckets less, this rises to about 30%, and this percentage continues to rise as the fractional load gets smaller. In terms of a practice recommendation, it could be said that under-loading by more than 1 bucket should not be contemplated.

4.6.3 Unit costs

The differences in unit cost, compared with single-sided loading, are shown in Figures 4.5a and 4.5b for all the loading policies. In getting to Figures 4.5a and 4.5b, the plots giving lowest production in Figure 4.2 are used. With similar trends and ranking to that observed with unit emissions, the unit costs are the least for double-sided loading, but increase as the fraction in fractional loading is reduced, with the greatest unit emissions being for zero waiting time loading. Double-sided loading reduces unit costs by up to about 20% compared with single-sided loading.



(a)



(b)

Figure 4.5. Percentage difference in unit cost (compared with single-sided loading) versus truck fleet size for different loading policies.

In terms of fractional loading, a result similar to the comment given on unit emissions applies. One bucket less than full load has about a 10% impact on unit cost for large truck fleets. A practice recommendation on fractional loading would be the same as for unit emissions.

4.6.4 Coincident unit emissions and unit costs

Figures 4.6 and 4.7 show the change in unit emissions and unit costs, respectively, with fleet size. Based on the results of the earlier figures, fractional loadings less than 0.67 would not be contemplated in practice, and are omitted.

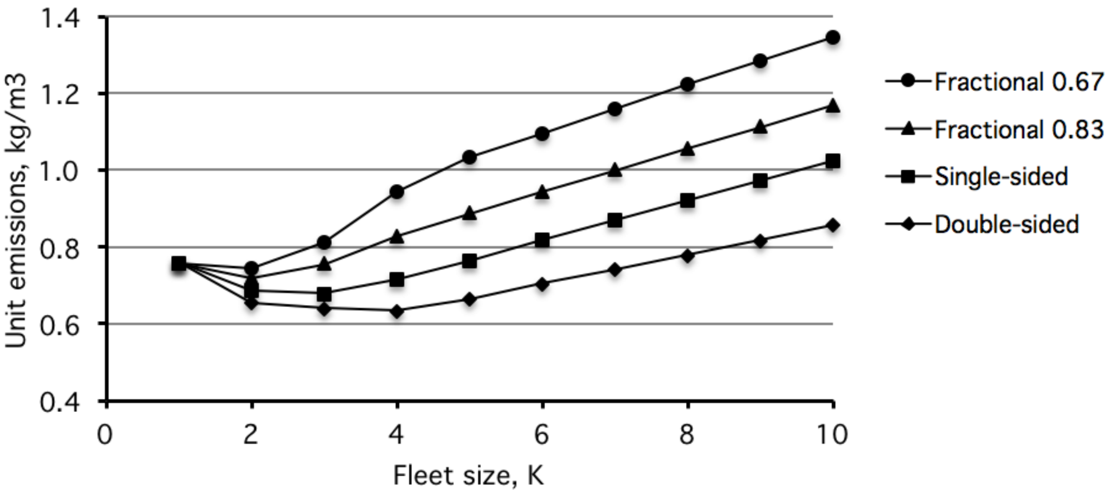


Figure 4.6. Influence of different loading policies on unit emissions for varying fleet sizes, K.

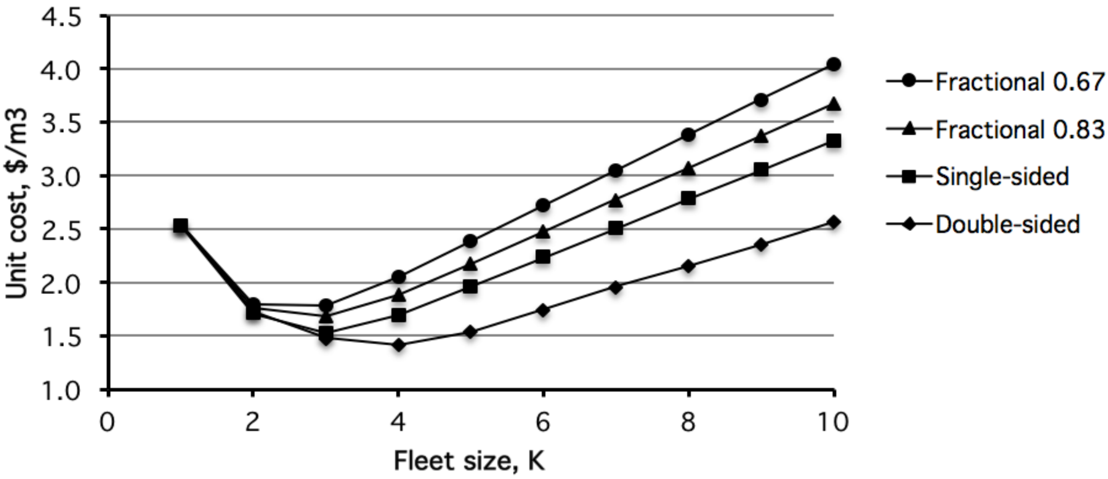


Figure 4.7. Influence of different loading policies on unit costs for varying fleet sizes, K.

Although the curves are reasonably flat near the optima, comparing Figures 4.6 and 4.7 for the respective loading policies, it is seen that the optimum fleet size for unit emissions and that for unit cost coincide for both single- and double-sided loading. This double-sided loading result is consistent with the earlier observation and proof made for single-sided loading (Carmichael et al., 2012, 2014a). As anticipated, the optimum fleet size for double-sided loading is greater than that for single-sided loading. For fractional loading, the optimum fleet size according to unit cost is greater than that for unit emissions. The absolute value of the optimum unit cost or unit emissions changes with each loading policy.

The implications of this, for single-sided loading and double-sided loading, are that managing excavator-truck operations efficiently according to least unit cost, is also best for the environment in terms of minimizing unit emissions, while not managing such operations efficiently creates unnecessary emissions. For fractional loading, the fleet size needs to be decreased below that for optimum unit cost in order to minimize emissions. For other reasons such as equipment reliability and availability, engineers might select a larger fleet size than those optima shown in Figures 4.6 and 4.7.

4.7 Discussion

In the Introduction it was mentioned that industry's lack of knowledge on loading policies was an impetus for this chapter. There it was stated that a large number of practitioners were informally interviewed as to what they thought would be the unit emissions and unit cost impacts and the magnitude and nature of these impacts due to different loading policies, and no one was able state with any confidence what these would be.

The following comments and the Conclusion are given based on the case study results. From an examination of the underlying equations (Appendix D), it can be seen that the comments on trends (but not the magnitude of the values) will hold generally true for other usual earthmoving operations.

All the examined loading policies reduced truck waiting times when compared with commonly used single-sided loading. Truck waiting time is idle or non-productive time. All the non-singled-sided loading policies also attempt to increase equipment utilization (percentage of time working). Reducing truck idle time and increasing equipment utilization might be anticipated to increase production and reduce emissions and costs (Lewis et al., 2012). However, with different loading policies, there can be a counter-balancing reduced production, and it is not immediately clear where the trade off lies between reduced truck idle time, increased equipment utilization and changed loading policy. The results demonstrate that solely concentrating on truck waiting time (and truck queue length) is not appropriate, but rather the optimum is obtained by balancing the excavator and truck utilizations, and taking regard of the ratios of emissions magnitudes and ratio of costs of the different equipment. Low truck waiting times may or may not lead to higher unit emissions and unit costs.

Figures 4.3 to 4.5 show the penalties/bonuses attached to different loading policies. Clearly the best loading policy in terms of both unit emissions and unit costs is double-sided loading, subject to its being physically possible on site through having accessible space and site layout allowing maneuvering, and appropriate equipment. Safety issues may also need extra attention over single-sided loading. The chapter demonstrates the bonus involved in using double-sided loading. The chapter’s results present a strong argument for designing earthmoving operations such that double-sided loading is possible. Fractional loading and zero waiting time loading policies all fared worse than single-sided loading, and should not be contemplated, except perhaps for large fleet sizes where underloading trucks by one bucket only gives a small penalty. The chapter demonstrates the unit emissions and unit cost penalties involved in fractional and zero waiting time loading policies, should they be employed.

Considerations relating to equipment wear and tear and maintenance are additional to the chapter's analysis, though these influences are not anticipated to differ much between different loading policies. Consideration of equipment operators being actively involved rather than sitting and waiting might also be important for people management purposes. The chapter emphasized unit emissions and unit costs relative to single-sided loading. Absolute unit emissions and absolute unit costs could be decreased further through, for example, haul road changes, equipment modifications, alternative fuel use (Carmichael et al., 2014b), and operator training (Jukic and Carmichael, 2016); however the relative results presented in this chapter will not change, and the same conclusions will hold.

4.8 Conclusion

This chapter demonstrated the penalties/bonuses associated with non-standard earthmoving loading policies on unit emissions, production, unit costs and optimum truck fleet sizes, in response to a gap in knowledge in the literature. Monte Carlo simulation was used for the analysis in conjunction with field data. Alternative loading policies led to different combinations of idle times, equipment utilizations and production.

The case study and underlying equations indicate the following, amongst other matters:

- A zero waiting time loading policy contributes the worst impact to the environment and is the least cost effective.
- Double-sided loading contributes the least impact to the environment and is the most cost effective.
- Minimizing truck waiting times through using fractional loading is generally not an attractive policy because it leads to an increase in unit emissions and unit costs.
- For fractional loading, loading to one bucket less than full load has a small impact on unit emissions and unit cost for large truck fleets. Underloading by more than one bucket should not be contemplated.
- Optimum unit emissions and optimum unit cost are coincident with respect to fleet size for single-sided and double-sided loading policies. That is, by minimizing unit cost, as in traditional practice, then least impact on the environment is obtained. Not minimizing unit cost will lead to unnecessary emissions.
- For fractional loading, the optimum fleet size according to unit emissions is less than that for unit costs. That is, least impact on the environment is obtained by running at cost inefficiency.

CHAPTER 5 - PARAMETER STUDIES FOR NON-STANDARD EARTHMOVING LOADING POLICIES

5.1 Introduction

A considerable amount of literature has been published on estimating production and determining the unit cost and unit emissions based on the configuration of common practice in earthmoving operations. A common practice can be described as when an operation of loader or excavator –truck utilizes single-sided loading of trucks, in which the trucks get loaded fully in turn. However, there are other possible loading policies which include double-sided loading, fractional loading and multiplier loading. The value of adopting other loading policies in terms of production and cost has been addressed separately by Chironis (1991), Smith et al. (1995), Nunally (2000), Hardy (2007) and Marinelli and Lambropoulos (2012). A recent study by Kaboli and Carmichael (2016) has turned to also looking at the influence of different loading practices on the emissions. It is important to note that the alternative loading policies may affect earthmoving parameters in terms of load, load time, cycle time, idle time and equipment utilization (percentage of time working). However, since these underlying parameters are interrelated with fuel use (and hence emissions), costs and operation production, it is unclear to what extent that the alternative loading policies will change these underlying parameters on unit emissions and unit costs outcomes. Therefore, this chapter aims to explore the influence of the underlying parameters on unit emissions and unit costs.

Earthmoving operations commonly utilize a large range of equipment that generates a considerable amount of greenhouses gas (GHG) emissions. According to the EPA Clean Air Act Advisory Committee (2006), all types of off-road diesel engines from construction and mining operations emitted approximately 32% of NO_x and 37% of PM emissions (Ahn and Lee, 2013). Reconfiguring loading policies has the potential to reduce emissions through reducing equipment idle time associated with loading or waiting to be loaded. In general, reducing 10% idling of the off-road diesel equipment will result in lower GHG emissions, which provide a sector-wide saving of approximately 1.8 billion lbs of CO_2 per year (EPA, 2009). Considering the significance of minimizing the equipment idle time that would result in a reduction of emissions, there is an identified need to study the effect of alternative loading policies on unit emissions and unit costs.

It is important to take note that the chapter extends the analysis of Monte Carlo simulation from Chapter 4 by incorporating the examination on slight overloading and slight underloading cases. A cut-and-fill operation on a residential construction site provides the data for the case study.

This chapter has been organized in the following way. First, discussion on different loading policies and the computational approach employed in this study are presented, followed by a case study using field data. The next section discusses the influence of underlying parameters on unit emissions and unit costs for different loading policies. The final section presents the conclusions.

The primary aim of this chapter is in establishing the effect of underlying parameters on unit emissions and unit costs for alternative loading policies in excavator-truck operations. The importance and originality of this study is to present an economical and environmental friendly method of designing and managing earthmoving operations.

The background to this chapter is given in Sections 2.3 and 2.4.

5.2 Alternative Loading Policies

5.2.1 Single-sided loading policy

Single-sided loading is a common loading policy that requires the following truck to wait for the preceding truck to complete loading. In most cases, trucks are loaded on one side of the excavator, and this particular loading is applied in the case study data and the single-sided loading benchmark for the present study.

This chapter has extended the analysis of the common single-sided loading by overloading every truck with one extra bucket and underloading every truck with one less bucket.

5.2.2 Double-sided loading policy

According to the common loading policy, the excavator will return to pick up the first bucket load after loading the last bucket on a truck, and then swing to load the following truck. In this case, the excavator is idle while waiting for the following truck to maneuver into a loading position. Double-sided loading can be adopted to reduce or eliminate excavator waiting time. Generally, double-sided loading can be described when the trucks are able to be loaded on either side of the excavator. Meanwhile, the following truck can start to maneuver (and possibly completed) without waiting for the preceding truck to complete its loading. Commonly, trucks are reversed into a loading position, but in some cases it might be driven directly in to be loaded as in the ‘in-line’ single-sided loading case if the site permits. The excavator will immediately start to load the following truck when it has finished loading the preceding truck. Therefore, this is believed to lower service time at the excavator, lower idle time for the trucks, and potentially increase production.

5.2.3 Fractional loading policy

Fractional loading refers to a truck load that is less than or equal to a full load which depends on the arrival time of the following truck. In this chapter, the fraction is preset to 0.83 in the case of fractional loading with one less bucket, using a minimum of 5 excavator buckets but could be 6 buckets depending on the available time prior to the arrival of the following truck. The preceding truck will be filled to at least the preset fraction before moving away from the loading point prior to the arrival of the following truck. Each truck is loaded between a fraction of full load and full load.

5.2.4 Multiplier loading policy

Multiplier loading policy adjusts the loading time such that loading of at least a single full load occurs, but can load to multiplier of a full load if time is available. The fraction is preset to 1.17 and corresponds to loading with one extra bucket for overloading case. This practice is believed to cause larger truck payload and higher hourly production despite the increase of fuel use resulting from the increase of load time and travel time.

5.3 Underlying Modeling

This chapter has extended the analysis in Chapter 4 by incorporating multiplier loading policy. The underlying models used in the chapter's analysis for single-sided, double-sided and fractional loading policies is given in Appendix D while the equations for multiplier loading policy are given in Appendix F.

5.4 Case Study Data

5.4.1 Outline

A field study on a cut-and-fill operation was undertaken 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. The haul road was broken down into two sections that have different distances and grades. The first section of the loaded haul was downhill (negative grade resistance), while its return haul having the same magnitude of grade resistances that were -6% and +6% respectively, with a distance of 250 m. The later section was a level road with a distance of 1150 m. The rolling resistance was estimated at 3%. The time measurement for field equipment was supplemented with data on fuel use, owning and operating costs, equipment capacities, distances, equipment engine power (HP), truck weight and engine tier. The hourly owning and operating cost ratio of a truck to that of the excavator was 0.47. The equipment details are shown in Table 5.1.

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

Table 5.1. Field study equipment characteristics.

5.4.2 Cycle data

Table 5.2 shows the result of average truck cycle component times, giving a servicing factor (S/B), for the excavator as the server, of 0.37. Table 5.2 illustrates the best fit Erlang distributions used in the chapter's simulations.

Truck cycle component	**Mean** (min)	**Standard deviation** (min)	**Erlang shape parameter**
Queue at load area	3.842	1.517	3
Maneuver at excavator	0.407	0.200	103
Load	1.912	0.663	19
Loaded haul	2.721	0.398	295
Maneuver at dump area	0.411	0.228	62
Dump	0.244	0.069	2625
Return	2.872	0.619	56
Backcycle	6.248	0.665	199
Service (at excavator)	2.319	0.660	28

Table 5.2. Field-observed truck cycle component times and best fit Erlang distribution shape parameters.

Truck cycles were observed for an extensive period of time and data were recorded both manually and by video, giving the following truck event times: arrival at the excavator; start of maneuvering to load; start loading; end loading; arrival at the dump; start of maneuvering at the dump; start dumping and end dumping. From the data, queue waiting times and maneuver times at both the excavator and the dump, loading times, dumping times and travel times were obtained. A summarised event time data for the truck cycles and cumulative distributions for each of the cycle component times are given in Appendix G.

5.5 Results and Analysis

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 policies can be established and compared in this section. The case study data and the single-sided loading benchmark used in the studies below are based on a truck that is loaded on one side of the excavator. In addition, the approach developed by Peralta et al. (2016) was adopted in this case study to examine the overloading and underloading cases, in which the loaded haul time, loaded haul speed and fuel use for loading with extra or less bucket cases were adjusted in line with the lesser and greater load being carried. The formulations employed in the analysis of this study are provided in Appendix H.

5.5.1 Production, unit emissions and unit costs

Figure 5.1 shows the production (expressed as m^3/h) plotted against truck fleet size for different loading policies based on the field study data. Double-sided loading performed by reducing idle time and maximizing equipment utilization is observed to have the highest production. This is followed by the overloading of the truck with one extra bucket (single-sided loading), which seems to increase the production up to 10% compared to the common single sided loading. It can also be observed that underloading the truck with one less bucket leads to the lowest production among other loading policies.

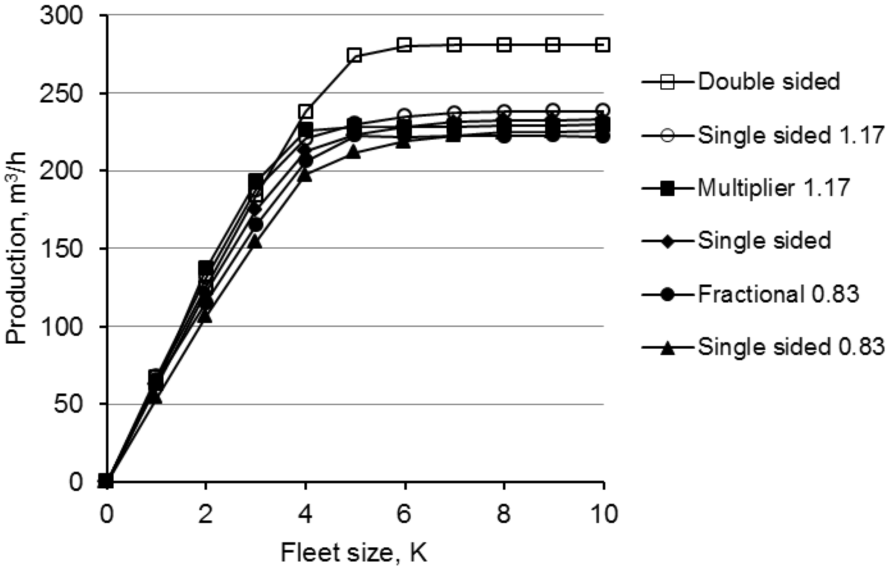


Figure 5.1. Production versus truck fleet size for different loading policies.

In the case of loading with one less or extra bucket, the findings reveal different trends between fractional, multiplier and single-sided loading, especially for small truck fleets. Fractional loading for loading with one less bucket seems to generate slightly higher production compared to underload using single-sided loading practice. The loading configuration in fractional loading policy is believed to increase both server utilization and truck utilization and leads to the increase of production up to 8% in small truck fleets compared to underloading the truck with always one less bucket. Contrastingly, the overloading with one extra bucket using multiplier loading shows 4% higher production in small truck fleets compared to the single-sided loading policy.

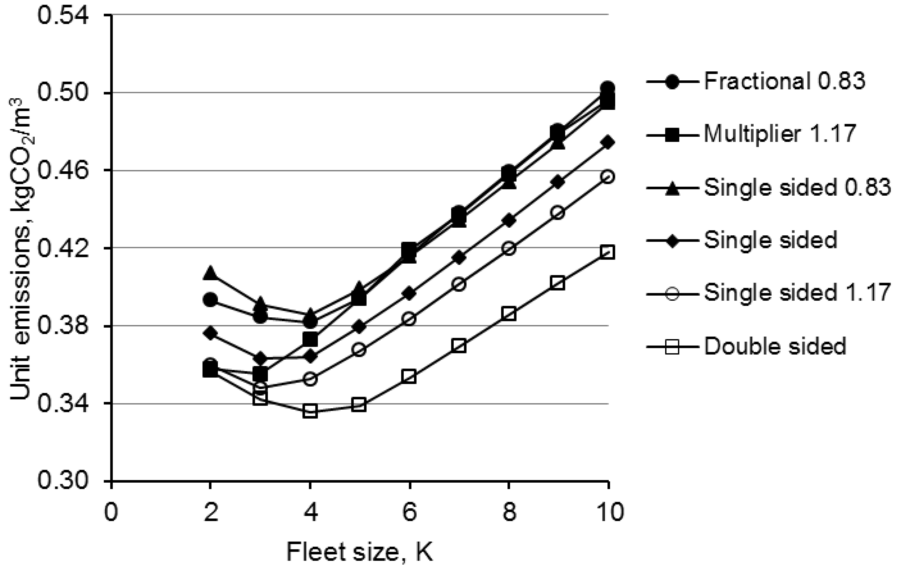


Figure 5.2. Unit emissions versus truck fleet size for different loading policies.

Figure 5.2 shows unit emissions (expressed as kg/m^3) plotted against truck fleet size for different loading policies. The unit emissions are found to be the least for double-sided loading, with a considerable increase in single-sided, multiplier and fractional loading. The results also show that the greatest unit emissions are achieved for fractional and single-sided with one less bucket loading, but depending on the fleet size. This is followed by multiplier loading where the unit emissions initially show an impact of about 5% lower than common single-sided loading for a small truck fleet, while the plot rises up to 6% for large truck fleets.

Figure 5.3 shows unit costs (expressed as \$/m^3) plotted against truck fleet size for all the loading policies. Unit costs for all loading policies are demonstrated to share similar trends to those observed with unit emissions in Figure 5.2. Apart from that, it can be seen that the optimum fleet size for minimum unit emissions and unit costs tend to change for each loading policy.

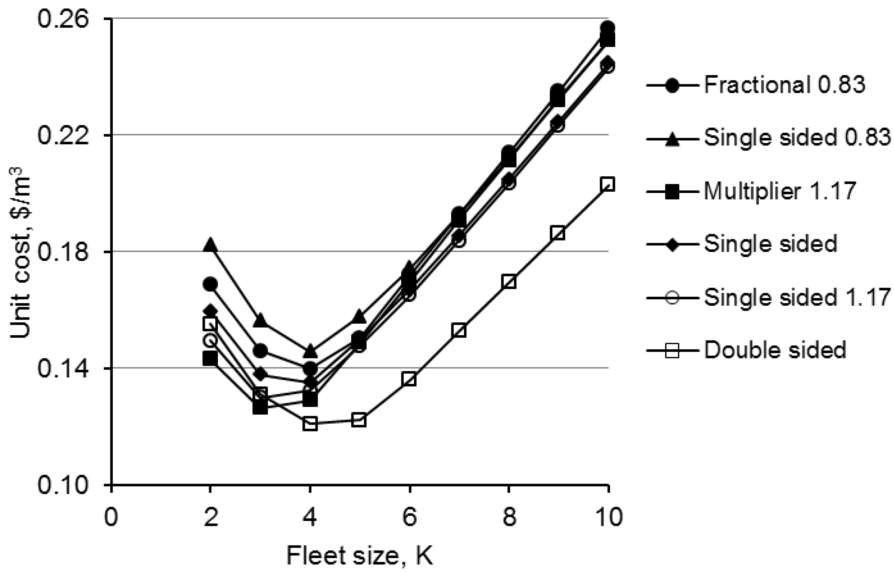


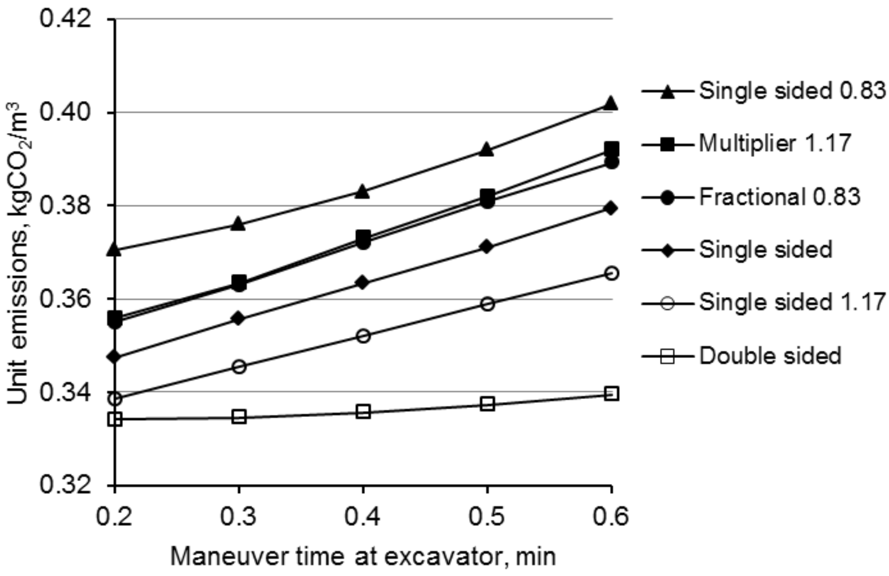
Figure 5.3. Unit cost versus truck fleet size for different loading policies.

The influence of varying the underlying parameters of earthmoving which include truck maneuver time at excavator, truck load time, truck service time, truck travel time, truck maneuver time at the dump, truck dump time, truck backcycle time and truck waiting time for different loading policies are demonstrated in the following section.

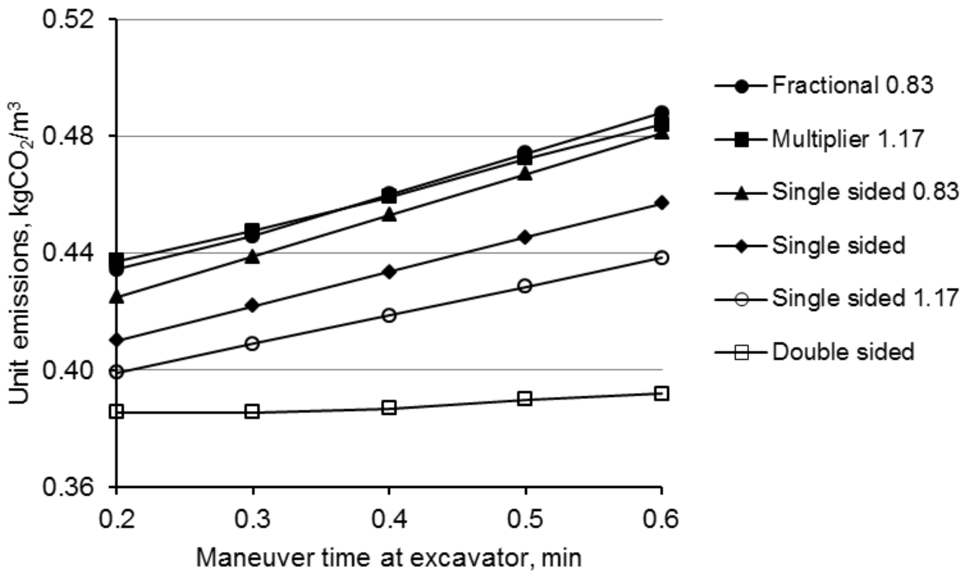
This analysis investigates the effect of varying truck cycle component times on unit emissions and unit costs for truck fleet size of K=2 to K=10. However, only K=4 and K=8 are shown and discussed in this section for the purpose of demonstrating the effect of changing parameters on different truck fleet size. The findings revealed that there is a change in the ranking of unit emissions and unit costs of each alternative loading policy when there is a change in truck cycle component time and truck fleet size.

5.5.2 Influence of maneuver time at excavator

Figures 5.4a and 5.4b show the effect of changing truck maneuver time at excavator from 0.2 min to 0.6 min on unit emissions for truck fleet size, K=4 and K=8. The average maneuver time at excavator of 0.407 min corresponds to the observed data obtained at the site. In the case of double-sided loading, the reduction of truck maneuver time has caused the unit emissions to increase only slightly based on the increase of truck maneuver time, while the increase of truck maneuver time for other loading policies demonstrates a relative increase of unit emissions.



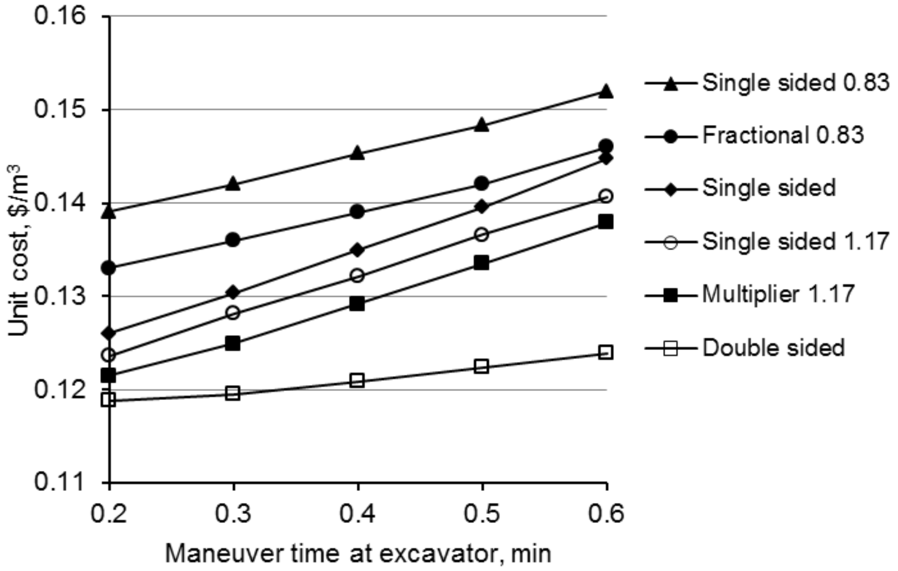
(a) Truck fleet size, K=4



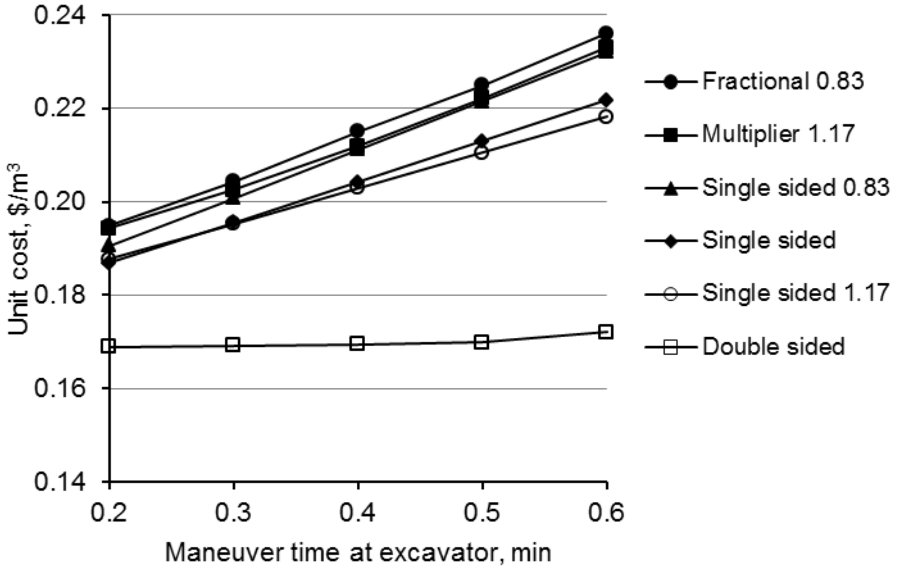
(b)Truck fleet size, K=8

Figure 5.4. Unit emissions versus truck maneuver time at excavator for (a) K=4 and (b) K=8.

As shown in Figures 5.5a and 5.5b, the trend of unit costs is consistent with unit emissions to those observed in both truck fleet sizes.



(a) Truck fleet size, K=4

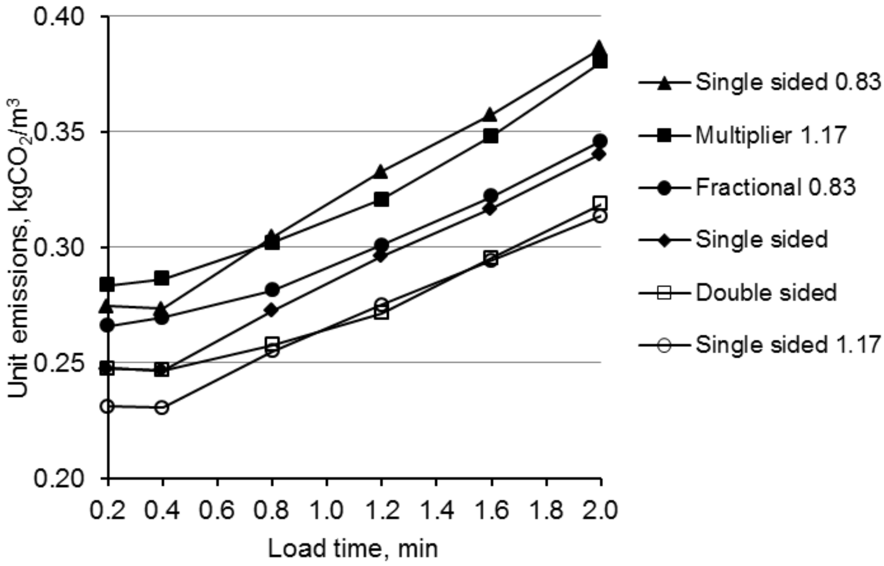


(b) Truck fleet size, K=8

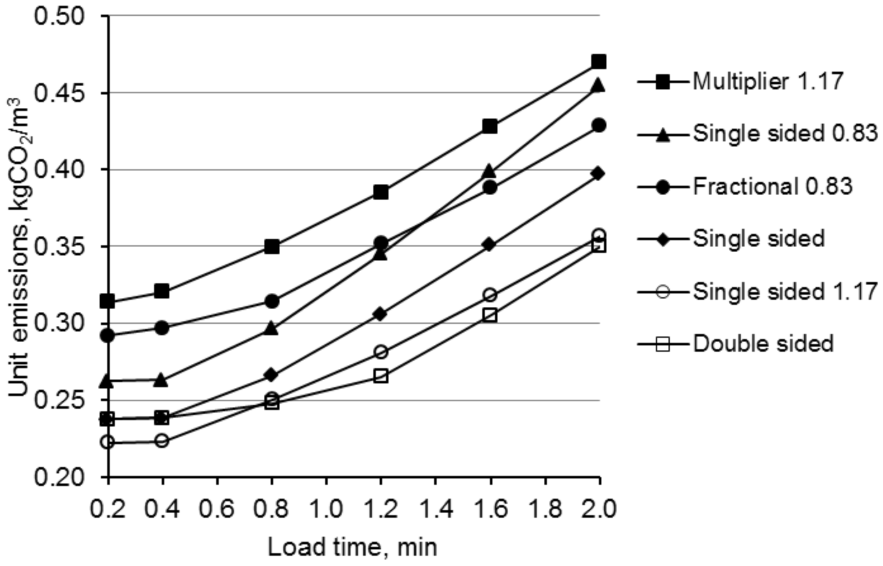
Figure 5.5. Unit cost versus truck maneuver time at excavator for (a) K=4 and (b) K=8.

5.5.3 Influence of load time

Figures 5.6a and 5.6b illustrate the effect of varying load time on unit emissions and unit costs for truck fleet size K=4 and K=8.



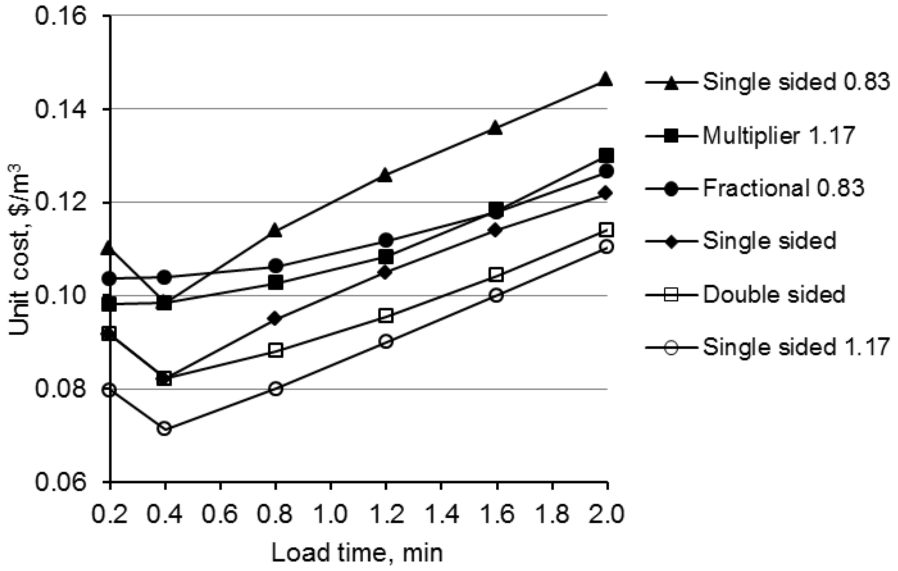
(a) Truck fleet size, K=4



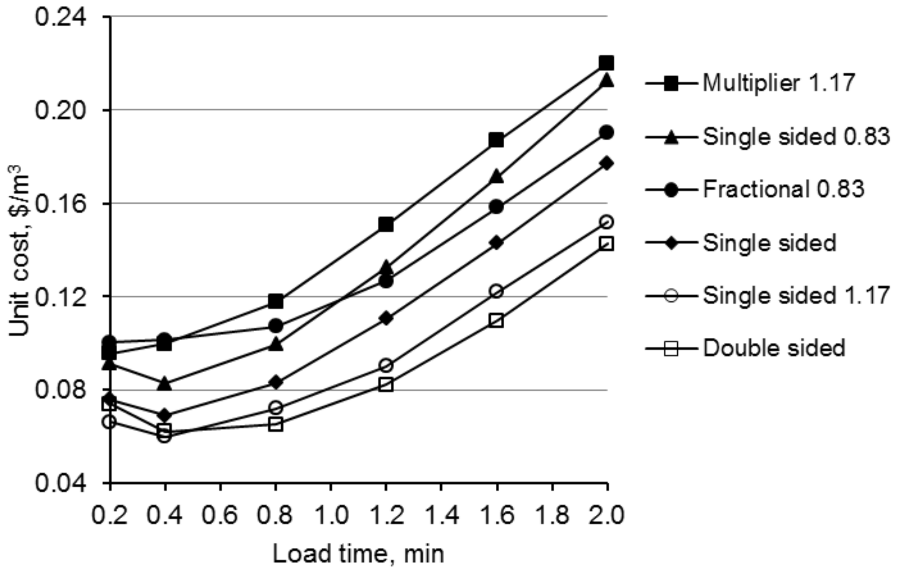
(b) Truck fleet size, K=8

Figure 5.6. Unit emissions versus truck load time for (a) K=4 and (b) K=8.

Generally, it can be observed that unit emissions for all loading policies tend to reduce with the increase of load time from 0.2 min to 0.4 min, but it increases for load time greater than 0.4 min. Apart from that, the plots for unit emissions flatten at the optimum load time, 0.4 min, before it increases for higher load time in the case of certain loading policies. The similar behavior is observed for the unit costs shown in Figures 5.7a and 5.7b.



(a) Truck fleet size, K=4

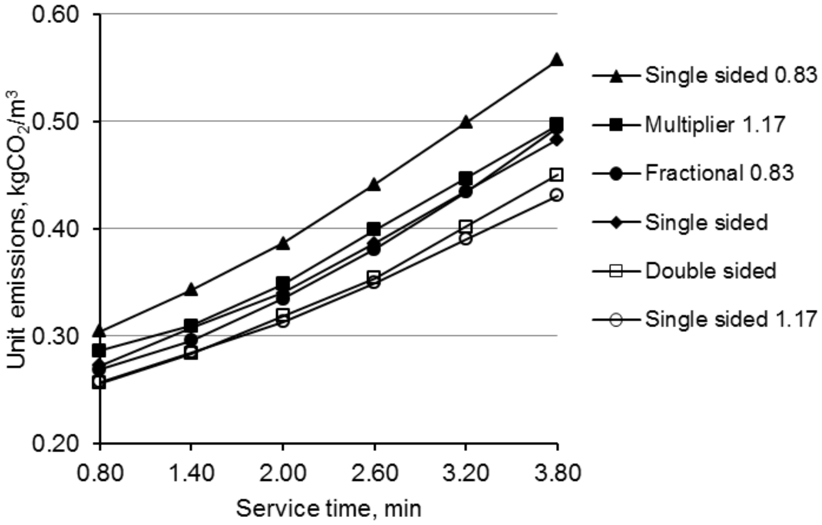


(b) Truck fleet size, K=8

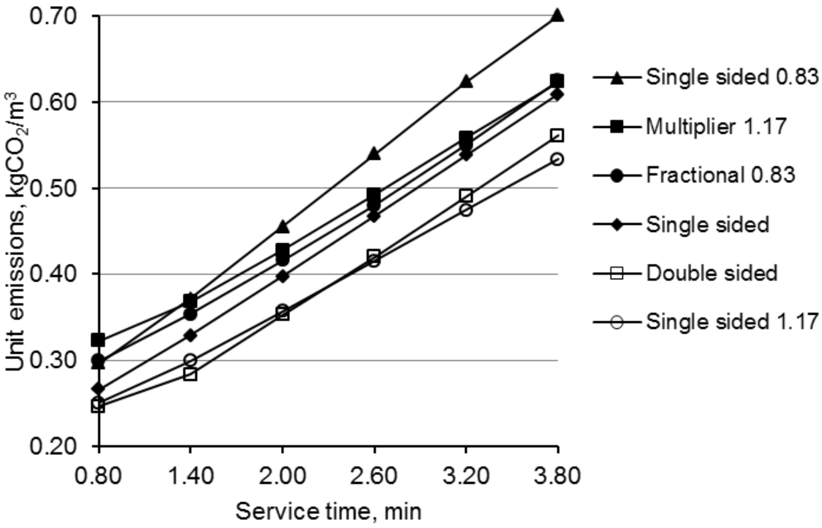
Figure 5.7. Unit cost versus truck load time for (a) K=4 and (b) K=8.

5.5.4 Influence of service time

The effect of service time on unit emissions for truck fleet size of K=4 and K=8 are shown in Figures 5.8a and 5.8b. Service time is obtained from the combined maneuver time at loader and load time. Other truck cycle component times are kept constant, while truck service time is varied from 0.8 min to 3.8 min. It is demonstrated that an increase in truck service time translates to a significant increase in unit emissions for all loading policies.



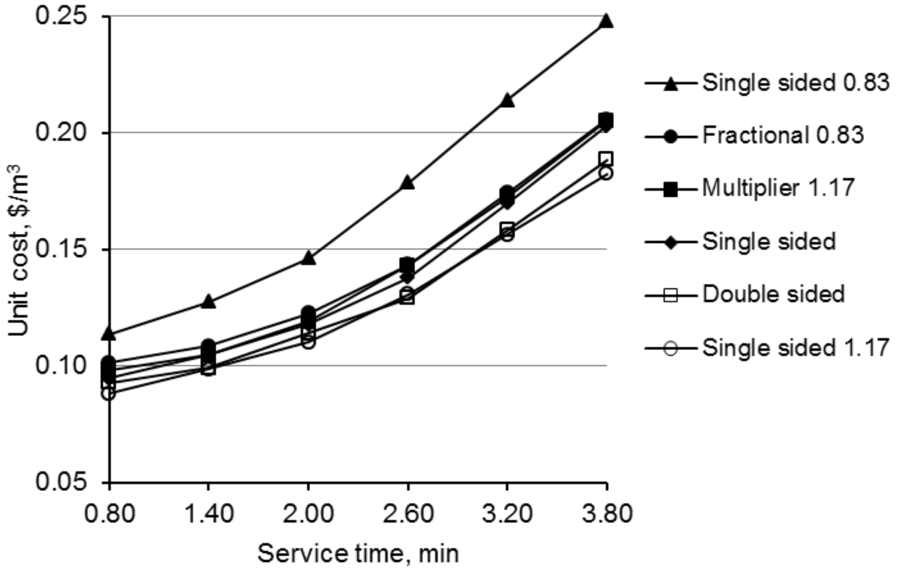
(a) Truck fleet size, K=4



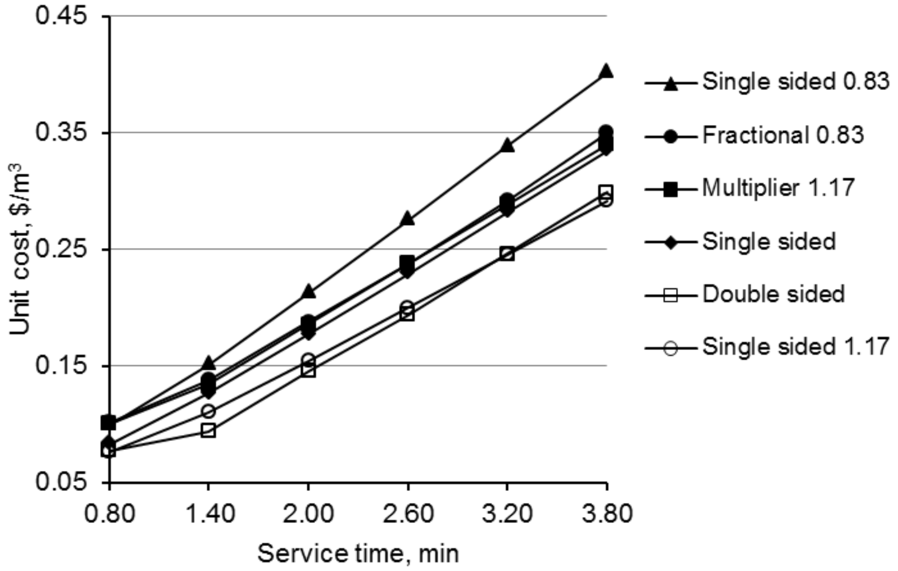
(b)Truck fleet size, K=8

Figure 5.8. Unit emissions versus truck service time for (a) K=4 and (b) K=8.

Figures 5.9a and Figure 5.9b show unit costs versus truck service time. Similar to that observed in unit emissions, unit costs are found to significantly increase with the increase of truck service time for both truck fleet sizes.



(a) Truck fleet size, K=4

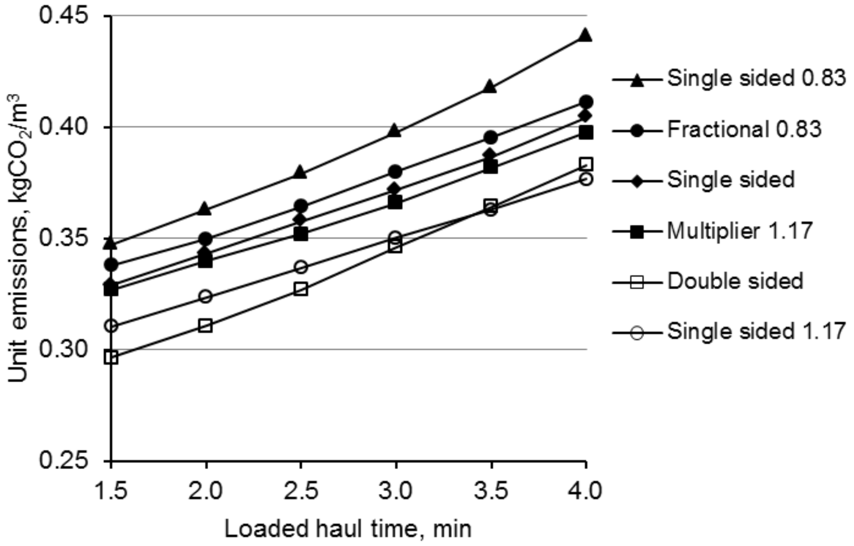


(b)Truck fleet size, K=8

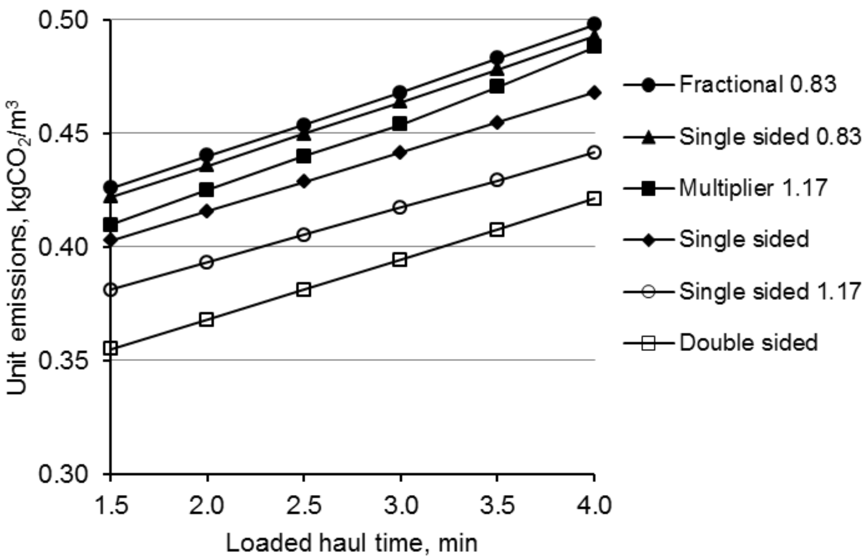
Figure 5.9. Unit cost versus truck service time for (a) K=4 and (b) K=8.

5.5.5 Influence of travel time

Figures 5.10a, 5.10b, 5.11a and 5.11b show the effect of unit emissions on a range of travel times for different loading policies. Travel time based on the site observations is described as the time taken of truck loaded haul and empty return. It can be observed that the increase in travel time has caused the unit emissions to increase in both truck fleet sizes for all loading policies.

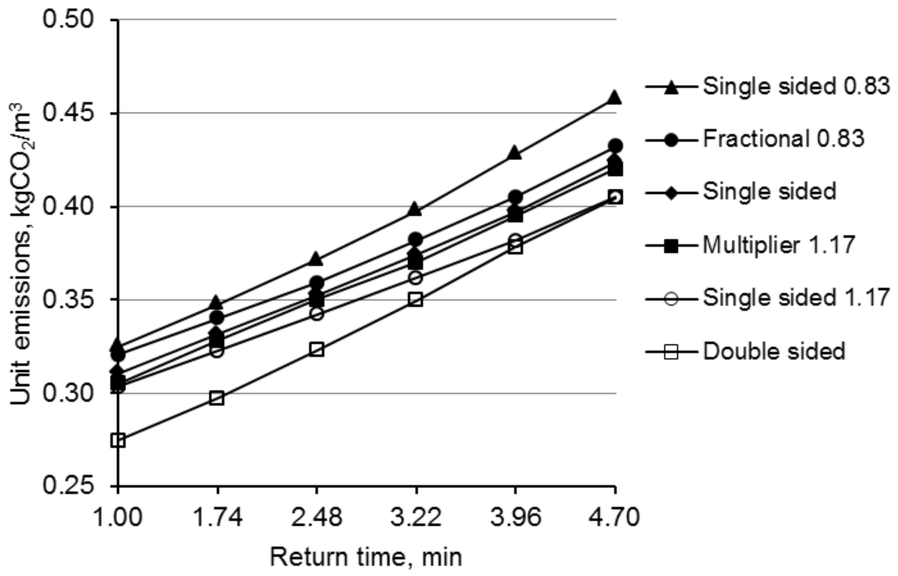


(a) Truck fleet size, K=4

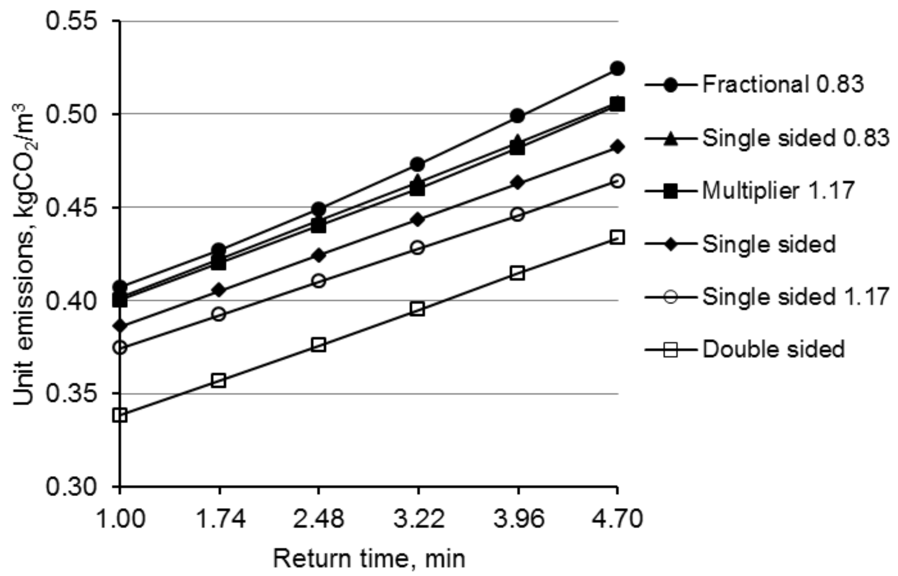


(b) Truck fleet size, K=8

Figure 5.10. Unit emissions versus loaded haul time for (a) K=4 and (b) K=8.



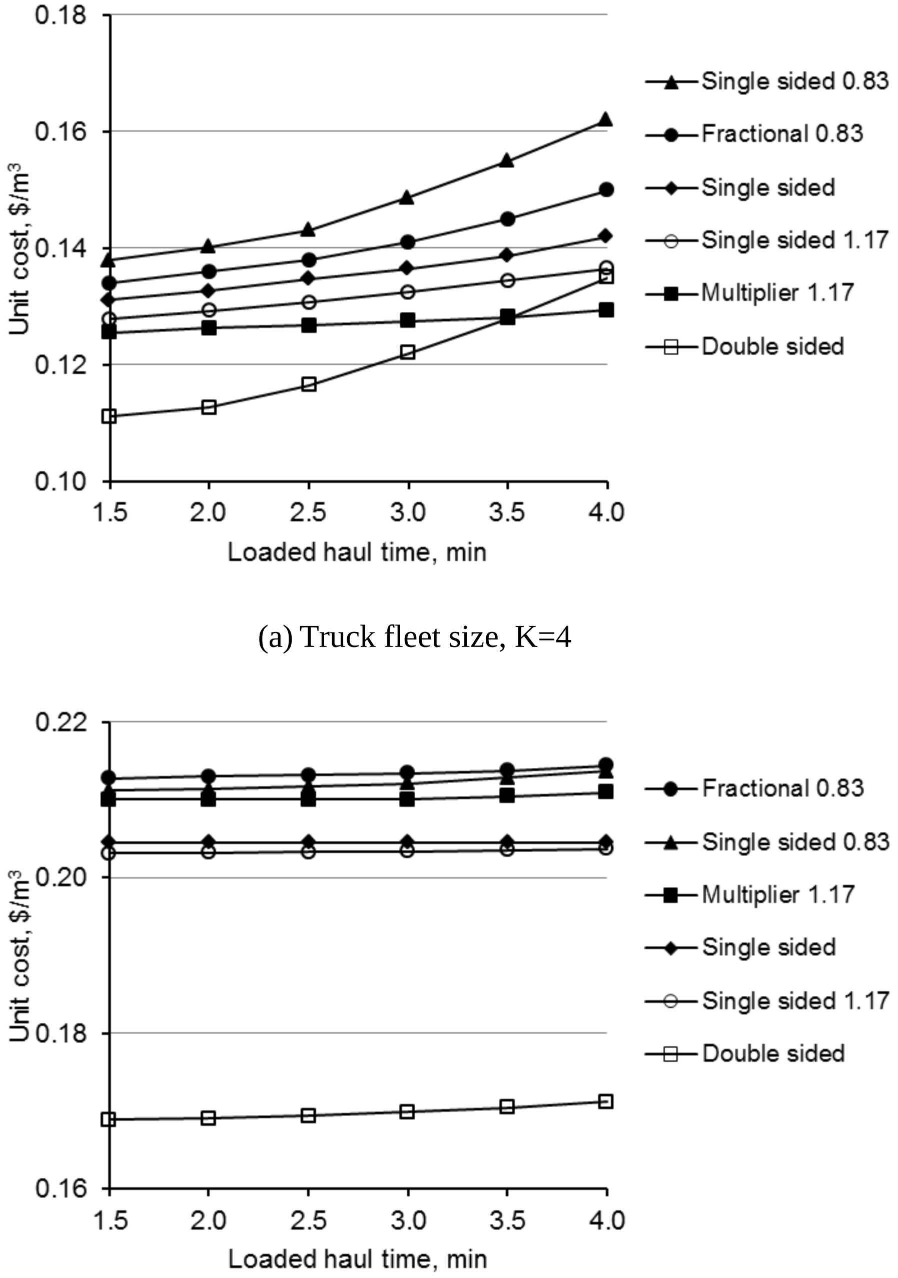
(a) Truck fleet size, K=4



(b) Truck fleet size, K=8

Figure 5.11. Unit emissions versus truck return time for (a) K=4 and (b) K=8.

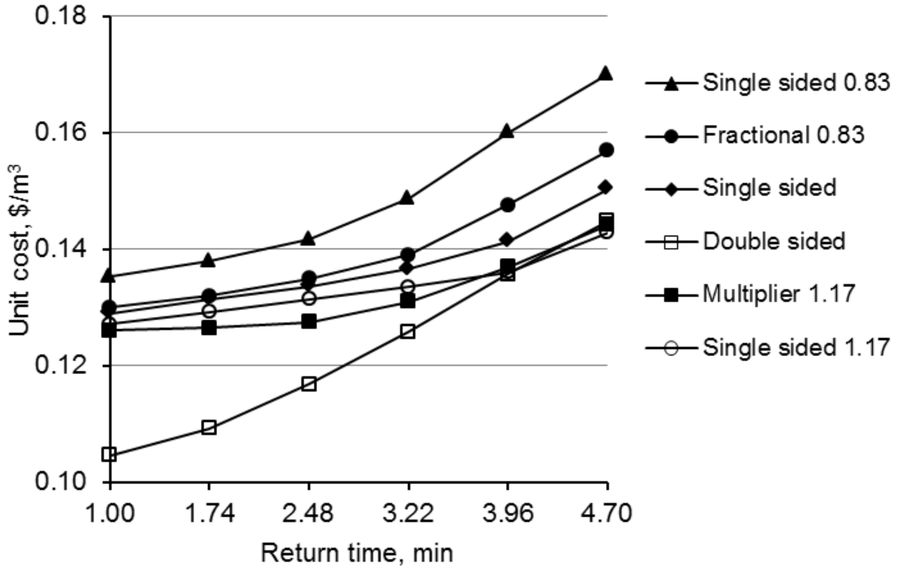
Figures 5.12a, 5.12b, 5.13a and 5.13b demonstrate the change of truck travel time on unit cost for different loading policies. The increase in truck loaded haul and empty return times has led to a slight increase in unit costs for small truck fleets. However, it remains approximately constant for large truck fleets.



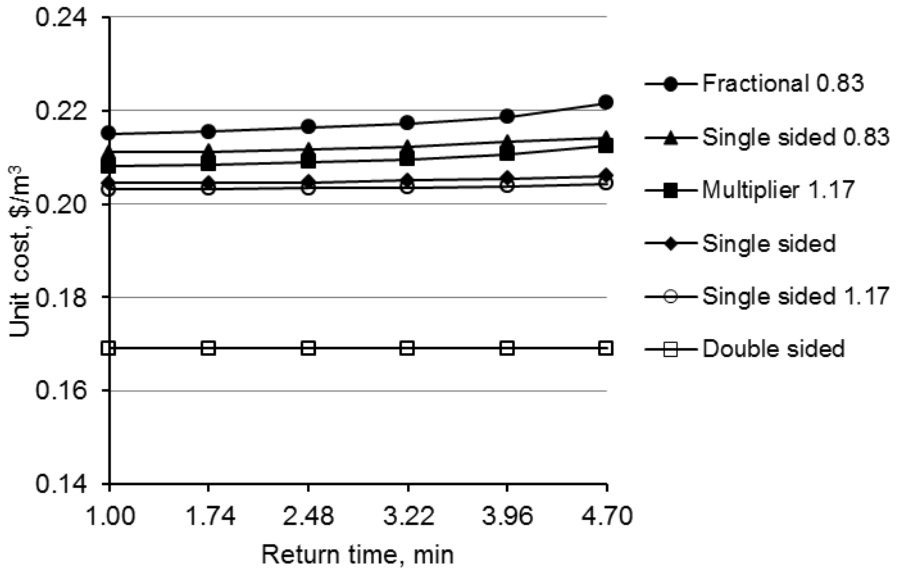
(a) Truck fleet size, K=4

(b) Truck fleet size, K=8

Figure 5.12. Unit cost versus truck loaded haul time for (a) K=4 and (b) K=8.



(a) Truck fleet size, K=4

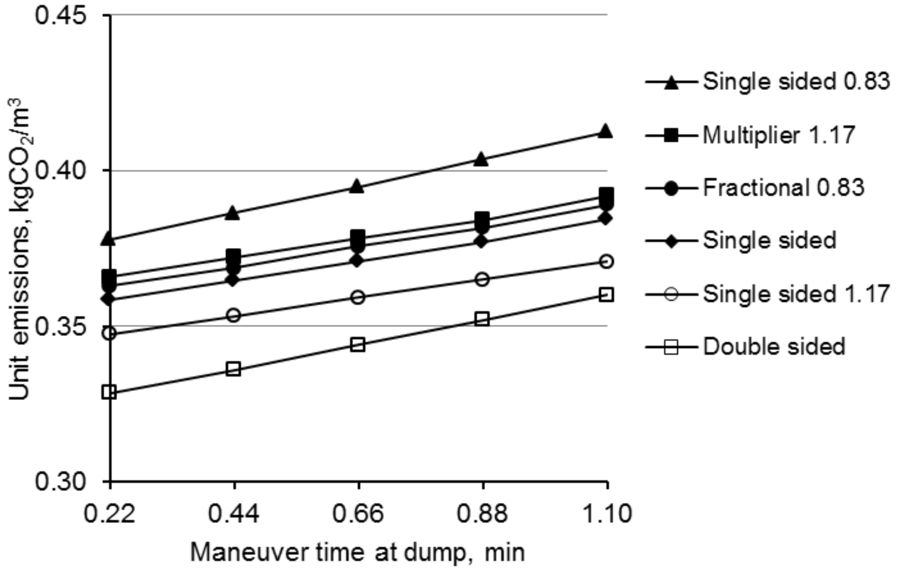


(b) Truck fleet size, K=8

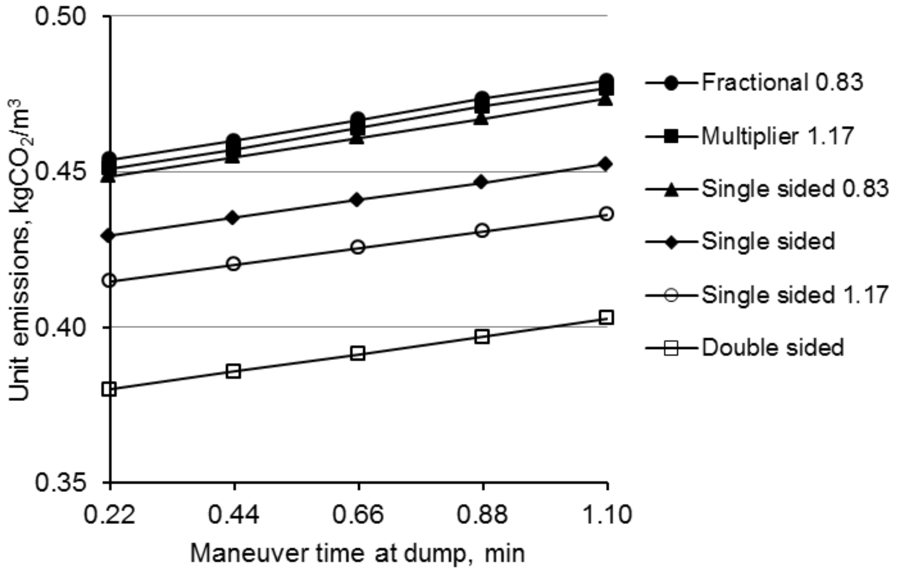
Figure 5.13. Unit cost versus truck return time for (a) K=4 and (b) K=8.

5.5.6 Influence of maneuver time at dump

Figures 5.14a and 5.14b show the change of truck maneuver time at dump ranging from 0.22 min to 1.1 min on unit emissions. The unit emissions for both truck fleet sizes have shown a relative increase with the increase of truck maneuver time at the dump for all loading policies.



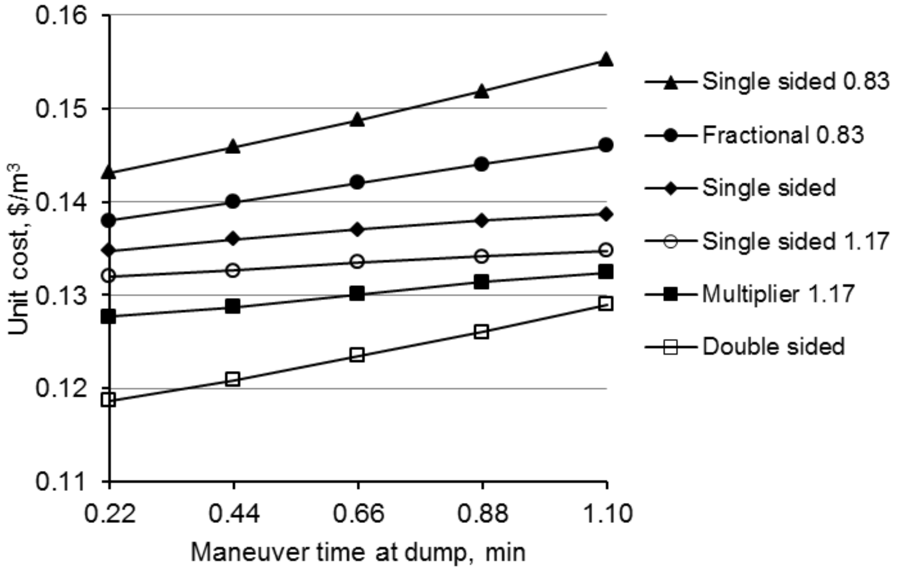
(a) Truck fleet size, K=4



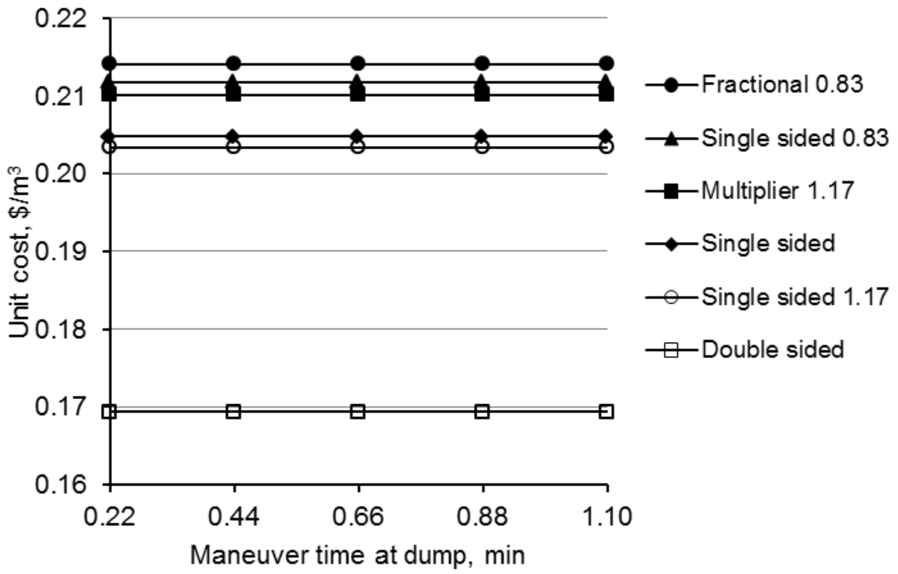
(b) Truck fleet size, K=8

Figure 5.14. Unit emissions versus truck maneuver time at dump for (a) K=4 and (b) K=8.

As shown in Figures 5.15a and 5.15b, a slight increase is observed in unit cost for small truck fleets. However, the unit cost remains constant despite the increase of truck maneuver time at the dump for large truck fleets.



(a) Truck fleet size, K=4

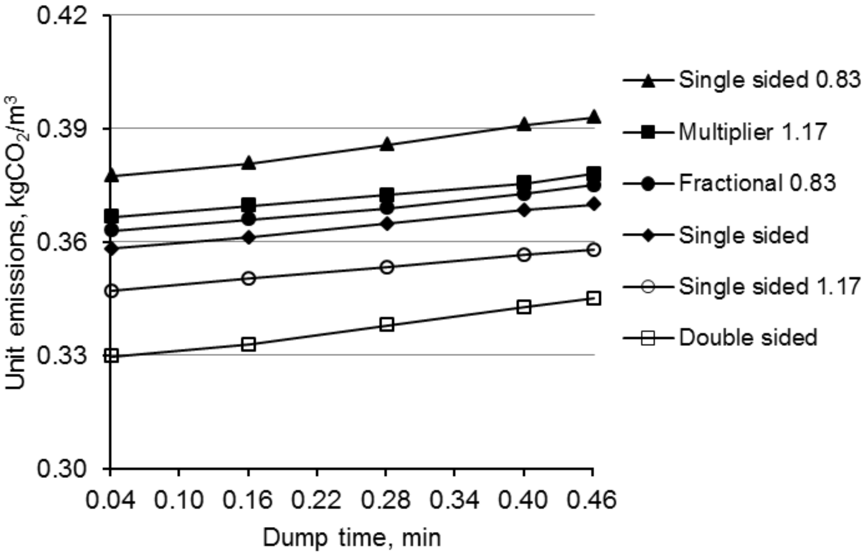


(b) Truck fleet size, K=8

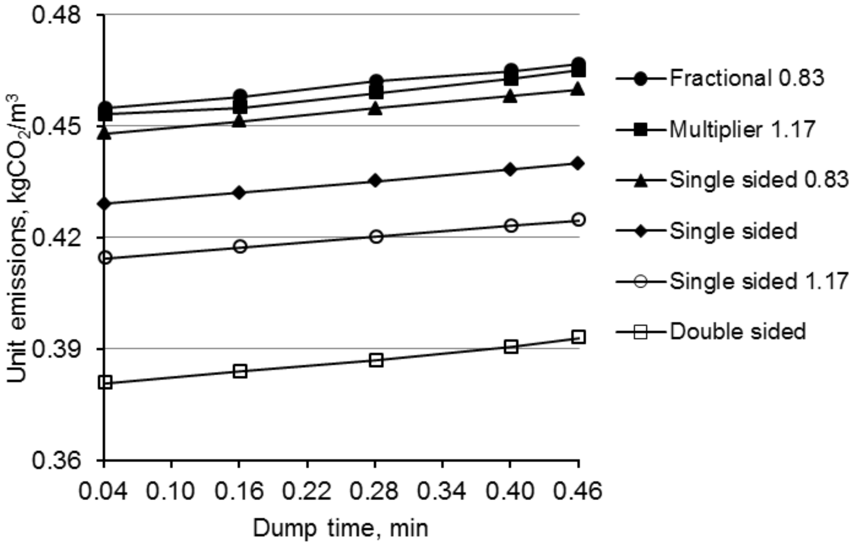
Figure 5.15. Unit cost versus truck maneuver time at dump for (a) K=4 and (b) K=8.

5.5.7 Influence of dump time

Figures 5.16a and 5.16b show the effect of varying truck dump time from 0.04 to 0.46 min on unit emissions. An increase in dump time has resulted in a slight increase of unit emissions for both truck fleet sizes in all loading policies.



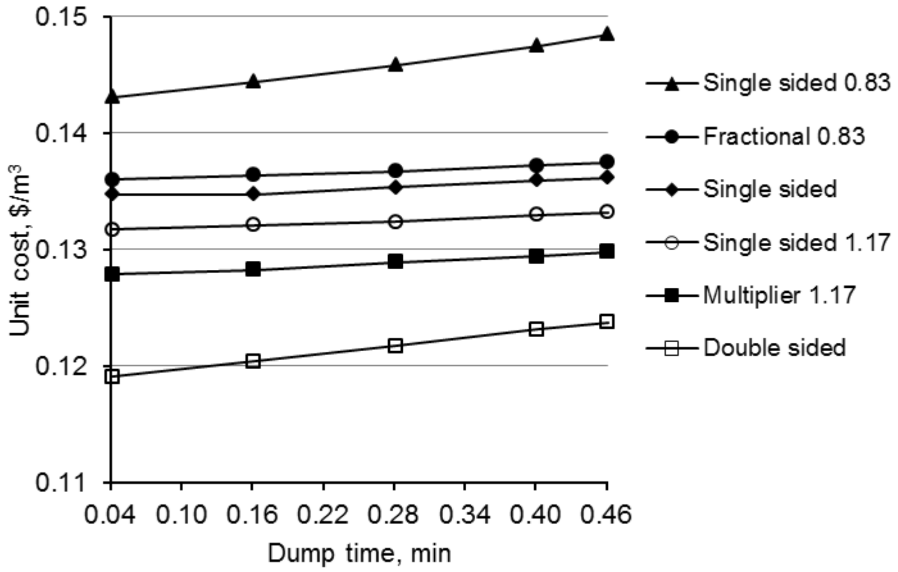
(a) Truck fleet size, K=4



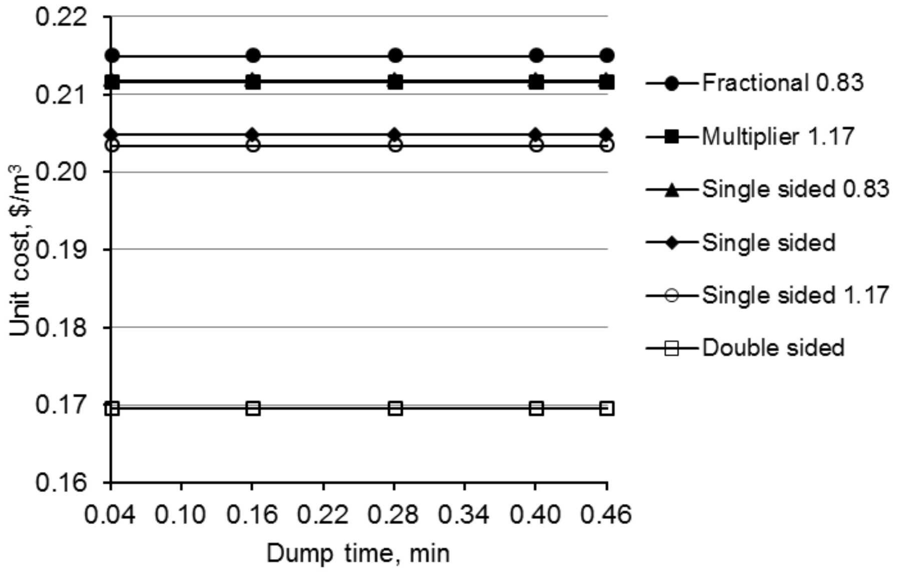
(b) Truck fleet size, K=8

Figure 5.16. Unit emissions versus truck dump time for (a) K=4 and (b) K=8.

Figures 5.17a and 5.17b show the change of truck dump time on unit costs. A slight increase in unit costs is demonstrated when the dump time is increased for small fleet size. However, the unit costs remain constant despite the increase of dump time for large fleet size.



(a) Truck fleet size, K=4

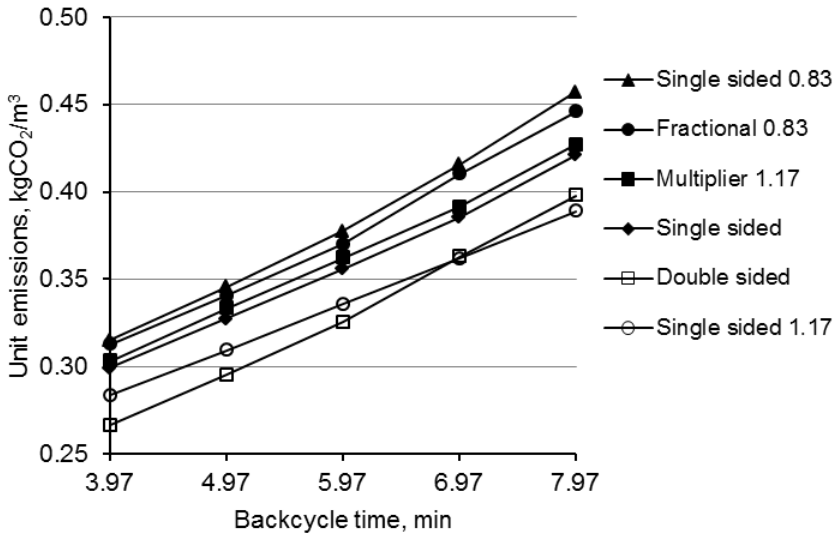


(b) Truck fleet size, K=8

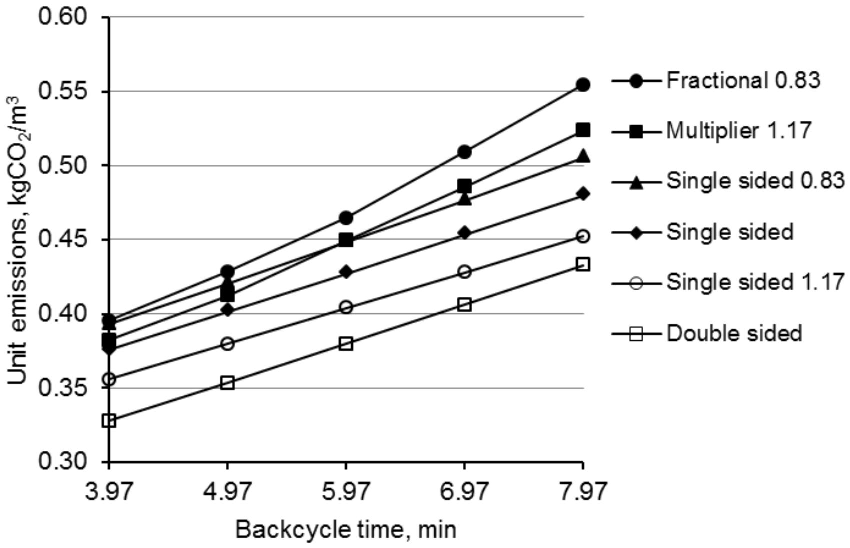
Figure 5.17. Unit cost versus truck dump time for (a) K=4 and (b) K=8.

5.5.8 Influence of backcycle time

Backcycle time refers to the time between the finishing of loading and the returning to the loading area. This cycle time includes the loaded haul, maneuver, dump and return times for each truck cycle. The service time is kept constant while the backcycle time is varied from 3.97 min to 7.97 min. As shown in Figures 5.18a and 5.18b, it can be observed that an increase in the backcycle time has caused a relative increase in unit emissions for all loading policies.



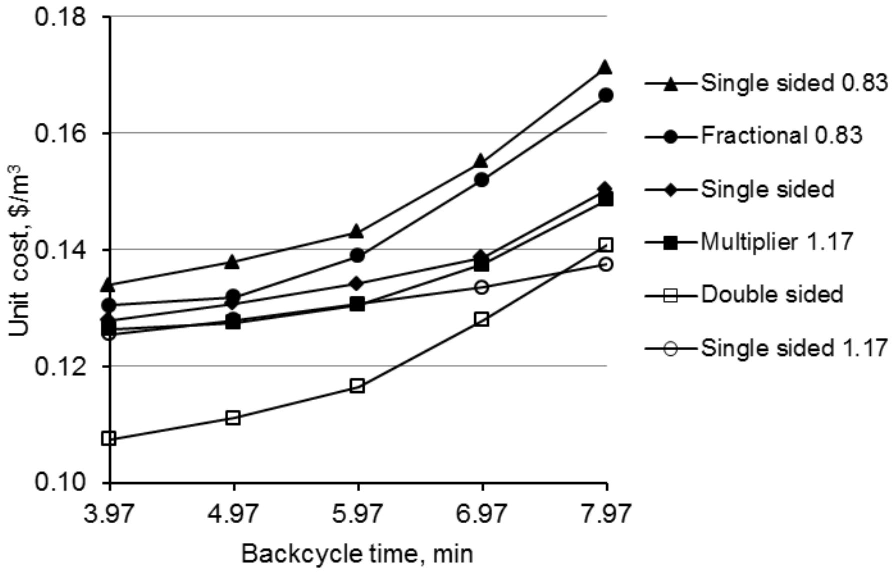
(a) Truck fleet size, K=4



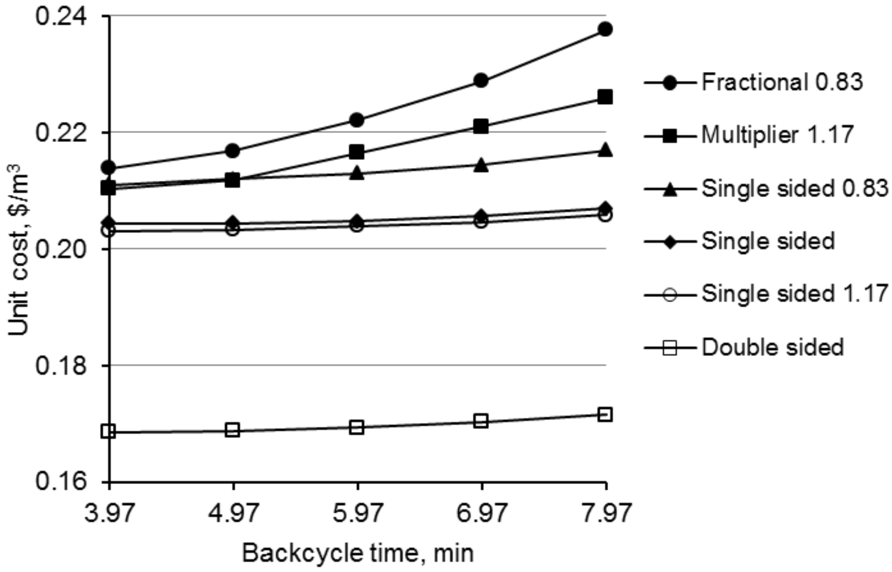
(b) Truck fleet size, K=8

Figure 5.18. Unit emissions versus truck backcycle time for (a) K=4 and (b) K=8.

Figures 5.19a and 5.19b show the change of truck backcycle time on unit costs. An increase in unit cost is demonstrated when the backcycle time is increased for small fleet size, K=4. Depending on loading policies, the plots for unit costs for small fleet size are observed to flatten or increase slightly at smaller backcycle before increasing relatively for larger backcycles. However, the unit costs remain approximately constant, apart from a slight increase in certain loading policies for large fleet size, K=8.



(a) Truck fleet size, K=4

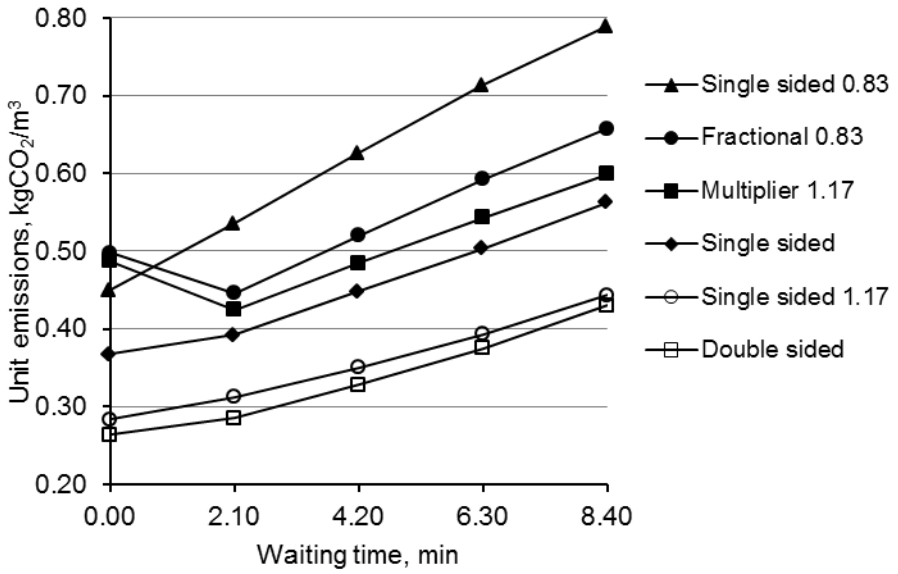


(b) Truck fleet size, K=8

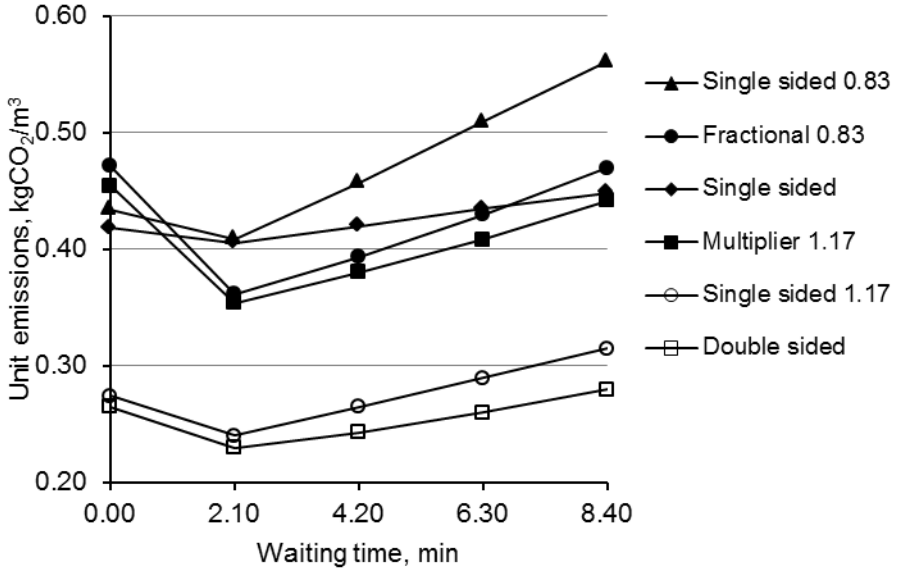
Figure 5.19. Unit cost versus truck backcycle time for (a) K=4 and (b) K=8.

5.5.9 Influence of waiting time

Waiting time can be described as the time between a truck arriving at the load point and the time truck starts maneuvering to load. Figures 5.20a, 5.20b, 5.21a and 5.21b show that the unit emissions and unit costs increase as the truck waiting time increases. It can be observed that the trends of the unit emissions and unit costs plots are found to be different for different fleet sizes and loading policies. The unit emissions are observed to decrease with the increase of truck waiting time from 0 min to 2.1 min for large truck fleets. However, the unit emissions will increase if the waiting time is greater than 2.1 min. Similar behaviour is observed to occur for fractional and multiplier loading cases in small truck fleets.



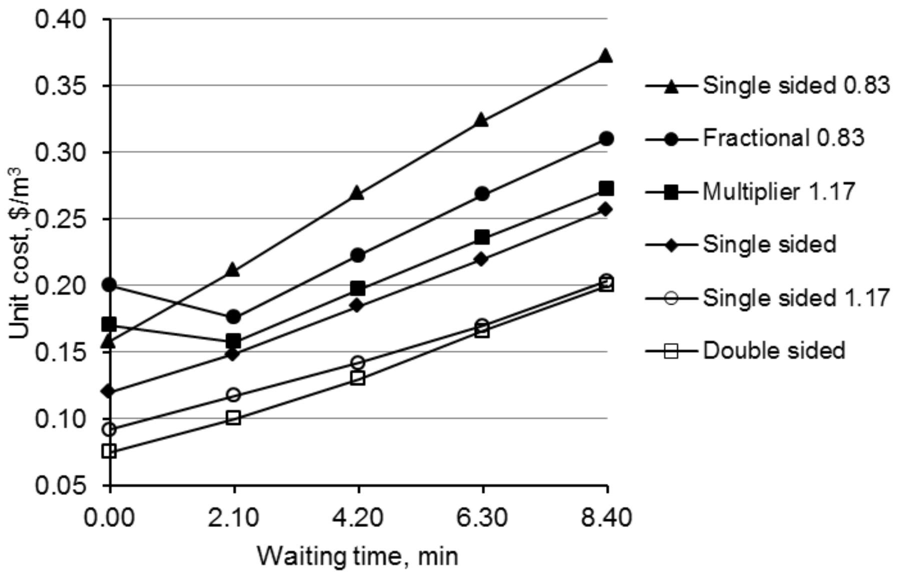
(a) Truck fleet size, K=4



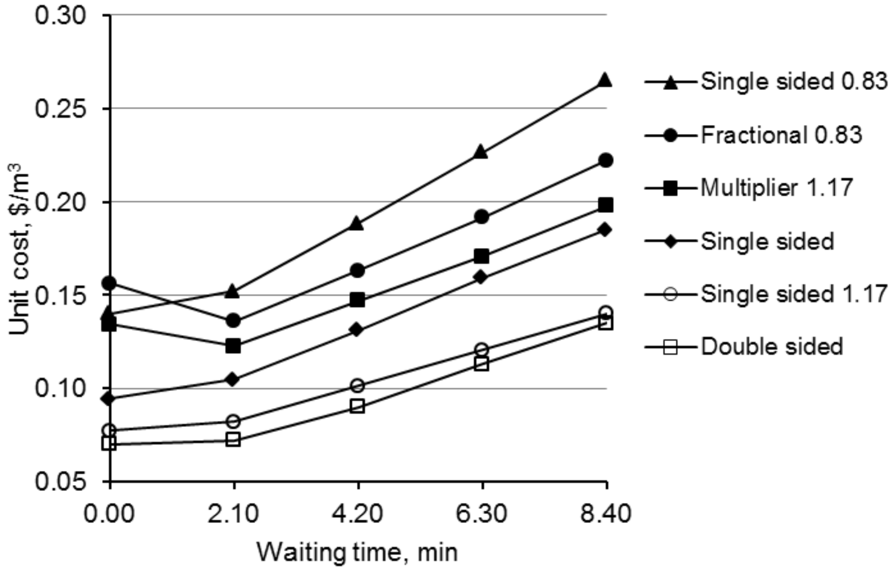
(b) Truck fleet size, K=8

Figure 5.20. Unit emissions versus truck waiting time for (a) K=4 and (b) K=8.

Figure 5.21a denotes the same pattern of unit costs with those observed in unit emissions for small fleet size. However, for large fleet size, the optimum unit cost can be observed at truck waiting time of 2.1 min for certain loading policies.



(a) Truck fleet size, K=4



(b) Truck fleet size, K=8

Figure 5.21. Unit cost versus truck waiting time for (a) K=4 and (b) K=8.

5.6 Discussion

The equipment waiting time is considered as idling and non-productive in earthmoving operations. This unnecessary idling is believed to affect the equipment performance, fuel use, production, unit emissions and unit costs of the operation. In this chapter, the influence of equipment waiting time and equipment utilization on the performance of production, unit emissions and unit costs of alternative loading policies in earthmoving operations are examined using the common single-sided loading policy as the benchmark. For this case study, the general result shows different impacts on the production of each alternative loading policy. Figures 5.1 to 5.3 show the results of production, unit emissions and unit costs based on different loading policies. Notably, double-sided loading with reduced maneuver time is found to cause higher production and lower unit emissions and unit costs. On the other hand, an underloading of the truck with one less bucket is found to generate the lowest production among all of the loading policies.

The findings of this study suggest that a slight overloading on the small fleet size of a truck using both single-sided and multiplier loading policies can increase the production and reduce unit emissions and unit costs compared to the common single-sided loading policy. However, a difference in production is observed between the overloading of the truck using these loading policies for large fleet sizes where an overloaded truck with multiplier loading policy demonstrates a slightly lower production compared to the overloading performed using single-sided loading policy. Further considerations on the long-term equipment reliability and maintenance should be adopted when overloading the trucks despite the positive remarks made by some authors on production and cost (Chironis, 1991; Smith et al., 1995) and emissions (Kaboli and Carmichael; 2016). The maximum safe loads on the tire should be regularly checked to prevent any truck damage and safety issues.

The findings of this study also show the effect of varying earthmoving parameters on unit emissions and unit costs. The findings revealed that there is a change in the ranking of unit emissions and unit costs of each alternative loading policy with a change in truck cycle component time and truck fleet size. In general, higher unit emissions and unit costs are achieved with the increase of each truck cycle component time. A significant difference of unit emissions and unit costs can be observed between service and backcycle component times. The results of unit costs in service time (Figure 5.8 and 5.9) seem to illustrate a consistent trend to that observed in unit emissions, in which longer service time will significantly increase both unit emissions and unit costs. It is different from the backcycle time presented in Figures 5.18 and 5.19, in which unit emissions show a relative increase resulting from longer truck cycle times. However, the increase of unit costs can only be observed for smaller fleet size, where the waiting time at the excavator is minimized, the excavator has extra idle time, and production is predominantly determined by the number of trucks, a result consistent with Carmichael (1987). For a large truck fleet size, where the excavator utilization is at its maximum, the production remains approximately constant while the operation is delivered at approximately the same cost.

Generally, the results of unit emissions and unit costs are revealed to be more sensitive to the change in service time compared to the backcycle time. Longer load time or service time leads to a significant reduction in production and increased both unit emissions and unit costs. This finding implies that loading facility has a great influence on the operation performance, where the maximum utilization of excavator can lead to maximum production. Interestingly, the ability of load time to deliver the production and cost benefits has also been highlighted in previous studies (Smith et al., 1995; Gransbergh, 1996, 2006).

In backcycles, a significant change was observed in the variability of the backcycle component times in unit emissions compared to unit costs. Hence, it is considered to be more sensible to design an earthmoving operation in minimum unit emissions instead of minimum unit costs, especially on long hauls. The change in the variability of the maneuver at dump and dump component times has demonstrated a small effect on both unit emissions and unit cost compared to the travel time. As the travel time contributes to the largest component in backcycle times, keeping the travel time at a minimum can lead to the efficient running of earthmoving operations.

Reducing truck waiting time is crucial for efficient operations. Figures 5.20a to 5.21b demonstrate an increase of unit emissions and unit costs as a result of the longer truck waiting time. The increased truck waiting time translates to the increase in total fuel use, with a consequent increase in the emissions (Lewis et al., 2012) and costs (Ercelebi and Bascetin, 2009). However, the findings of this study reveal that eliminating most truck waiting time also results in the increase of unit emissions for large truck fleet size. Eliminating truck waiting time on large truck fleet size translates to higher utilization of both trucks and loader, thus increasing the non-idle fuel use and consequently increases emissions.

Nevertheless, it should be noted that different loading policies lead to a different effect on production and fuel use, which in turn affects the unit emissions and unit costs. The chapter’s findings demonstrate that the changed loading policies tend to affect the load time, service time, waiting time and travel time. Reducing maneuver time in double-sided loading has resulted in decrease of the service time. The idle time fuel use of truck decreases, but no change is observed for fuel use and cost in terms of hauling operation. This implies to lower unit emissions and unit costs. Loading with one less bucket initially translates to, on average, smaller truck waiting times, truck underloading and reduced production per truck, and a small reduction in fuel used and fuel cost of load time and loaded haul time because of lighter loads. However, the decrease in the average truck payload of loading with one less bucket tends to result in lower hourly production and increased unit emissions and unit cost. Contrastingly, a slight overloading using single-sided loading policy is found to increase fuel use (and hence emissions) due to the increased payload and travel time. In terms of unit cost, the overloading of trucks resulted in an increase of the haulage rate. However, only a little change in operating cost is observed which resulted from the slight increase in the fuel cost, while non-fuel costs do not change greatly. As a result, unit emissions and unit cost decrease with larger truck payload and higher hourly production. On the other hand, it is revealed that overloading the truck using multiplier loading policy tends to result in higher unit emissions and unit cost in the case of large truck fleet size despite the increase of payload.

5.7 Conclusion

This chapter examined the influence of varying operation parameters on production, unit emissions and unit costs for non-standard earthmoving loading policies in response to the knowledge gap. Monte Carlo simulation in conjunction with the field data was used for analysis purposes. The present study has essentially demonstrated the relationship between load, load time, truck cycle times, equipment idle times, equipment utilizations, emissions, cost and the production of each loading policy.

The study highlighted the following matters:

- Double-sided loading contributes to the least impact on the environment and is the most cost-effective.

- The absolute results for the overloaded truck with always one extra bucket are subject to the concerns of maintenance and equipment reliability although the finding showed a reduction in unit emissions and unit costs. Hence, it appears more rational to load a truck based on their rated capacity considering the drawbacks of overloading which may increase maintenance cost and decrease a truck's component life.
- For multiplier loading, loading to one bucket extra than full load can lead to increase total production and has a positive impact on unit emissions and unit cost for small truck fleets. However, overloading through using multiplier loading is generally not an attractive policy for large truck fleets because it leads to an increase in unit emissions and unit costs.
- Overall, it can be deduced that minimizing truck cycle component times can lead to increase total production, lower impact on the environment and is more cost-effective.
- Service time has shown to greatly influence the production, unit emissions and unit costs. Hence, there is a great opportunity to improve productivity by keeping a minimum service time.
- Minimizing travel time and waiting time will also lead to more efficient earthmoving operations.
- The results of this study suggest that load, load time, service time, travel time, waiting time and truck fleet size are robust to changing the operation parameters of all loading policies. Therefore, careful consideration must be given to these parameters in order to maximize production and reduce unit emissions and unit costs when designing an earthmoving operation.

CHAPTER 6 - CONCRETING OPERATIONS - THE RELATIONSHIP BETWEEN UNIT COSTS AND UNIT EMISSIONS

6.1 Introduction

Concreting operations involve the cycling of pre-mixed concrete trucks between a concrete batching plant and a construction site where a pump (or crane) is located. With concrete's limited shelf life, it must be placed in its final location within a restricted time (Anson et al., 2002). However, due to the nature of the operations, many unplanned disruptions occur both on site and in the trucks travelling, and this introduced variability affects production, concreting duration, equipment emissions and cost. The variability might be reflected in the pump being idle while waiting for a truck, or a truck queuing at the site.

Past researchers on concreting operations have focused on cost and production, with little attention being given to emissions. The latter is the basis of this chapter – a study of unit emissions (emissions/production) for concreting operations, the link with unit costs (cost/production), and associated optimum equipment configurations. Such a study is original and fills a gap in knowledge. The effects of truck size, unloading policy, travel times, pumping rate, fuel type, and fleet size on unit emissions and unit costs are examined. This chapter is significant as it essentially establishes, for concreting operations, the relationship between unit emissions and unit costs, and the influence of constraints and operation parameters on these.

The analysis in this chapter uses queuing theory because of its analytical tractability, though it is acknowledged that numerical approaches such as Monte Carlo simulation or discrete event-oriented simulation could be used. Queuing theory is an established tool for operations such as described in the chapter, and has been used to analyse concreting operations at least back to the 1980s (Carmichael, 1985, 1987). The chapter uses, in particular, a finite source queuing analysis, because of its direct applicability to the operation at hand. Good fits to field data are obtained by averaging the constant

(D/D/1)/K case and the exponential distribution (M/M/1)/K (Carmichael, 1989). In this notation, D refers to a constant distribution and M an exponential distribution used to model service times and backcycle times; 1 refers to the number of servers; K refers to the finite source truck fleet size.

This chapter is organized as follows. The next section introduces the underlying analysis while Section 3 provides the case study and the field data. Section 4 presents the unit emissions and unit cost results. Section 5 gives the conclusions.

The background to the present chapter is given in Sections 2.3 and 2.5.

6.2 Underlying Analysis

6.2.1 Production

A concreting operation involves trucks hauling concrete between a batching plant and an unloading point at a construction site (Figure 6.1), where there is a specified volume of concrete required at a specified rate. A queue of trucks may occur at both the loading and/or unloading points.

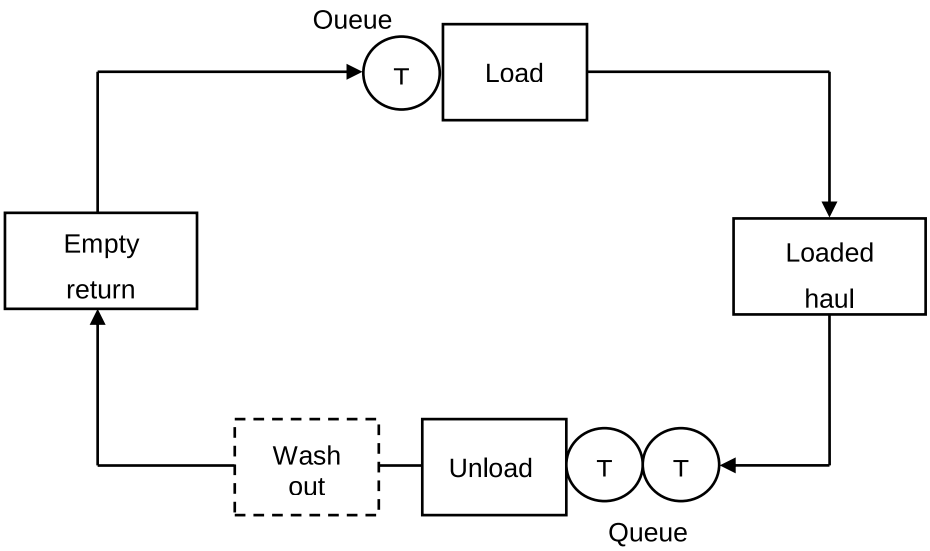


Figure 6.1. Schematic of concreting operation. Truck denoted as T.

In this chapter, the pump is chosen as the server, but the same overall analysis applies with the batching plant as the server. The trucks are the customers. The finite source queuing results and notation follow Carmichael (1987). For a single pump (equivalently, server), the average truck cycle time is given by,

$$\text{Truck cycle time} = \frac{1}{\mu} + \frac{1}{\lambda} + W_q = \frac{K}{\mu\eta} \tag{6.1}$$

Where: $1/\mu$ is the average service time (the sum of truck maneuver time and unload time at the site); $1/\lambda$ is the average backcycle time (the sum of times for: empty truck return, queue, maneuver and load at the batching plant, and loaded haul time); W_q is the average truck waiting time at site; η is the server utilization (proportion of time the server is busy); and K is the truck fleet size. Production becomes,

$$\text{Production} = \mu\eta\text{CAP} \tag{6.2}$$

Where CAP is the capacity of a truck in m^3.

6.2.2 Unit cost

For concreting operations, there are two cost possibilities that might be considered. The first case is where the total cost of the operation is borne by the contractor, in which both the loading and unloading facilities are owned by one company. All hourly owning and operating costs include the cost of trucks, pump, operator, site workers, maintenance and other applicable charges. Then, cost/production or unit cost becomes,

$$\text{Cost/production} = \frac{C_P + KC_T}{\mu\eta\text{CAP}} \tag{6.3}$$

Where the subscripts P and T refer to pump and truck respectively; C_P is the hourly owning and operating cost of the concrete pump; and C_T is the hourly owning and operating cost of a truck. The cost of the concrete is not included; this is assumed constant irrespective of any equipment configuration.

The second case is where the concrete supplier owns the trucks. For calculations from the point of view of the site contractor, truck costs are not considered. Hence, the optimum solution (from the viewpoint of the site contractor) involves a continuous supply of concrete at the required rate, and no optimization calculations are necessary. Accordingly, this chapter only considers the first case.

6.2.3 Unit emissions

Truck times and pump times can be broken into idling (I) and non-idling (N) components. For trucks, the service and queuing times are considered to be idling time, while the backcycle time is regarded as non-idling time. The emissions per production or unit emissions for a single concrete pump operation become,

$$\text{Emissions/production} = \frac{N_P\eta + I_P(1-\eta) + K(N_T(\mu\eta/K\lambda) + I_T(1-\mu\eta/K\lambda))}{\mu\eta CAP} \qquad (6.4)$$

Here, respectively, η and 1-η are the proportions of time that the pump is idling and non-idling (pumping), while $\mu\eta/K\lambda$ and $(1-\mu\eta/K\lambda)$ are the proportions of time that a truck is idling and non-idling (as defined above) (Carmichael et al., 2012, 2014a). For the case study below, the cycle component times are obtained from field measurements. The approach of Frey and Kim (2009) is then employed to determine the average of fuel used for idling and non-idling of the trucks. The fuel used for idling and non-idling of the pump is obtained from the equipment manufacturer. The fuel used is multiplied with a specific energy content factor and an emissions factor provided by DCCEE (2017) to obtain the total carbon dioxide equivalent (CO_2-e) emissions.

6.3 Case Study

6.3.1 Outline

A continuous concrete slab pouring operation, involving approximately 200 m^3 of concrete, and which took approximately 10.5 hours to complete, was observed in its entirety. Trucks cycled between a batching plant and the site. The batching plant was located 3.4 km from the construction site. A fleet of seven trucks, each of 8 m^3 capacity, and a trailer-mounted concrete pump, with a 0.7 m^3 hopper capacity, were employed in the operation. The pumping rate capability was 85 m^3/h. The equipment details are shown in Table 6.1. The cost ratio of a truck to that of the concrete pump was 0.43.

Equipment	Engine power (HP)	Engine tier
Pump	250	3
Truck (8 m^3)	300	2

Table 6.1. Field study equipment characteristics.

6.3.2 Cycle data

The total operation involved twenty-five truck cycles, with trucks going repeatedly between a concrete batching plant and the site. These data were recorded both manually and by video, giving the following truck event times: arrival at the batching plant; start maneuver to load; start loading; end loading; arrival at the site; start maneuver at site; start unloading; end unloading and wash out at construction site. From these data, queue waiting times and maneuver times at both the batching plant and site, loading times, unloading times, wash out, and travel times were obtained. In this study, the loading time is considered from the time a truck enters the loading bay until it leaves the batching plant. The case study was supplemented with data on fuel use, owning and operating costs, capacities, distances, equipment engine power (HP), engine load and engine tier. All observed mixer trucks were the same model - Isuzu FVY 240-300. Each truck had a 6 cylinder 24 valve SOHC with a 300 HP diesel engine, and one front and two rear axles. The vehicle unloaded mass and loaded mass were 13,000 kg and 24,000 kg respectively. Table 6.2 shows the average truck cycle component times, giving a servicing factor (λ/μ), for the pump as the server, of 16.925/51.625 or 0.33. A summarised event time data for the truck cycles and cumulative distributions for each of the cycle component times are given in Appendix I.

Truck cycle component	Average	Standard deviation
Queue-at-load	19.712	8.413
Maneuver at batching point	1.525	0.441
Load	9.921	0.921
Loaded haul	9.347	1.113
Queue-at-unload	38.504	14.837
Maneuver at pump	1.402	0.470
Unload	15.523	0.944
Wash out at pump	1.996	0.115
Return	9.124	0.939

Table 6.2. Field observed average truck cycle component times (min).

6.4 Results and Analysis

Using the field data as a basis, unit emissions and unit costs vary with the truck fleet size according to Figure 6.2. Without production constraints, it is seen that for minimum unit emissions and minimum unit cost, the optimum truck fleet sizes coincide. Considering other issues such as truck reliability and the relative flatness of the plots in Figure 6.2, a prudent contractor would choose a fleet size greater than indicated by this minimum.

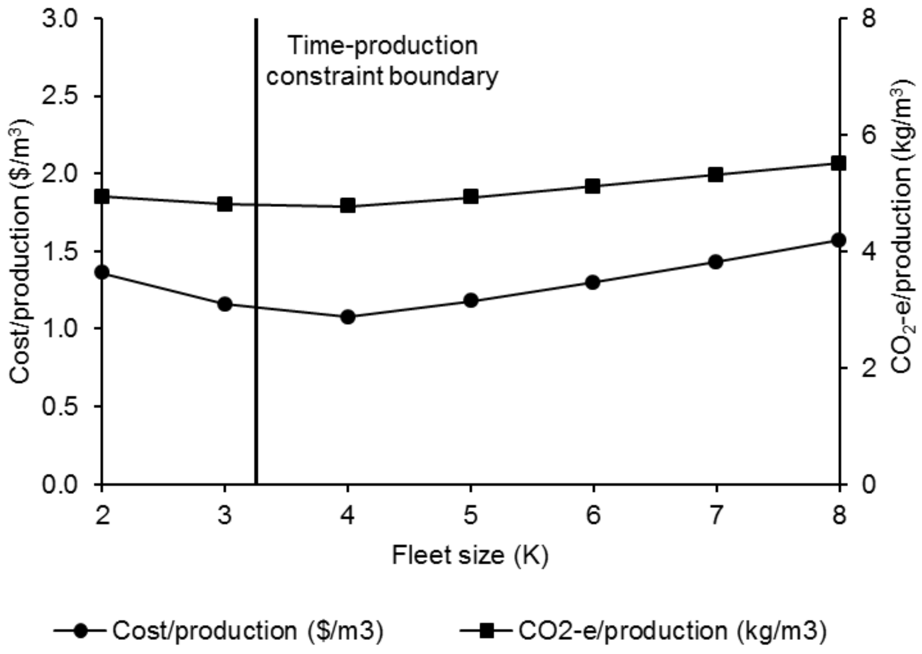


Figure 6.2. CO_2-e /production and cost/production versus fleet size, K.

In Figure 6.2, a time-production constraint line is also drawn. Fleet sizes to the left of this line are inadmissible. This constraint is shown also in Figure 6.3 (and later figures). There is a constraint on the operation in terms of a time limitation for the supply of concrete, in order to observe the project schedule, and to ensure an appropriate utilization of the concreting crew. The concreting operation had been scheduled to complete in 10.5 h. However, from Figures 6.2 and 6.3, it is seen that the optimum is not affected by this constraint, and the constrained optimum is almost the same as the unconstrained optimum. That is, with or without the constraint, the conclusion stays the same, namely that the minima for unit emissions and unit cost coincide. This is consistent with earthmoving operations results (Carmichael et al., 2012, 2014a).

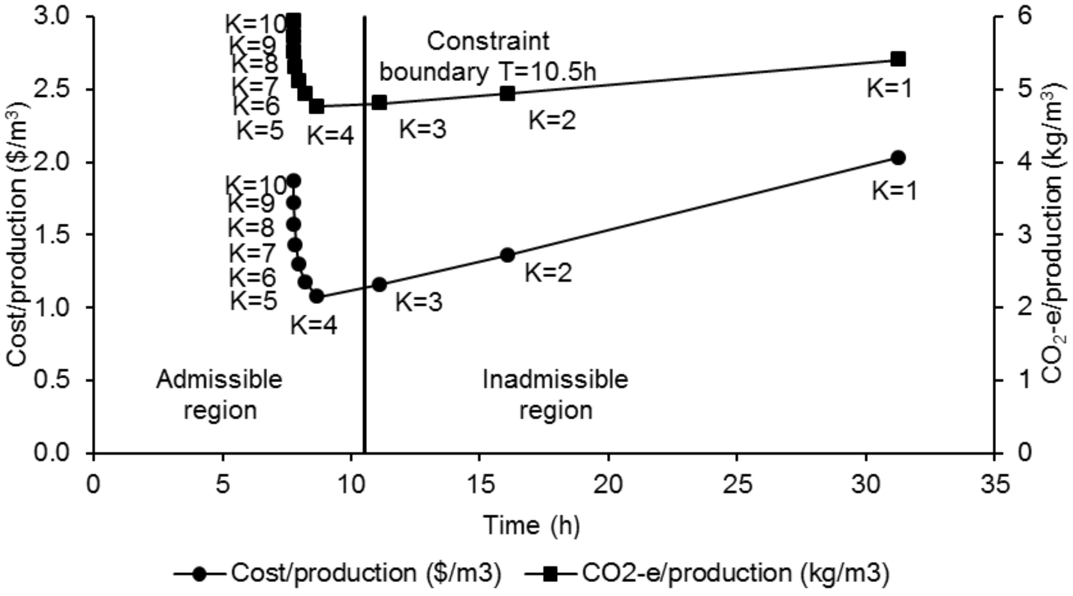


Figure 6.3. CO_2-e /production and cost/production versus time.

The influence of changing the operation parameters - truck capacity, unloading policy, pumping rate, travel time and fuel type - on unit emissions and unit cost is demonstrated in the following sensitivity-style studies.

6.4.1 Influence of truck capacity

The influence of increasing the truck capacity from 8 m^3 to 10 m^3 is shown in Figure 6.4. Employing higher capacity trucks increases production and decreases both the unit emissions and unit cost. This result is consistent with the studies conducted by Carmichael (1985, 1987) and Smith (1999b). The optimum truck fleet sizes for unit emissions and unit cost coincide regardless of the truck capacity.

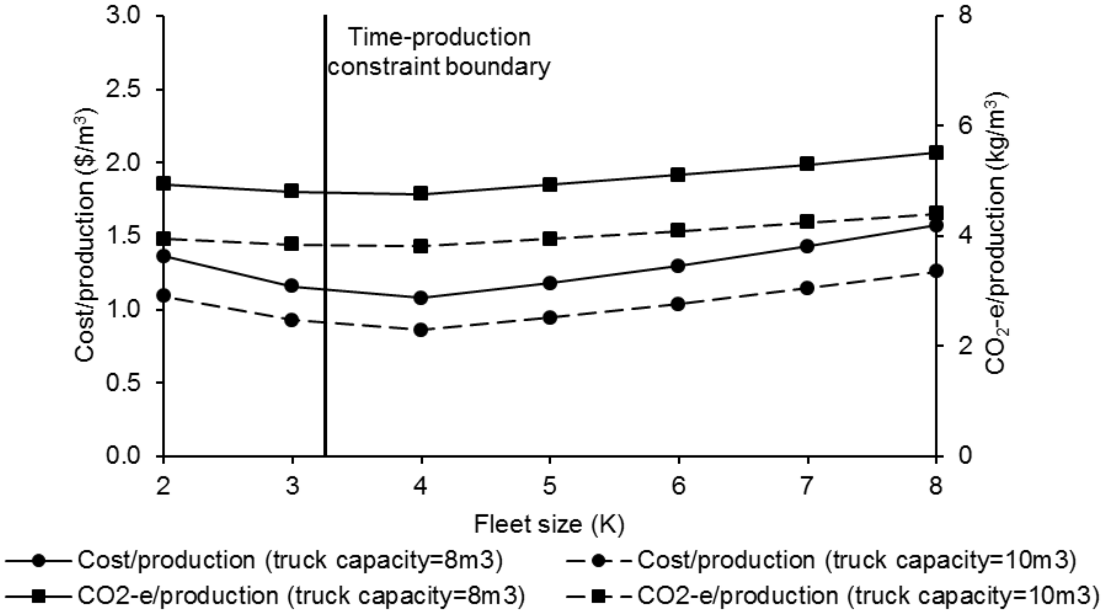


Figure 6.4. The influence of truck capacity on unit emissions and unit cost for varying fleet size, K.

6.4.2 Influence of unloading policy

With double-sided unloading, trucks can be unloaded to either side of the pump. The following truck starts its maneuver without having to wait for the preceding truck to finish unloading. This gives a lower service time, higher production, and lower unit emissions and unit cost. A comparison of double-sided and single-sided unloading is shown in Figure 6.5, with the latter being that used in the case study operation. The optimum fleet sizes for unit emissions and unit cost remain coincident for double-sided unloading.

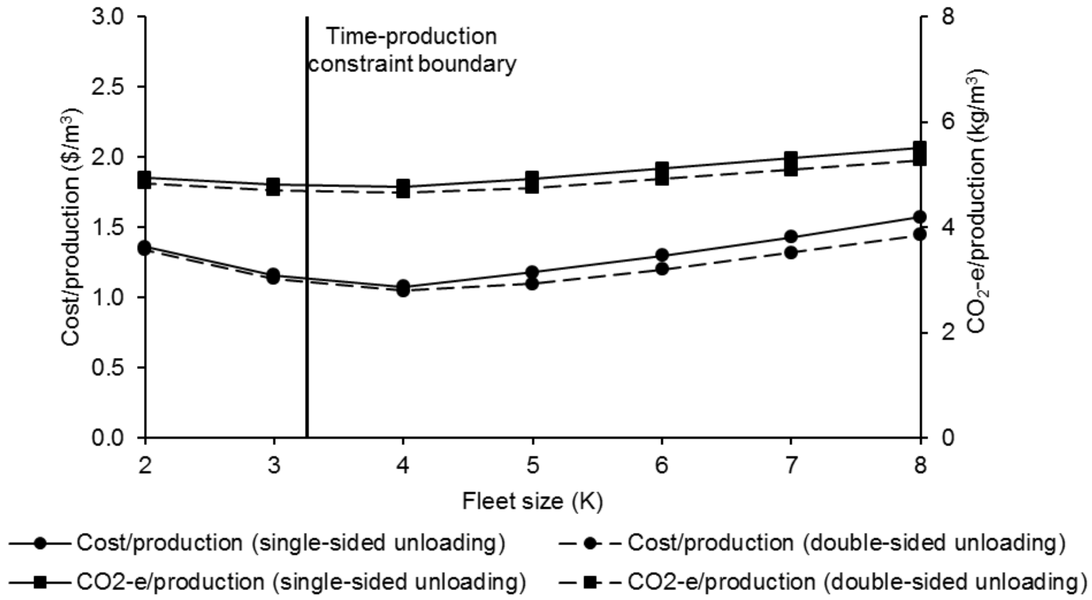


Figure 6.5. The influence of unloading policy on unit emissions and unit cost for varying fleet size, K.

6.4.3 Influence of pumping rate

The influence of decreasing the pumping rate on unit emissions and unit cost is shown in Figure 6.6. A lower pumping rate translates to an increase in unloading time and higher utilization of the pump, but also an increase in the length of the truck queue. The increase in truck idle time translates to a higher total fuel usage, decreases the production and increases the unit emissions and unit cost. The optimum fleet sizes for unit emissions and unit cost coincide, with the truck fleet size being smaller for lower pumping rate capability.

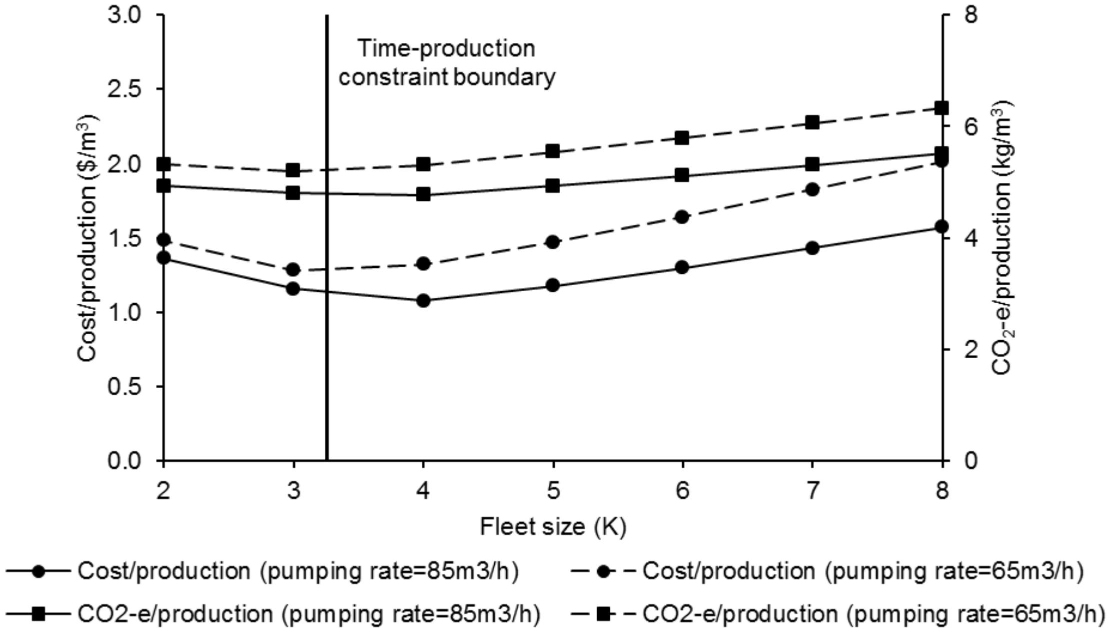


Figure 6.6. The influence of unloading time on unit emissions and unit cost for varying fleet size, K.

6.4.4 Influence of travel time

Figure 6.7 shows the influence of increasing truck travel times, corresponding to longer routes and/or increased route traffic. Route A, with a distance of 3.4 km and corresponding to the field study, is shorter than an alternative route considered here (route B - 6.1km). For longer travel times, the fuel consumption and unit emissions increase. Unit cost is only different for small fleet sizes, where the waiting time on site is minimized, the pump has extra idle time, and production is predominantly determined by the number of trucks, a result consistent with Carmichael (1985, 1987), Smith, (1998) and Dunlop and Smith (2002). For a large truck fleet size, where the server utilization is at its maximum, the production remains constant while the concrete is delivered at approximately the same cost. The optimum fleet sizes for unit emissions and unit cost coincide irrespective of the travel time.

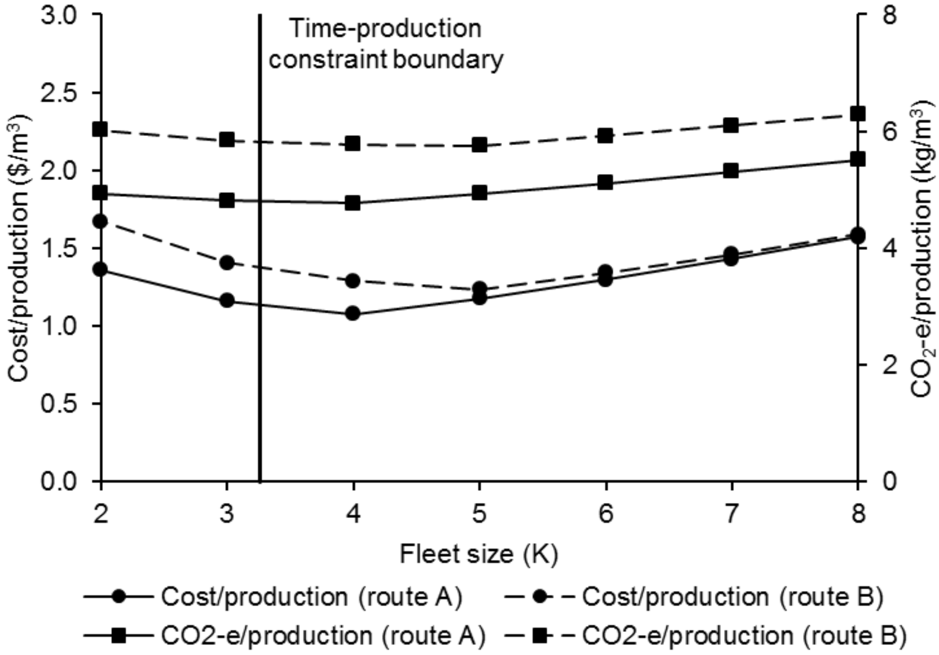


Figure 6.7. The influence of backcycle time on unit emissions and unit cost for varying fleet size, K.

6.4.5 Influence of fuel type

The effect of fuel type on unit emissions and unit cost is shown in Figure 6.8. Diesel is compared with B10 biodiesel (a blend of 10% palm biodiesel with 90% diesel). The amount of fuel used remains similar for both, but they have different specific energy content factors. This leads to lower emissions for the B10 blend fuel. By contrast, the unit cost does not change greatly with lower fuel usage, because the fuel cost contributes only a small portion to the total owning and operating costs. For each fuel type, the same optimum fleet size is achieved with unit emissions and unit cost.

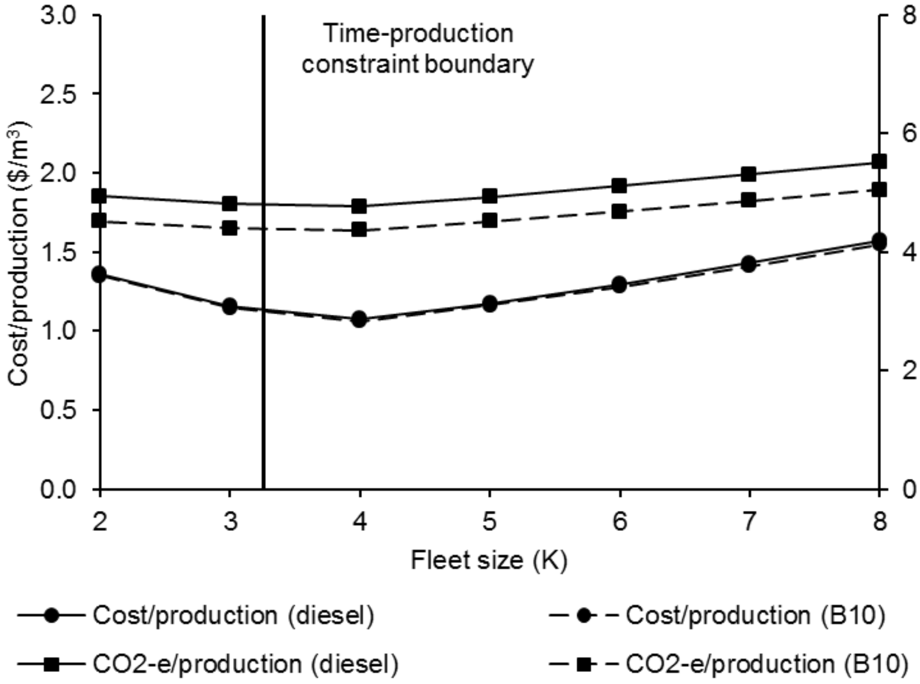


Figure 6.8. The influence of fuel type on unit emissions and unit cost for varying fleet size, K.

6.5 Discussion

The results of the case study analyses demonstrate that irrespective of the configuration of the concreting operation, minimizing unit cost will also result in the least impact on the environment. The time-production constraint guarantees a minimum supply of concrete to the construction process. However, the existence of the constraint did not alter this general conclusion for the case study, and it is not anticipated to do so for other concreting operations because of the shape of the unit emissions and unit cost curves. As well, prudent contractors would operate with fleet sizes greater than this optimum in order to cater for equipment reliability and worker utilization.

The results apply to optimizing existing concreting configurations. The introduction of new emissions-saving technology (Carmichael et al., 2014b), or using driver training (Jukic and Carmichael, 2016) would lower absolute emissions, but would not alter the chapter's overall conclusion. Observed practice on site was for the truck drivers to leave their engines idling continually. Further emission savings would be possible here through adopting a practice of turning engines off while at site.

6.6 Conclusion

The chapter demonstrated on a case study that the optimum truck fleet size for unit emissions coincides with that for unit cost. This was so even for differing operation parameters of truck capacity, unloading policy, unloading time, travel time and fuel type. And based on the underlying analysis used, it is anticipated that this result will be generally true beyond the given case study.

It can be concluded that for a given concrete pump and truck operation, work carried out in such a way that minimizes unit cost will also minimize unit emissions. On the other hand, not undertaking the work at minimum unit cost will result in unnecessary emissions.

CHAPTER 7 - MINIMUM EMISSIONS IN CONCRETE DELIVERY AND PLACEMENT

7.1 Introduction

The chapter compares the emissions, production and cost performance of different concrete placement methods in concreting operations. For comparison purposes, the results for a concreting operation using a crane and bucket are given. The differences between using a pump and using a crane relate to service times, cycle times, waiting times for trucks at site, and energy usage of the crane compared with a pump.

According to Guggemos and Horvath (2006), the consumption of fuel from construction equipment emits significant amounts of greenhouse gases into the environment. Considering the pronounced negative impacts on the environment, there is an urgent requirement to reduce the emissions from concreting operations. Existing publications have focused on examining the relationship between trucks and concrete placements in a construction site as a way of maximizing production while minimizing operational cost (Carmichael, 1985, 1987; Anson and Shou-qing, 1994, 1998; Smith, 1998; Dunlop and Smith, 2000, 2002 and 2003). However, no analytic attention has been given to looking at minimizing emissions for the related truck-placement equipment operations. This is the basis of this chapter.

In concreting operations, the selection of the placement method defines the placing rate and the equipment utilization on site (Anson et al., 2002). A longer duration of placing process may result in an increase of truck idle time on site. Studies have shown that an increase in equipment waiting times translates to an increase in total fuel use, with a consequent increase in emissions (Lewis et al., 2012) and costs (Ercelebi and Bascetin, 2009). Since equipment idle time, equipment utilization (percentage of time working), fuel use (and hence emissions), operational costs and production are interrelated, different placement methods may potentially lead to different placing rates. As a result, these factors can also lead to different waiting times, equipment utilizations, production, fuel use, emissions and costs. This chapter investigates the link between idle time, equipment utilization, production, emissions, costs and optimum equipment configurations. Sensitivity-style analysis are used to evaluate the influence of truck capacity, server capacity, unloading policy, the fuel type, and the fleet size of different placement methods on optimum unit emissions and unit costs.

Monte Carlo simulation is used in this chapter to develop a model for cyclical concreting operations. However, it should be noted that discrete event-oriented simulation or modified finite source queuing theory could be equally used. Transporting and placing concrete on a residential construction site provides case study data.

This chapter is organized as follows. The first section highlights the model's development and the computational approach. Field data from the case study is then given, followed by discussion and analysis of the unit emissions and unit costs.

In summary, this chapter will be of interest to those who design and manage concreting operations. The comparison of emissions, production and cost performance of the truck-placement method operations provide useful insights in assessing the most environmental friendly and economical way to design and manage concreting operations.

The background to this chapter is presented in Sections 2.3 and 2.5.

7.2 Underlying Modeling

The typical concreting operation studied here involves the cycling of truck-mixers, repeatedly hauling between a batching plant and an unloading point where a pump (or crane) is located at a construction site. Figure 7.1 shows a schematic of such an operation.

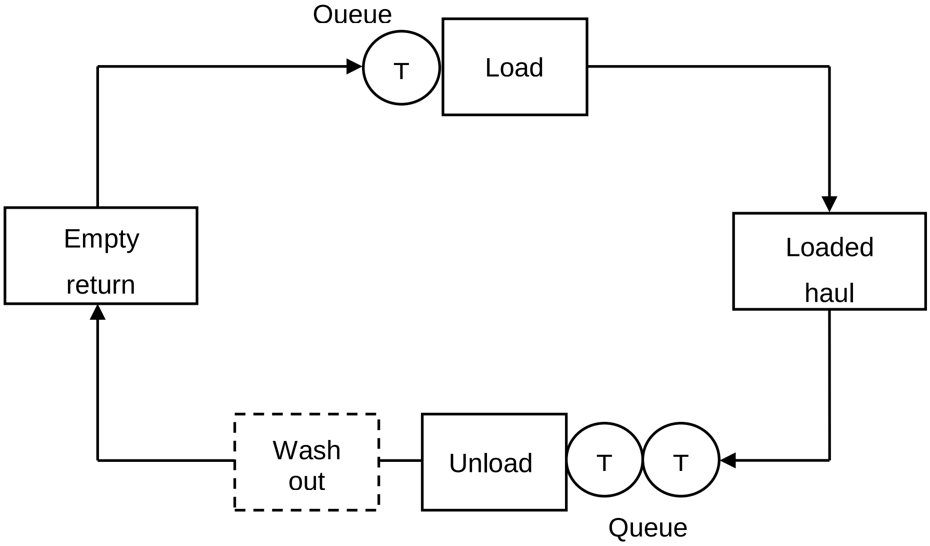


Figure 7.1. Schematic of concreting operation. Truck denoted as T.

Initially, the process commences at the batching plant where trucks are loaded with concrete before proceeding to the construction site. As trucks arrive at the unloading point, there are two conditions likely to occur: either the trucks will be served simultaneously (when no trucks are present) or they will join the back of the queue and wait to be served. In the process of placing concrete by pump, the service time begins when the trucks maneuver into an unloading position and discharge the concrete into the hopper of the pump. The concrete is then pumped into the placement location through a steel pipeline. On the contrary, in the process of placing concrete by crane and bucket, the service time is considered when the trucks start to maneuver and unload the concrete into the bucket before being hoisted vertically by the crane to its desired height. Backcycle time refers to the time between finishing unloading and returning to the unloading site.

A queue of trucks may occur while trucks wait at the loading or unloading points, because of variability in the truck cycle component times. Frequent truck arrivals to site or to the batching plant lead to trucks waiting and low truck utilization. Infrequent truck arrivals lead to pump/crane or batching plant idle times, leading to low pump/crane or batching plant utilization. A preferred concreting operation will represent a balance between these two arrival frequency scenarios. However, different concrete placement methods offer different placing rates as well as different waiting times, equipment utilizations, productions, costs, fuel use and emissions. Therefore, it is anticipated that unit emissions and unit costs for the pump and the crane with bucket will vary.

A study of unit emissions (emissions/production) for concreting operations, the link with unit costs (cost/production), and associated optimum equipment configurations will be examined in this chapter.

7.3 Underlying Analysis and Calculations

Truck cycle component times can be related through recursive relationships. The queue simulation approach of Carmichael (1988) is extended in this chapter to model concreting operations which includes emissions, cost and production calculations. The pump or crane is considered as a single server case. Trucks are viewed as the customers.

For each truck cycle n, n = 1, 2,…, ζ, a service time, S(n), backcycle time, B(n), maneuver time, M(n), and load time, LT(n), are variously generated by sampling from field data distributions for S, B, M and LT respectively, as in usual Monte Carlo simulation. ζ, the total number of truck cycles, is chosen as reasonably large.

To start the recursive calculations, introduced cumulative time measures for the first set of cycles, CUM(n), n = 1, 2,…, K+1, are set to some reasonable values with K as the truck fleet size. Then, for the remaining cycles, n = K+2, K+3, …, ζ, waiting times, W(n), and the cumulative time measures, CUM(n), are calculated recursively based on previous cycles' values. Production, PROD (n), and emissions, E (n), are calculated for each cycle, and cost is included to get a total picture of the operation.

For example,

$$CUM(1) = S(1)$$

n = 2, 3, …, K+1

$$CUM(n) = CUM(n-1) + S(n)$$

(Exclude first K+1 cycles from calculations below).

n = K+2, K+3, …

$$W(n) = \max\{CUM(n-1)-[CUM(n-K) + B(n-K)], 0\}$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

$$PROD(n) = CAP$$

$$E_{P/C}(n) = I_{P/C}[CUM(n) - CUM(n-1) - S(n)] + N_{P/C}S(n)$$

$$E_T(n) = I_T[W(n) + S(n)] + N_T B(n)$$

(If turn engine off while waiting, then leave out W.)

Information collected during the calculations is: number of truck cycles, total duration, total production, equipment utilization, total emissions, total cost, unit emissions and unit cost.

7.3.1 Production

For a single pump/crane with bucket operation, the number of truck cycles is given as,

$$\text{Number of truck cycles, NC} = \zeta - (K+1) \qquad (7.1)$$

Thus, the total duration is defined as,

$$\text{Total duration, TD} = CUM(\zeta) + B(\zeta) - CUM(K+1) \qquad (7.2)$$

$CUM(\zeta)$ is the cumulative time for the total number of truck cycles and $B(\zeta)$ is the backcycle time for the total number of truck cycles.

The total production/unit time is given by,

$$\text{Total production, TP} = \sum_{NC} PROD(n) = (\zeta - K - 1)CAP \qquad (7.3)$$

$$\text{Total production/unit time} = \frac{TP}{TD} \tag{7.4}$$

Where PROD(n) = CAP is the capacity of a truck.

The server (pump/crane) utilization (the proportion of time that the server is busy), η, is calculated from,

$$\text{Server utilization, } \eta = \frac{\sum_{NC} S(n)}{TD} \tag{7.5}$$

The truck utilization, u, is the proportion of time that trucks are either in service or travelling with respect to total truck cycle time. It excludes truck waiting time. It is calculated from,

$$\text{Truck utilization, } u = \frac{\sum_{NC} B(n) + \sum_{NC} S(n)}{K \times TD} \tag{7.6}$$

7.3.2 Unit emissions

The total pump/crane emissions, $TE_{P/C}$ is calculated from,

$$\text{Total pump/crane emissions, } TE_{P/C} = \sum_{NC} E_{P/C}(n) \tag{7.7}$$

The total truck emissions, TE_T is calculated from,

$$\text{Total truck emissions, } TE_T = \sum_{NC} E_T(n) \tag{7.8}$$

The total emissions per production is given by, Total emissions/unit time = $\dfrac{TE_{P/C} + TE_T}{TD}$ (7.9)

Alternatively,

Total emissions/unit time = $N_{P/C}\eta + I_{P/C}(1-\eta) + K(N_T(\mu\eta / K\lambda) + I_T(1-\mu\eta / K\lambda))$ (7.10)

And

Unit emissions = Total emissions per unit time / Total production per unit time (7.11)

η and 1 - η are the proportion of time that the pump/crane is idling and the proportion of time non-idling, respectively, while $\mu\eta / K\lambda$ and (1 - $\mu\eta / K\lambda$) are the proportion of time that the trucks are idling and the proportion of time non-idling, respectively. For emission calculation purposes, pump/crane utilization is taken to be the same as the server utilization where it is assumed to start working when the truck starts maneuvering. For trucks, the time for unloading and queuing at pump is regarded as idling time while backcycle time is considered as non-idling time. For the case study below, the cycle component times are obtained from field measurements. The approach of Frey and Kim (2009) is employed to determine the fraction of emission for idling (I_T) and non-idling (N_T) of the trucks. I_P, I_C, N_P and N_C are idling and non-idling emissions of the pump and crane, respectively; and these are obtained from the equipment manufacturer and the approach of Hasan (2013). The emissions factor provided by DCCEE (2017) is used to determine the total carbon dioxide equivalent (CO_2-e) emissions.

7.3.3 Unit cost

For concreting operations, there are two cost possibilities that might be considered. The first case is where the total cost of the operation is borne by the contractor; that is, both the loading and unloading facilities are owned by one company. All hourly owning and operating costs include the cost of trucks, pump, crane, operator, site workers, maintenance and other applicable charges. The cost of the concrete is not included, as this is assumed constant irrespective of any equipment configuration.

For any single pump/crane-trucks operation, the cost per production is,

$$\text{Total cost/unit time} = C_{P/C} + KC_T \tag{7.12}$$

Where $C_{P/C}$ is denoted as the owning and operating cost per unit time of the pump/crane and C_T is the owning and operating cost per unit time of truck. Then, cost/production or unit cost becomes,

$$\text{Cost/production} = \text{Total cost per unit time/Total production per unit time} \tag{7.13}$$

The second case is where the concrete supplier owns the trucks. For calculations from the point of view of the site contractor, truck costs are not considered. Hence, the optimum solution (from the viewpoint of the site contractor) involves a continuous supply of concrete at the required rate, and no optimization calculations are necessary. Accordingly, this chapter only considers the first case.

It is important to take note that the cost of crane is based on a specific case study of concreting operations and should not be misleading with the total operating cost of a crane as a crane is also been used for other purposes on site.

7.4 Case Studies

7.4.1 Outline

Two field studies involving placement of slab concrete structures using two placement methods, (1) pump and (2) crane with bucket, were considered. The case studies involve trucks cycling between a batching plant and a residential construction site.

Field study A

A fleet of seven trucks, each of 8 m^3 capacity were used to deliver concrete for pouring a 200 m^3 slab structure. The batching plant was located 3.4 km from the construction site. A trailer-mounted concrete pump, with a 0.7 m^3 hopper capacity and pumping rate capability of 85 m^3/h, was employed in the operation.

Field study B

The operation analyzed here involved pouring a 64 m^3 slab and a fleet of two concreting trucks, each of 8 m^3 capacity. The batching plant was located 4.1 km from the construction site. A 16 tonne capacity tower crane with a 55 m luffing-jib and 1 m^3 bucket was used. The lifting height was approximately 40 m. The hourly owning and operating cost ratios and equipment details are shown in Table 7.1.

For a cost comparison, the cost of trucks was assumed to be similar for both field studies and the total hourly owning and operating cost ratios were relative to the crane.

Equipment	**Engine power**	**Engine tier**	**Cost ratio**
Crane	45 kW	3	1
Pump	250 HP	3	0.95
Truck (8 m^3)	300 HP	2	0.41

Table 7.1. Field study equipment characteristics.

7.4.2 Cycle data

For both field studies, truck cycles were observed over an extensive period and data were recorded both manually and by video, giving the following truck event times: arrival at the batching plant; start maneuver to load; start of loading; end of loading; arrival at the site; start maneuver at site; start of unloading; end of unloading and wash out at the construction site. Based on these data, queue waiting times and maneuver times at both the batching plant and the site, loading times, unloading times, wash out and travel times were obtained. In this study, the loading time is considered from the time the trucks enter the loading bay until they leave the batching plant. Table 7.2 shows the resulting average truck cycle component times for two field studies, giving a servicing factor (S/B), for the pump as the server, of 0.33 and bucket crane as the server, of 0.97.

Summarised event time data for the truck cycles and cumulative distributions for each of the cycle component times for crane and truck operation are given in Appendix I and J.

	Field study A	**Field study B**
Truck cycle component	**Time** (min)	**Time** (min)
Queue-at-load	19.712	26.826
Maneuver at batching point	1.525	1.621
Load	9.921	7.096
Loaded haul	9.347	11.660
Queue-at-unload	38.504	6.367
Maneuver at site	1.402	0.417
Unload	15.523	59.768
Wash out at site	1.996	2.417
Return	9.124	12.181
Backcycle	51.625	61.801
Service at (pump/crane)	16.925	60.185

Table 7.2. Field observed average truck cycle component times (min).

For crane cycles, the crane event times observed are as follows: start of bucket filling; end of bucket filling; start of bucket uplifting; arrival of bucket at final position; start of bucket emptying; end of bucket emptying; start of bucket down-lifting; and arrival of bucket on the ground. From these data, fill bucket times, uplifting bucket times, empty bucket times and down-lifting bucket times were obtained. Table 7.3 shows the resulting average crane cycle component times.

Crane cycle component	**Time** (min)
Fill bucket	0.826
Uplift bucket	1.601
Empty bucket	2.830
Down-lift bucket	1.460
Total cycle	6.717

Table 7.3. Field observed average crane cycle component times (min).

7.5 Results and Analysis

Based on the outlined analysis method and observed field data of the previous sections, production, waiting times, unit emissions, unit costs and optimal fleet sizes for different placement methods, pump and crane with bucket can be established and compared.

7.5.1 Production, unit emissions and unit costs

Figure 7.2 shows the production (expressed as m^3/h) and truck waiting time plotted against truck fleet size for different placement methods. Inevitably, concrete placement using pump, through a higher placing rate and a lower service time, generates a significantly higher production. In contrast, the use of crane with bucket to place concrete slab results in a lower production than pump due to a lower placing rate and it consumes a longer service time to complete the placing process. It is noticeable that the process of placing concrete using a crane is not continuous, where the crane cycles with only a bucket at any one time. The increase of service times and a higher idle time of trucks while waiting for the crane in every cycle will result in a significant decrease of production per hour. Alternatively, the use of the two buckets instead of one with the crane could increase the productivity and minimize the equipment idle time (Alkoc and Erbatur, 1998).

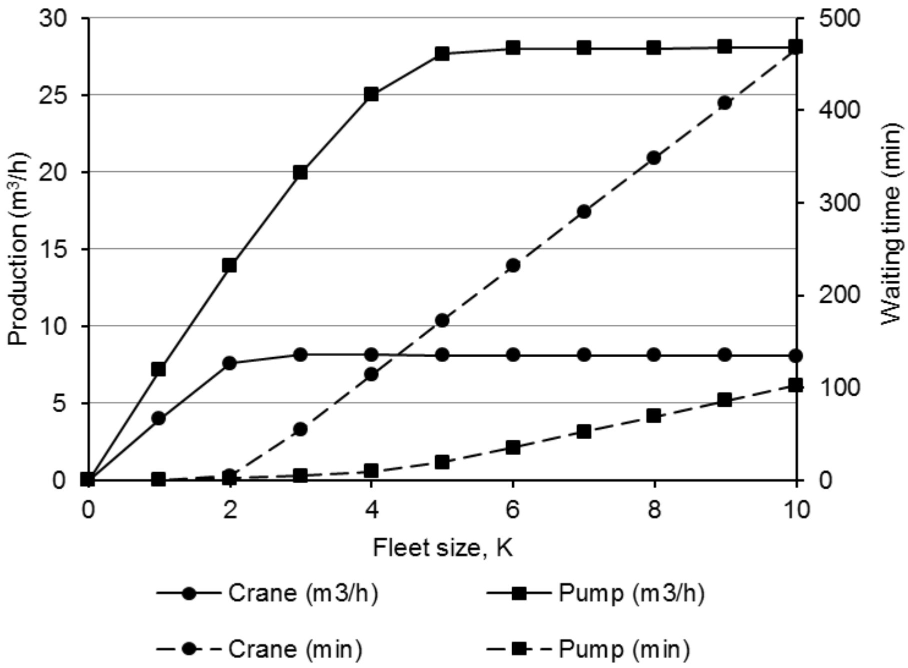


Figure 7.2. Production and truck waiting time versus truck fleet size for different placement methods.

In placing concrete using crane with bucket, the production reaches a maximum value of approximately two trucks, while more trucks (approximately 5 trucks) are required for the pump. The capability of the pump to supply a large volume of concrete at a higher rate contributes to a significant reduction in service time. Therefore, with less time required to complete the placing process compared to the crane, the pump can serve more trucks before it reaches the maximum production. It also can be observed in both placement methods that, as the production reached maximum values at matching point, the truck waiting times increased over the fleet sizes. However, it should be noted that the increasing truck fleet sizes beyond the matching point will not increase the production, but will significantly increase waiting time of trucks at site.

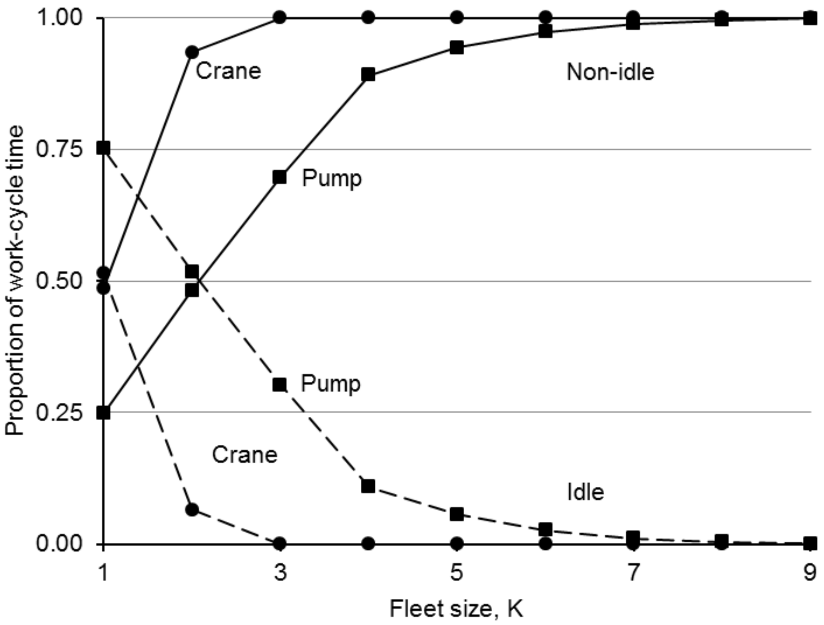


Figure 7.3. Idle and non-idle times of the crane and pump.

Figure 7.3 demonstrates the idle and non-idle times of the crane and pump as a server. 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. However, it should be noted that the slopes become approximately constant at the transition between the sloped portion and the flat portion. 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 Figure 7.4. 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. Apart from that, it is also demonstrated that different placement methods tend to have different effect on the level of equipment utilization.

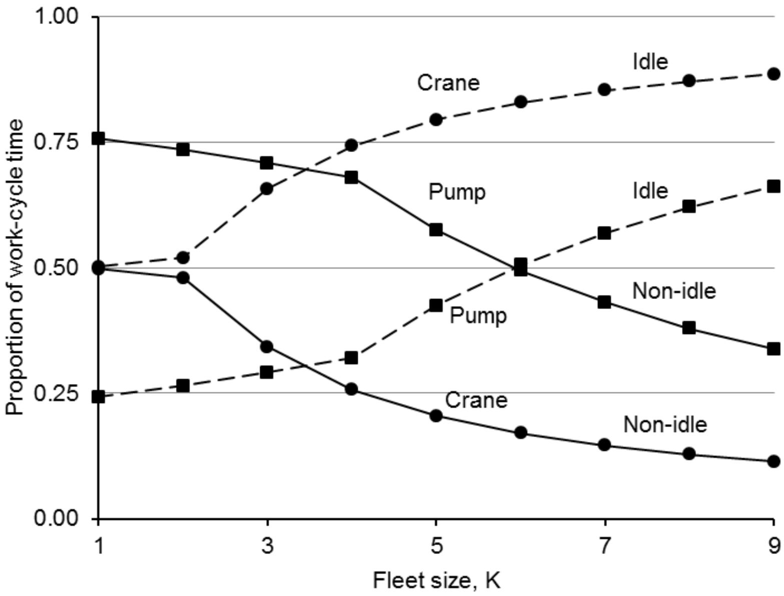


Figure 7.4. Idle and non-idle times of the truck.

Based on the observed field data in Figure 7.5, it is discovered that unit emissions and unit costs with the truck fleet size varied. As anticipated, unit emissions and unit costs for crane are higher than pump. This is due to the lower production per hour achieved by using the crane compared to the pump as observed in Figure 7.2. The increase of service times when using the crane resulted in a decrease of production per hour and an increase of truck waiting times simultaneously. Consequently, this outcome leads to the increase of fuel use, emissions and costs.

It is revealed that the optimum truck fleet sizes coincide for minimum unit emissions and minimum unit costs in the two placement methods. However, it can be observed that the curves are reasonably flat near the optima for placing concrete using the pump. The outcome is such because the utilization of truck fleet sizes which are greater than those optima will only increase unit emissions and unit costs. In fact, the coincidence of optima results for both unit emissions and unit costs in the concrete placement is consistent with the studies of Ahn et al.(2009) and Carmichael et al.(2012, 2014b) in earthmoving operations.

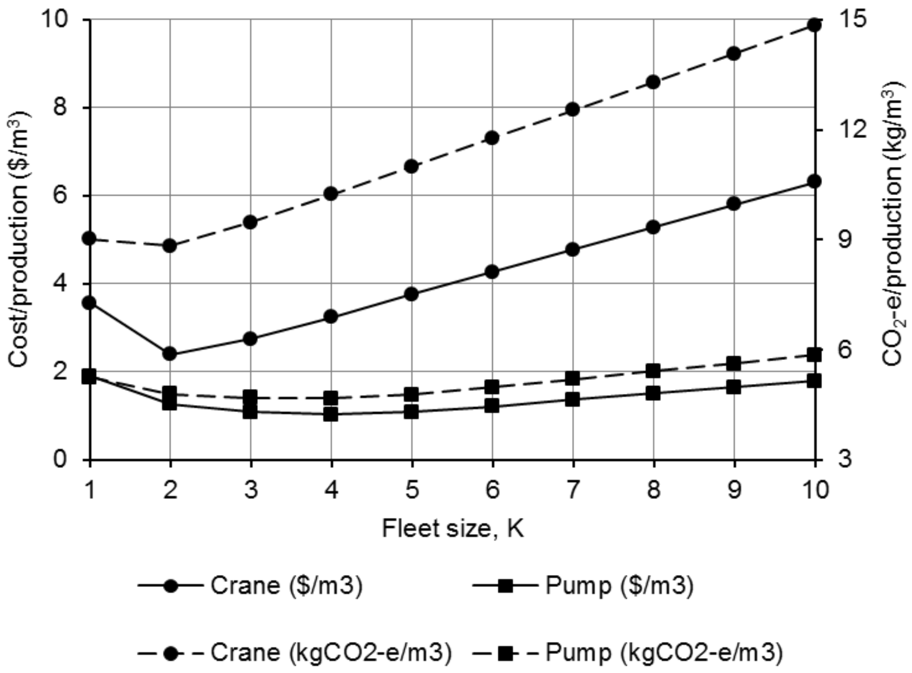
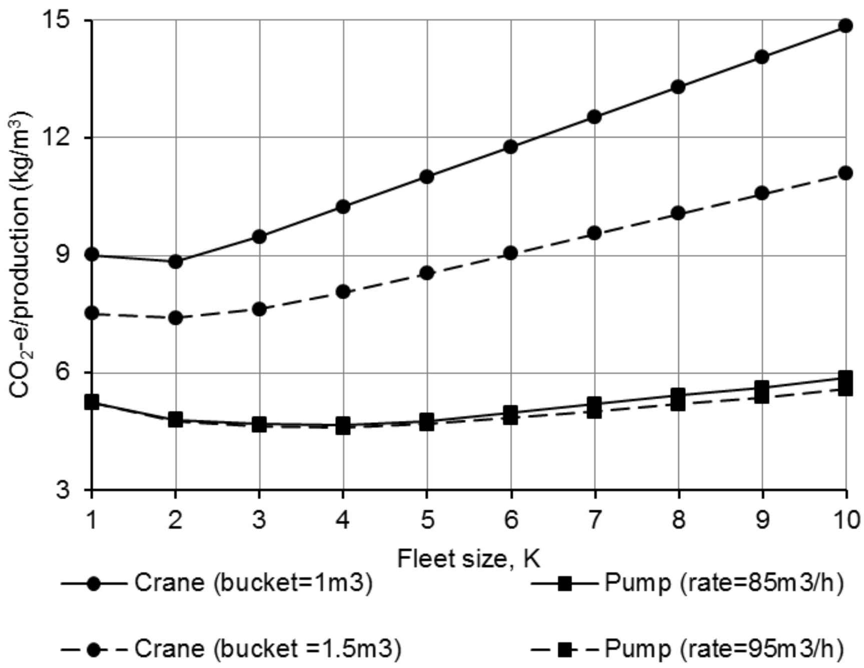


Figure 7.5. Unit emissions and unit costs versus truck fleet size for different placement methods.

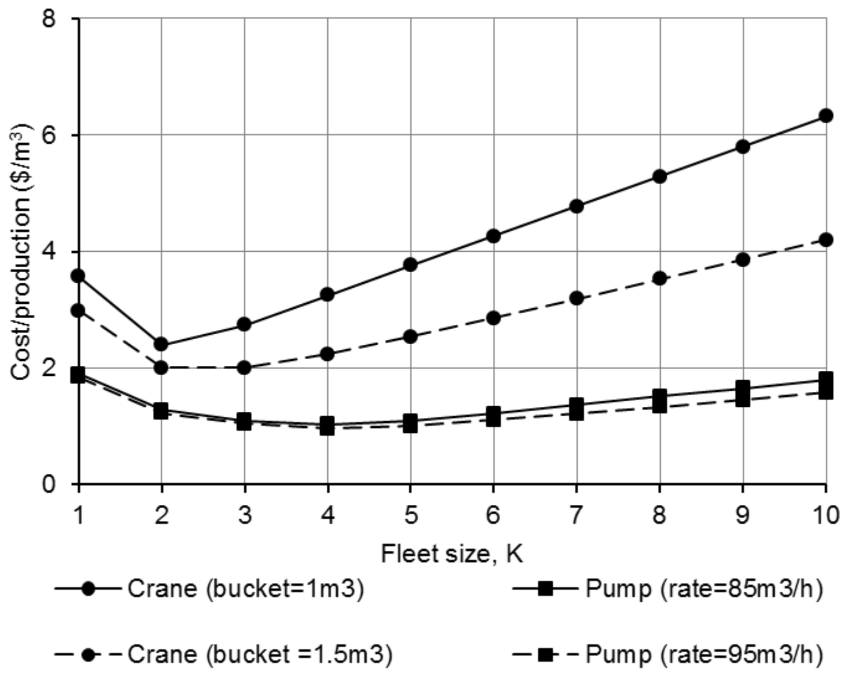
The influence of changing the operation parameters which includes server capacity, truck capacity, unloading policy, and fuel type on unit emissions, unit costs and the optima coincidence between both placement methods is demonstrated in the following studies below.

7.5.2 Influence of server capacity

Figures 7.6a and 7.6b show the influence of increasing the server capacity of pumping rate capability from 85 m^3/h to 95 m^3/h and 1m^3 to 1.5 m^3 for the method of placement using bucket and crane on unit emissions and unit costs.



(a)



(b)

Figure 7.6. The influence of server capacity for different placement methods on (a) unit emissions and (b) unit costs for varying fleet size, K.

A higher pumping rate translates to a decrease in unloading time and a decrease in the length of truck queue. Specifically, the decrease in truck idle time translates to a lower total fuel use, increase in production and decrease in unit emissions and unit costs. For placing with crane and bucket, there is a limitation on the amount of concrete that can be lifted at a certain period of time. However, increasing the bucket size from 1 m^3 to 1.5 m^3 contributes to a lower service time, increases production and significantly reduces unit emissions and unit costs. Alkoc and Erbatur (1997) reiterated that increasing the capacity of bucket in crane, results in a considerably higher productivity at a lesser cost.

Figure 7.7 shows the influence of server capacity on coincidence of optimum unit emissions and optimum unit cost in terms of fleet sizes. It is noted that the optimum fleet sizes for unit emissions and unit costs coincide for both the pump and crane. However, it can be seen that, for the crane, the optimum fleet size according to unit cost is relatively flatter than that for unit emissions.

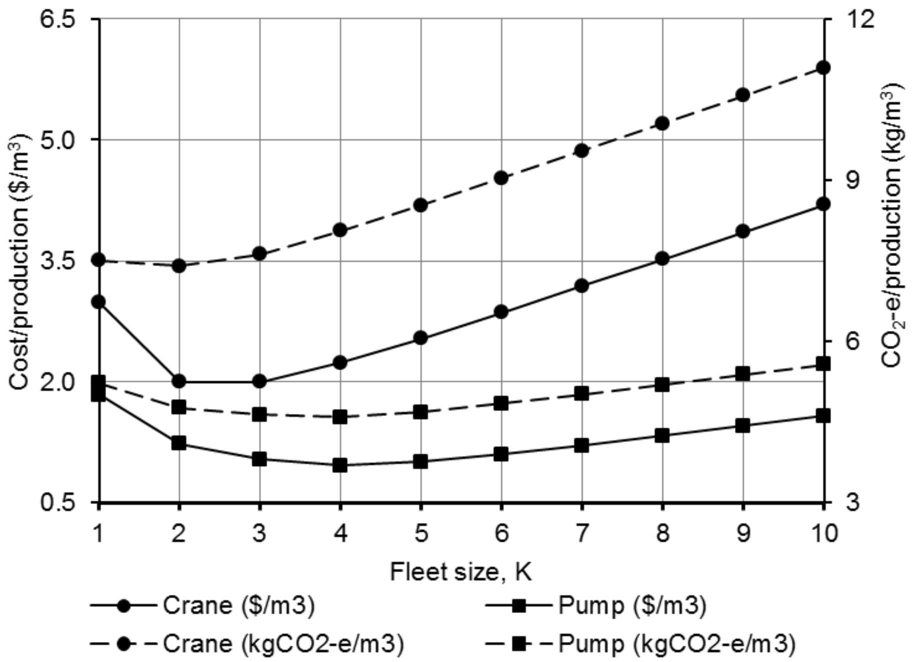
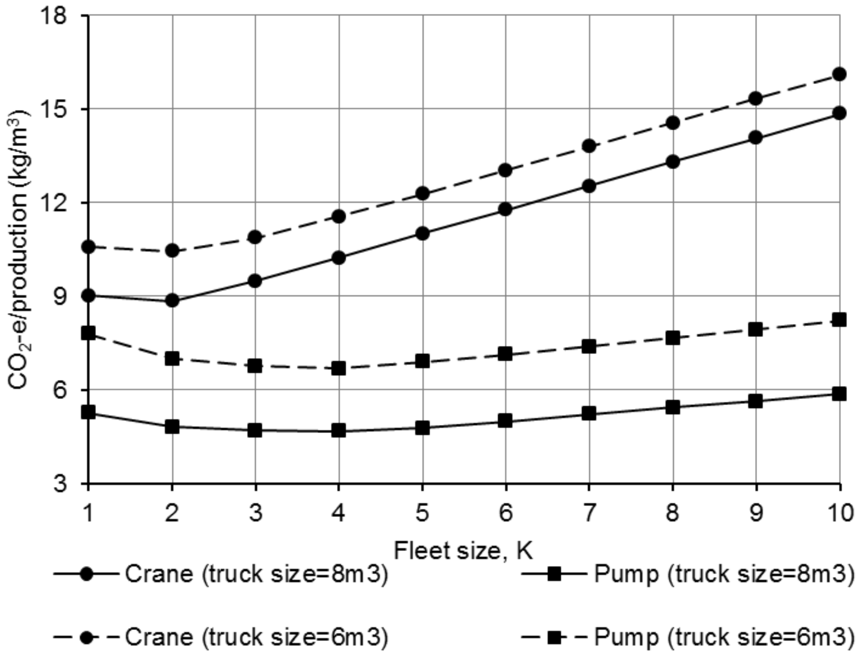


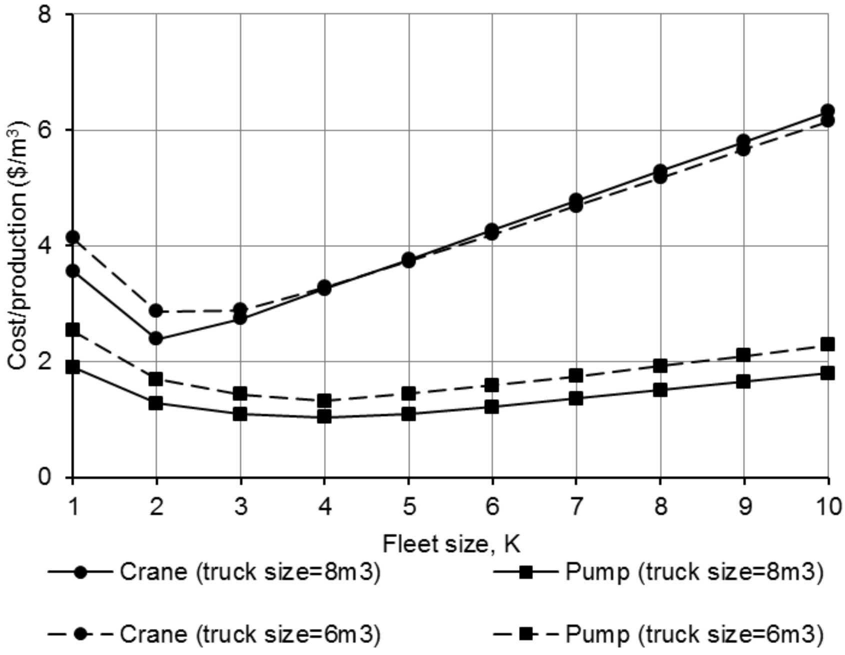
Figure 7.7. The influence of server capacity on coincidence of unit emissions and unit costs for varying fleet size, K.

7.5.3 Influence of truck capacity

The influence of decreasing the truck capacity from 8 m^3 to 6 m^3 for both placement methods on unit emissions and unit costs is shown in Figures 7.8a and 7.8b. When a lower capacity truck is employed, the results show a decrease in production and an increase of unit emissions for both placement methods. This result is consistent with the studies conducted by Smith (1999b). In placing concrete with pump, it is demonstrated that the unit cost increases when the capacity of trucks decreases. On the contrary, the placement method of concrete with crane and bucket shows a minor difference only in unit cost for small fleet size, where the waiting time on-site is minimized and production is predominantly determined by the number of trucks. For a large truck fleet size, where the server utilization is at its maximum, the production remains constant while the concrete is delivered at approximately the same cost.



(a)



(b)

Figure 7.8. The influence of truck capacity for different placement methods on (a) unit emissions and (b) unit costs for varying fleet size, K.

Figure 7.9 shows that, although the curves are reasonably flat near the optima of unit cost for the crane, the optimum truck fleet size for unit emissions and unit cost coincide regardless of the truck capacity used for both placement methods.

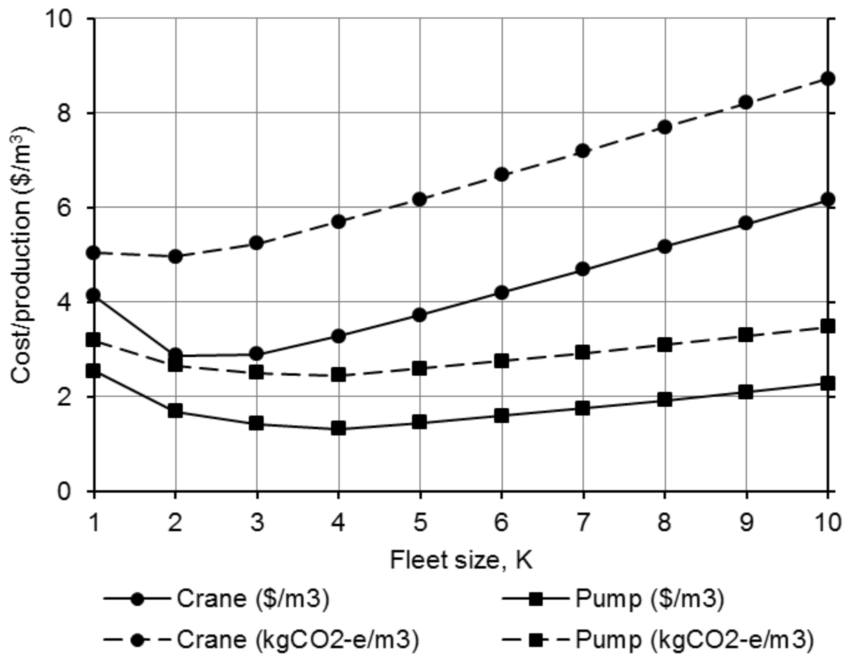


Figure 7.9. The influence of truck capacity on coincidence of unit emissions and unit costs for varying fleet size, K.

7.5.4 Influence of loading policy

A comparison of double-sided and single-sided unloading for pump and crane for unit emissions and unit costs is shown in Figures 7.10a and 7.10b. In this study, double-sided unloading means trucks can be unloaded to either side of the pump or crane. For the following truck, its maneuver can be started (and possibly completed) without waiting for the preceding truck to complete unloading. When the pump or crane finishes unloading the preceding truck, it starts directly to unload any following truck present. The reduction in the maneuver time leads to a reduction in service time and potentially increases the production.

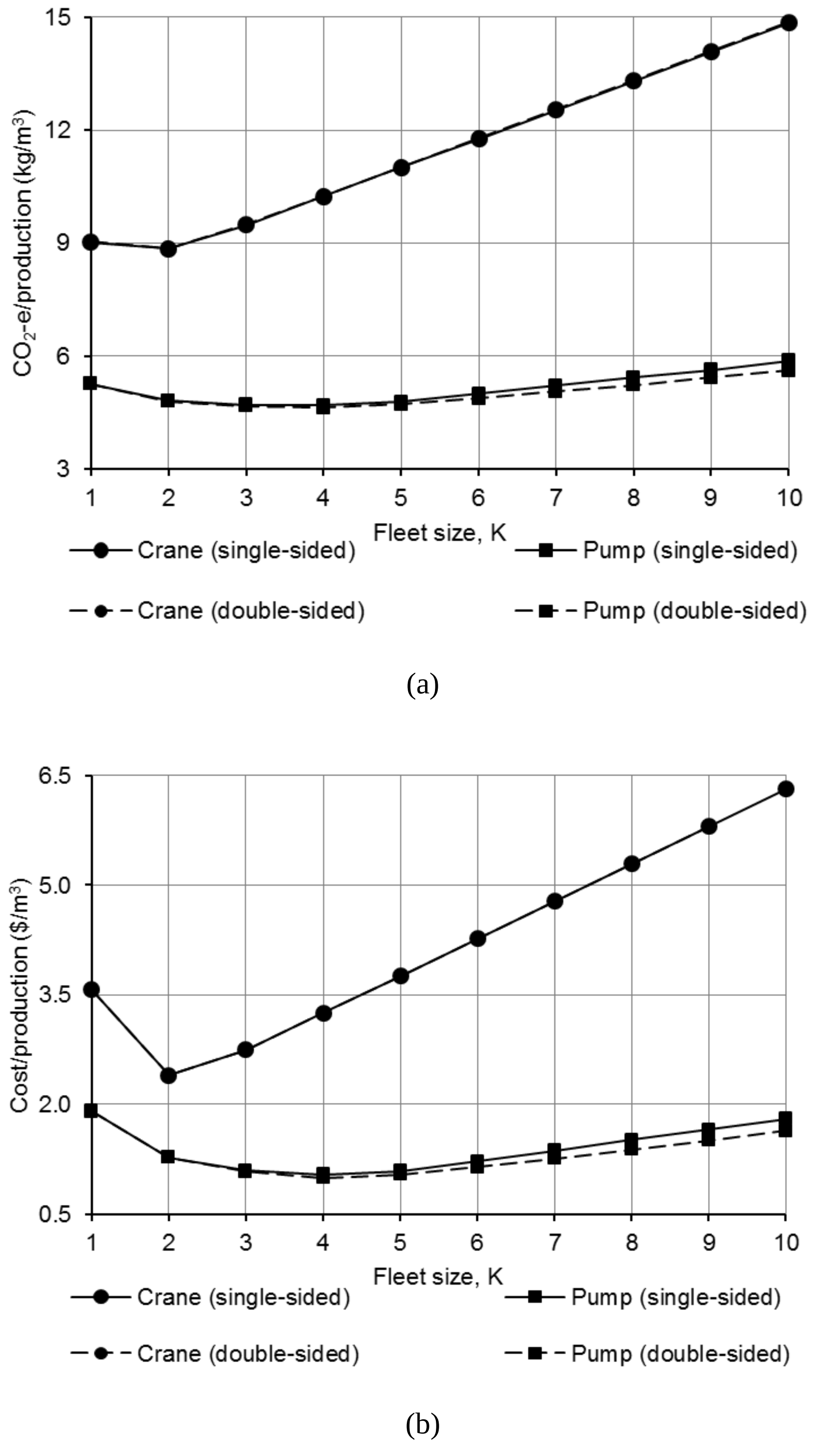


Figure 7.10. The influence of loading policy for different placement methods on (a) unit emissions and (b) unit costs for varying fleet size, K.

For placing concrete using a pump, reducing maneuver time through double-sided unloading leads to lower unit emissions and unit cost. However, it is observed that unit emissions and unit cost for the crane remain the same regardless of the unloading policy imposed. Since the unloading time using the crane is longer, reducing maneuver time will not contribute any significant effect towards service time. The finding of this study suggests that the advantages of double-sided loading could be significant only when the unloading time is shorter.

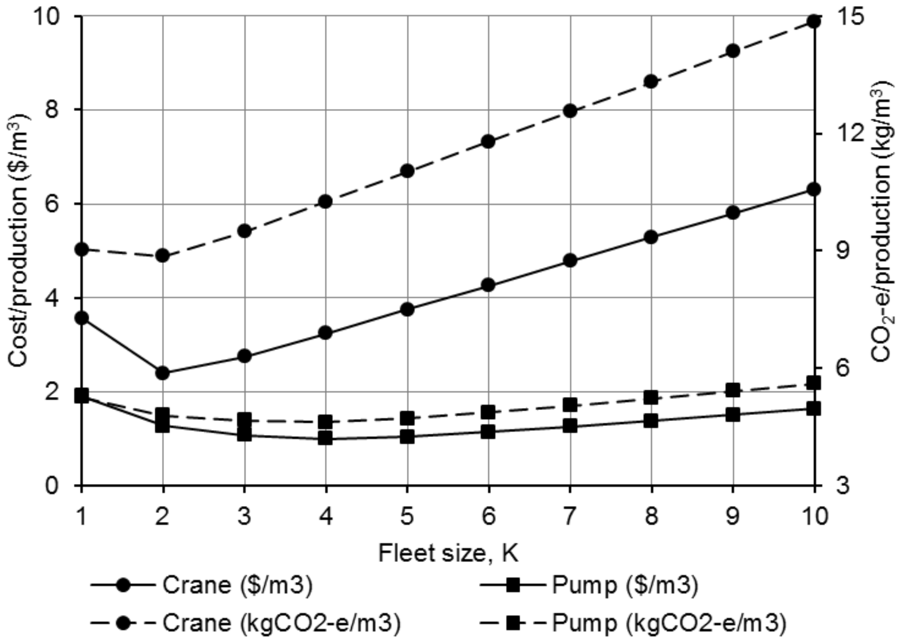


Figure 7.11. The influence of loading policy on coincidence of unit emissions and unit costs for varying fleet size, K.

Figure 7.11 shows the coincidence on unit emissions and unit costs, respectively, with fleet size. It can be observed that the optimum fleet size for unit emissions and unit cost remain coincident for double-sided unloading for both pump and crane placement methods.

7.5.5 Influence of fuel type

Figures 7.12 a and Figure 7.12b show the effect of fuel type on unit emissions and unit cost plotted against truck fleet size for different placement methods.

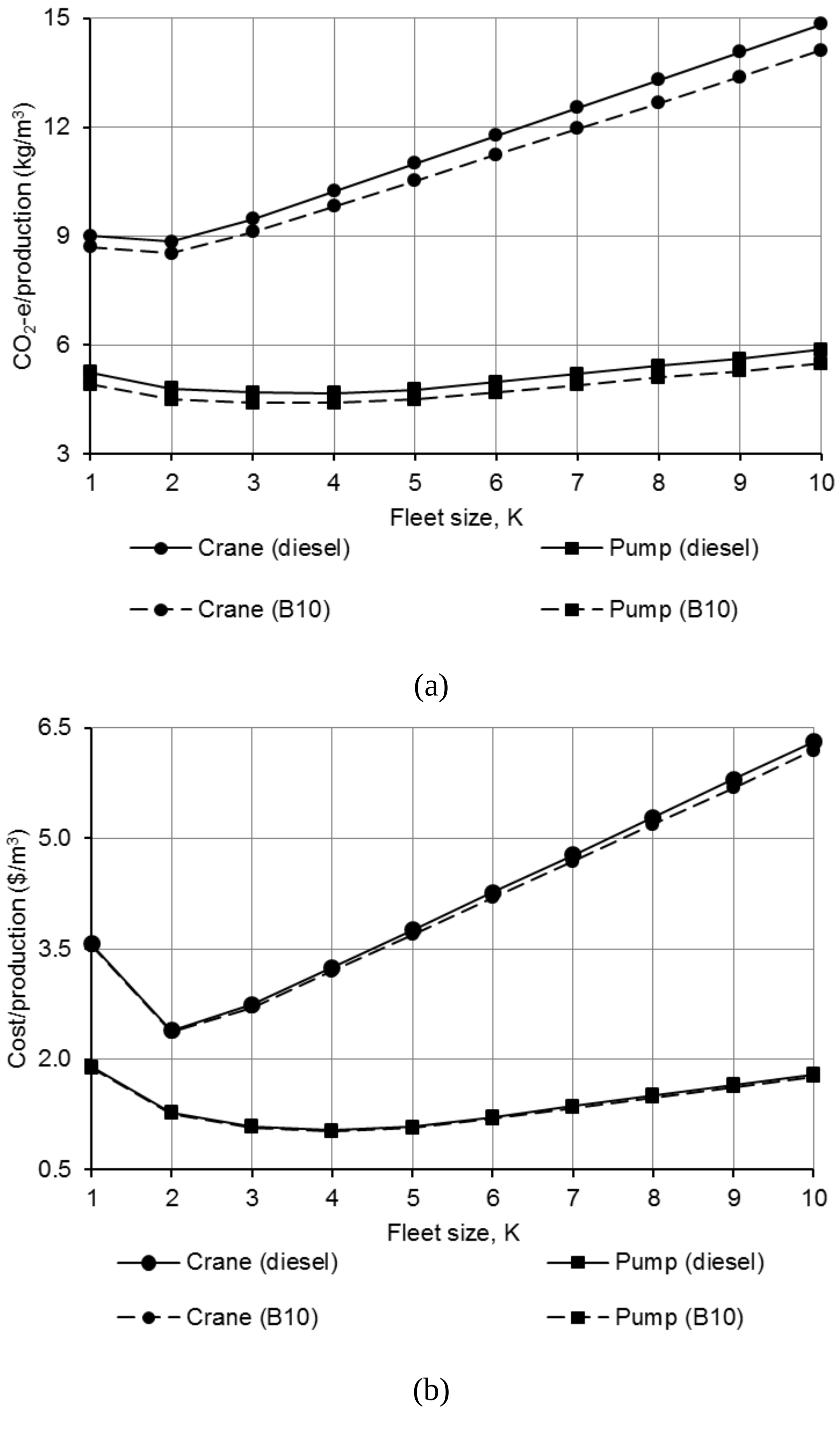


Figure 7.12. The influence of fuel type for different placement methods on (a) unit emissions and (b) unit costs for varying fleet size, K.

In this study, fuel type diesel is compared with B10 biodiesel (a blend of 10% palm biodiesel with 90% diesel). The amount of the fuel used remains similar for both, but the difference is in the specific energy content factors. For this particular case study, both trucks and pump used diesel fuel while the crane generated power from the main electricity grid. The substitution of diesel with B10 blend fuel for both trucks and pump leads to lower unit emissions for both placement methods. However, the unit cost is not affected much by the fuel type. This is because the fuel cost only contributes a small portion of the total owning and operating costs.

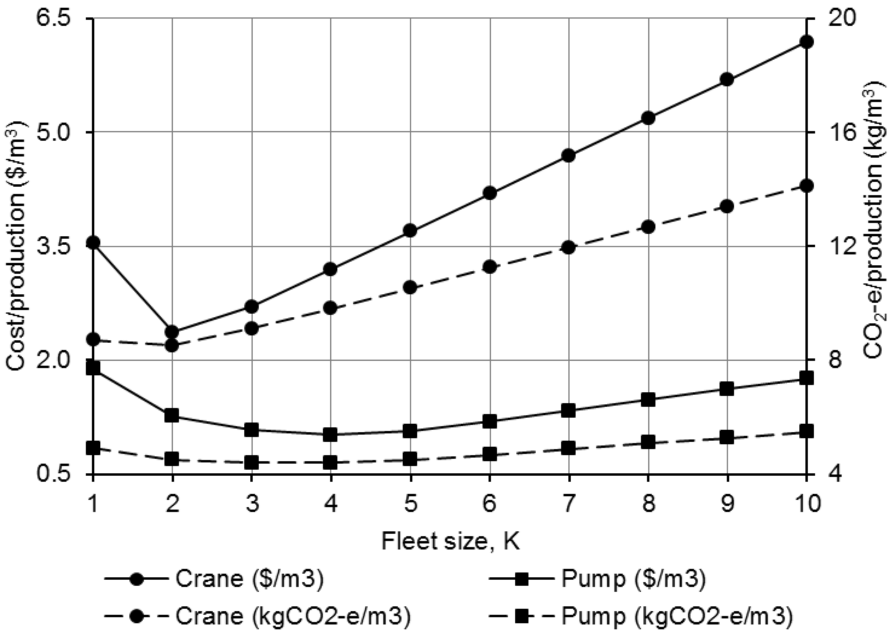


Figure 7.13. The influence of fuel type on coincidence of unit emissions and unit costs for varying fleet size, K.

It is shown in Figure 7.13 that the same optimum fleet size is achieved in both unit emissions and unit costs with different fuels for the two placement methods.

7.6 Discussion

In this case study, the general result shows the trade-off between equipment utilization, idle time and production of concrete placing using the pump and crane. Different concrete placement methods translate to different service times and equipment utilizations. Notably, the placement of concrete using a pump, through a lower service time and a higher placing rate than the crane, contributes to a higher production and a lower unit emissions and unit cost. In contrast, the increase of idle time for trucks due to a lower placing rate of the crane could be anticipated to decrease the production and consequently increase emissions and cost. Although the pumping method exhibits more advantages, the selection of placement equipment is also governed by the equipment availability, the location, size of pour, managerial team decision and time restriction (Anson and Shou-qing, 1998).

The result of the analysis shows that for pump and crane placement methods, the increase in server capacity and truck capacity lead to the overall increase of production as well as reduction in emissions and costs. In the context of unloading policy, whilst double-sided loading for pumping is executable and consistent with the discussion made by Kieffer and Selby (1983) and Dunlop and Smith (2000, 2003), reconfiguring the unloading policy will result in no significant effect on production, emissions and cost for crane placement method. This chapter also highlights the coincidence of the optimum fleet size for unit emissions with unit costs regardless of the different configurations of the concreting operation. Ideally, this indicates that contractors would prefer to operate with fleet sizes greater than the optimum in order to cater for equipment reliability and availability.

7.7 Conclusion

Placing concrete by crane is much slower than by pump, leading to a lower production rate, because of a number of reasons such as the crane cycling with only one bucket at any one time, and having greater unloading times. Unit emissions and unit costs will consequently be different for concrete placement by pump and by crane. Existing publications have focused on establishing the optimum fleet size in terms of minimum unit cost, while no publications have examined these optima in terms of unit emissions for concrete placement. This chapter fills this gap by demonstrating the link between production, unit emissions and unit cost with respect to optimum fleet size for placing methods: pump and crane. Monte Carlo simulation was used for the analysis in conjunction with field data. Sensitivity-style analysis was performed by changing some underlying parameters such as server capacity, truck capacity, unloading policy, and fuel type.

The implications of this study, irrespective of different methods used for placing concrete and even for different operation parameters, are that managing concreting operations efficiently according to least unit cost is also best for the environment in terms of minimizing unit emissions, while not managing such operations efficiently creates unnecessary emissions.

CHAPTER 8 - CONCLUSION

This chapter presents the summarized findings and conclusions of the study. A discussion on the limitations of the current study as well as directions for future research is also included in the later part of this chapter.

8.1 Summary of Findings

The key elements of the research and the practical implications of the findings are summarized as follows:

In Chapter 3, the current perception of the construction industry on matters relating to emissions was examined with the emphasis on the lack of quantitative measures on the attitude towards emissions. A quantitative measure was established through the medium of utility and utility functions to model the industry attitude. The implication of this measure is demonstrated in terms of unit emissions and unit costs in earthmoving operations by highlighting the results for differing degrees of risk aversion.

Chapter 4 highlighted possible alternative loading policies which have the potential to reduce equipment idle time and emissions. A case study was used to illustrate the emissions, production and cost of non-standard earthmoving loading policies. The underlying models for all loading cases were developed using Monte Carlo simulation. Truck cycle component times can be related through recursive relationships. Alternative loading policies were found to lead to different combinations of idle times, equipment utilizations and production. The implication is that managing excavator-truck operations efficiently according to least unit cost is also best for the environment in terms of minimizing unit emissions, while not managing such operations efficiently creates unnecessary emissions. This is true for both single-sided and double-sided loading. For fractional loading, the fleet size needs to be decreased below that for optimum unit cost in order to minimize emissions.

Chapter 5 evaluated the effect of varying underlying parameters on production, unit emissions and unit costs on non-standard earthmoving loading policies. Monte Carlo simulation was used for the analysis in conjunction with the field data. This research has essentially managed to demonstrate the relationship between load, load time, truck cycle times, equipment idle times, equipment utilizations, emissions, cost and production for each loading policy. The findings revealed that there is a change in the ranking of unit emissions and unit costs of each alternative loading policy with a change in truck cycle component time and fleet size. In general, it was demonstrated that higher unit emissions and unit costs were achieved with the increase of each truck cycle component time. The examination of the overloading case demonstrated that different loading policies employed led to different effects on production, unit emissions and unit costs. The findings suggested that slight overloading through using single-sided loading policy showed an increase in production, hence, lower unit emissions and unit costs. On the other hand, overloading through using multiplier loading should not be contemplated for large fleet sizes because it leads to an increase in unit emissions and unit costs.

Chapter 6 investigated unit emissions in concreting operations, and proposed guidelines for their reduction. Unit emissions and unit costs for concreting operations were calculated using a queuing model that looks at the trucks cycle between a batching plant and site. The findings of the study revealed that for a given concrete pump and truck operation, the concreting work that is carried out in such a way that minimizes unit cost, will also minimize unit emissions. In other words, minimizing emissions does not lead to extra cost. On the other hand, not undertaking the work at a minimum unit cost will result in unnecessary emissions. There is a time-production constraint but it does not alter the general conclusion for the case study.

Chapter 7 justified the two placement methods used for the purpose of comparing the minimum unit cost and minimum unit emissions configurations based on different equipment utilizations, server capacity, truck capacity, unloading policy and fuel type. The results of this study demonstrated that the optimum truck fleet size for unit emissions is the same as the unit costs regardless of the different methods used for placing concrete and even for different operation parameters.

This thesis has examined the following three main concerns that have driven the conduct of this research:

1. No publication has attempted to quantify or model the construction industry's attitudes on emissions, apart from some nominal statistics.

2. No publication has explored loading influence on unit emissions, emissions or production, or optimality with respect to fleet size in the sense of unit emissions or unit cost.

3. No publication has examined the coincidence optima in terms of minimum unit cost and minimum unit emissions for other types of construction operations, apart from earthmoving operations.

These concerns have been translated into seven research questions which this thesis has successfully addressed as follows:

1. What is the attitude of the construction industry towards emissions?

   Generally, it is found that construction personnel are risk aversive to emissions, but at differing degrees. In this case, risk is interpreted in the same way as that applied to money, but instead units of emissions are involved; it is used in the sense of the magnitude and likelihood of an outcome involving emissions. The findings also indicated that attitudes towards emissions vary between people occupying different positions within the industry. The results obtained are indicative, but not definitive because different people display different utility under varying circumstances.

2. How can the attitude of the construction industry towards emissions be measured quantitatively?

   Utility has been considered as a useful method for measuring and comparing attitudes towards emissions. Without such a measure, attitudes would be difficult to compare (except for extremes in attitude) in any meaningful way. Surveys and questionnaires can be flawed if they are not done rigorously. The establishment of industry attitudes towards emissions makes it possible to gauge any changes that could help improve the attitudes over time.

3. To what extent do the alternative loading policies lead to different unit emissions and unit costs outcomes in earthmoving operations?

   It is worth noting that all the loading policies are able to reduce equipment idle time and the associated reduction in consumption of fuel and emissions, but they may have different impacts on production. With different loading policies, there can be a counter-balancing reduction in production, and it is not immediately clear where the trade-off lies between reduced truck idle time, increased equipment utilization and changed loading policy. The results demonstrated that it is not appropriate to solely concentrate on truck waiting time (and truck queue length). Hence, it is suggested that the optimum can be obtained by balancing the excavator and truck utilizations, while also taking into account the ratios of emissions magnitude and costs of different equipment. However, low truck waiting times may or may not lead to higher unit emissions and unit costs.

4. How much gain/loss in the production, and how much extra/less unit emissions and unit cost are involved in non-standard earthmoving loading policies?

   Double-sided loading was found to have the least impact on the environment. Meanwhile, zero waiting time loading performed the worst in terms of environmental impact and cost. Minimizing truck waiting time through using fractional loading is generally not an attractive policy because it leads to an increase in unit emissions and unit costs. The consequences of adopting fractional loading have been discussed in detail. Optimum unit emissions and optimum unit cost are coincident with respect to fleet size for single-sided and double-sided loading policies. The traditional practice of minimizing unit cost provides the least impact on the environment. Not minimizing unit cost will lead to unnecessary emissions.

5. To what extent do the different loading policies influence the earthmoving underlying parameters on production, unit emissions and unit costs?

   The results of unit emissions and unit costs suggest that load, load time, service time, travel time, waiting time and truck fleet size are robust in changing the operation parameters for all loading policies. It was further implied that different loading policies lead to different effects on production and fuel use, which in turn affect the unit emissions and unit costs. The findings of this study also revealed that the changed loading policies tend to affect the load time, service time, waiting time and travel time. Service time has been shown to significantly influence the production, unit emissions and unit costs. Hence, there is a promising opportunity to improve the productivity by keeping a minimum service time. Minimizing travel time and waiting time will also lead to more efficient earthmoving operations.

6. To what extent does managing the concreting operations in terms of minimum unit cost change the unit emissions?

   The optimum truck fleet size for unit emissions was found to be similar to the unit cost under a range of different operation parameters. The results further indicated that the operation must be carried out at minimum unit cost to prevent the increase of emission; hence, this is regarded as the most environmentally aware method to configure and manage concreting operations.

7. How can different configurations and operation parameters influence the optima in terms of unit emissions and unit costs in concreting operations?

   Managing concreting operations efficiently according to least unit cost is the best approach to minimize unit emissions, while not managing such operations efficiently creates unnecessary emissions despite the different methods used for placing concrete and even for various operation parameters.

Having answered all the above research questions, this study have thus managed to achieve all of its research objectives as listed below:

1. Examining the attitudes of the construction industry towards emissions and establishing a quantitative measure to evaluate their risk attitude.
2. Exploring loading influence and demonstrating the implications associated with alternative loading policies on unit emissions and unit costs in earthmoving operations.
3. Investigating the optima coincidence with respect to minimum unit emissions and minimum unit costs and exploring the influence of constraints and operation parameters on the optimum equipment configurations in concreting operations.

8.2 Implications and Contribution to Knowledge

This chapter concludes the study by collating the findings with the research objectives. Construction operations commonly utilize a large range of equipment that generates a considerable amount of greenhouse gas (GHG) emissions. Historically, the industry has focused on cost, production and time, but now adds emissions to this list. Industry attitudes towards emissions have been the subject of a number of surveys, but these only provide qualitative information. This study takes a quite different approach and establishes, for the first time, quantitative measures of industry attitude. It does this through the medium of utility and utility functions. The thesis is original in terms of offering a different view of emissions in the construction industry.

The performance of earthmoving operations, in terms of emissions, production and cost, is dependent on many variables and has been the study of a number of publications. Such publications look at typical operation design and management, without establishing what the penalties or bonuses might be for non-standard, but still observed, practices. The importance and originality of this thesis is in examining alternative loading policies of zero waiting-time loading, fractional loading and double-sided loading, and compares the performance of these with standard single-sided loading of earthmoving operations. Several loading policies studied may only be seen intermittently in practice. However, there is no publication which tells how they perform relative to one another, how much gain/loss in production occurs and how much extra/less unit emissions and unit cost are involved. This thesis quantifies these and provides useful information for assessing the most environmentally aware and economical way to design and manage earthmoving operations. Original recursive relationships, that are amenable to Monte Carlo simulation, are derived in this study.

This thesis also examines the unit emissions for concreting operations and links it with unit costs and associated optimum equipment configurations. The results indicate the most environmentally aware way to configure and manage concreting operations. This study is original in establishing the configuration of concreting operations for least unit emissions.

The main practical implication of this thesis is to provide information that is beneficial for the assessment of the most environmentally conscious and economical way to design and manage construction operations and will be of interest to those looking to reduce or manage construction emissions.

The present study adds to the growing body of research by emphasizing that the least impact on the environment can be obtained through the traditional practice of minimizing unit cost. Failure to minimize unit cost will lead to unnecessary emissions.

8.3 Research Limitations and Recommendations for Future Research

This thesis has made some significant theoretical and empirical contributions to the operational management strategies in construction operations. However, there are some limitations in this study that may lead to a few relevant directions for future research as outlined below:

The findings in Chapter 3 are based on the attitudes extracted from scenarios designed by the author. Testing by others along the same lines as outlined in the thesis would assist in adding weight to the findings. Different scenarios for establishing utility functions could be tried. The thesis used composite measures such as unit emissions in order to avoid the issues associated with multi-criteria or multi-attribute analysis. However, individual attributes could be examined separately and together to gain a better understand of the attitudes.

The findings further indicated that construction personnel display risk averse tendencies with respect to emissions. The results obtained are indicative, but not definitive because different individuals display different utility in different circumstances. Apart from that, it is crucial to acknowledge the importance of decreasing the carbon footprint of projects in relation to the costs and safety program. It is undeniable that a more environmentally conscious industry will encourage the construction firms to prioritize solutions to climate change.

This thesis assessed operational emissions and costs for existing field equipment set ups. However, it did not examine any issues related to the introduction of new emissions-saving technology such as equipment modifications, utilization of newer equipment or adoption of operator training. Nevertheless, it is believed that the absolute results in terms of unit emissions and unit costs could be decreased further through adopting these possible solutions; however, the relative results presented in this thesis will not change, and the same conclusions will hold.

The case study data also were observed based on existing configurations of field operation. It does not include the process involved in altering the conduct of the operations to reduce emissions, particularly use of alternative haul routes, lower haul route grade or improved haul road bends. Nevertheless, it is worth noting that other possible parameters such as haul road conditions and characteristics occurring on sites different to the case studies may affect the results obtained in this study. Therefore, further studies need to be carried out in order to expand the conclusion.

Consideration of equipment operators being actively involved rather than sitting and waiting might also be important for people management purposes. Observed practice on site was for the truck drivers to leave their engines idling continually. Further emission savings would be possible here through adopting a practice of turning engines off while on site.

The absolute results for the overloaded truck presented in Chapter 5 remain subject to maintenance and equipment reliability concerns despite the findings showing a reduction in unit emissions and unit costs. Further considerations related to the hidden cost of equipment wear and tear and maintenance would further expand the analysis of this study.

Consideration of the other operation parameters, such as the effect of swing angle and depth of cut of excavator performance in Chapter 5 and the analysis of unit emissions and unit cost with other placing methods, such as hoists in Chapters 6 and 7, remains for further investigation in assisting better design and management of operations

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Appendix A. Utility Function Case Studies

Utility Function Scenario I: Earthmoving

A cut-and-fill operation will be undertaken on a residential development construction site. The operation involves excavation by using a 1 m^3 bucket capacity of excavator and trucks with 6 m^3 capacity, hauling soil from load to fill area.

There are two possible routes that can be used by haul trucks. The longer route is sealed and smooth traffic whiles the alternative route has a shorter distance, but with unpredictable traffic conditions. If the traffic is denser, the travel times, fuel use and CO_2-e will be greater. If the traffic is lesser, the travel times, fuel use and CO_2-e will be lesser.

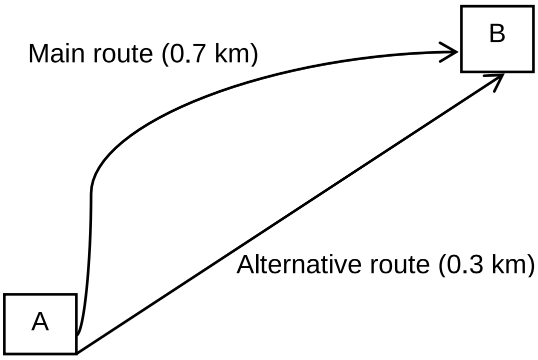


Figure A1. Possible routes between loading area (A) and dumping area (B).

There are two choices:

C1 Certain outcome - longer (sealed) route with smooth traffic condition. Travel time, fuel use and CO_2-e are always the same on every trip, or

C2 Uncertain outcome - alternative route with a shorter distance but with unpredictable traffic conditions. If the traffic is denser, the travel times, fuel use and CO_2-e will be greater. If the traffic is lesser, the travel times, fuel use and CO_2-e will be lesser.

At what probability, p (out of 100%) would you decide to utilize alternative route?

Table A1 shows truck fuel consumption and CO_2-e emissions for different truck travel times in earthmoving operation. The preference order in Table A1 is based on lower to higher unit emissions (kg CO_2-e/m^3).

Attributes	Routes (km)	Traffic level	Travel time (min)	CO_2-e (kg/h)	Production (m^3/h)	Unit emissions (kg CO_2-e/m^3)
X_1	0.3	Smooth	1.43	73.14	145.19	0.504
X_2	0.3	Less	3.37	103.00	151.69	0.679
X_3	0.3	Moderate	3.37	133.01	162.61	0.818
X_4	0.3	Slightly dense	3.37	165.96	162.07	1.024
X_5	0.3	Dense	6.44	200.27	162.54	1.232
X_6	0.7	Smooth	8.02	217.45	162.24	1.340
X_7	0.3	Highly dense	10.39	242.48	161.18	1.504

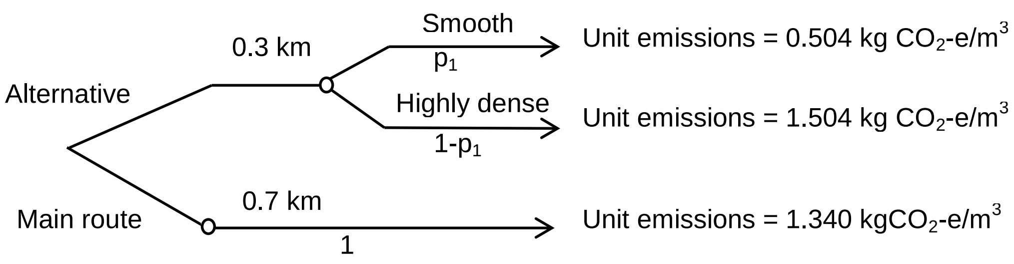
Table A1. Unit emissions versus travel time.

Question 1

Based on the decision tree below, there are two choices:

C1 Longer (sealed) route with smooth traffic condition. Travel time, fuel use and CO_2-e are always the same on every trip, or

C2 The alternative route with a shorter distance but unpredictable traffic conditions. If the traffic is denser, the travel times, fuel use and CO_2-e will be greater. If the traffic is lesser, the travel times, fuel use and CO_2-e will be lesser.



At what probability, p_1 (out of 100%) would you decide to utilize alternative route with smooth traffic?

Give your answer here:

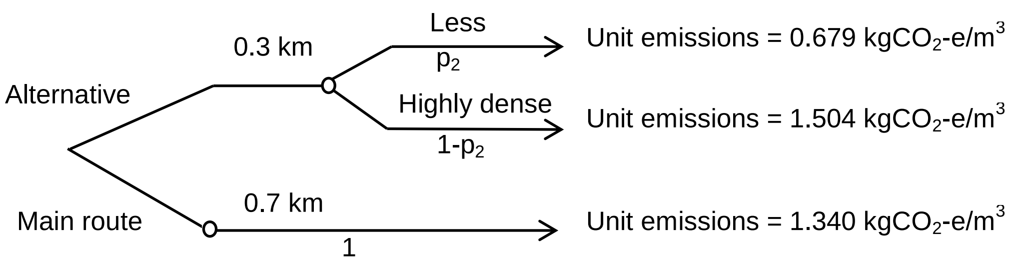
p_1	

Question 2

Much like the previous question, there are another two choices:

C1 Longer (sealed) route with less traffic condition, or

C2 The alternative route with a shorter distance but unpredictable traffic conditions. If the traffic is denser, the travel times will be greater. If the traffic is lesser, the travel times will be shorter.



At what probability, p_2 (out of 100%) would you decide to utilize alternative route with less traffic?

Give your answer here:

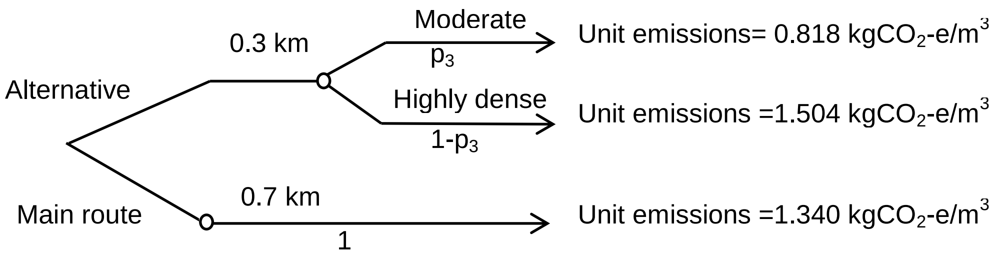
p_2	

Question 3

There are another two choices:

C1 Longer (sealed) route with moderate traffic condition, or

C2 The alternative route with a shorter distance but unpredictable traffic conditions. If the traffic is denser, the travel times will be greater. If the traffic is lesser, the travel times will be shorter.



At what probability, p_3 (out of 100%) would you decide to utilize alternative route with moderate traffic?

Give your answer here:

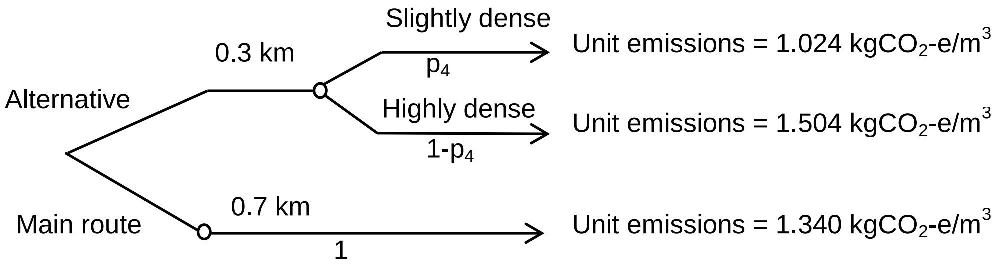
p_3	

Question 4

There are another two choices:

C1 Longer (sealed) route with slightly dense traffic condition, or

C2 The alternative route with a shorter distance but unpredictable traffic conditions. If the traffic is denser, the travel times will be greater. If the traffic is lesser, the travel times will be shorter.



At what probability, p_4 (out of 100%) would you decide to utilize alternative route with slightly dense traffic?

Give your answer here:

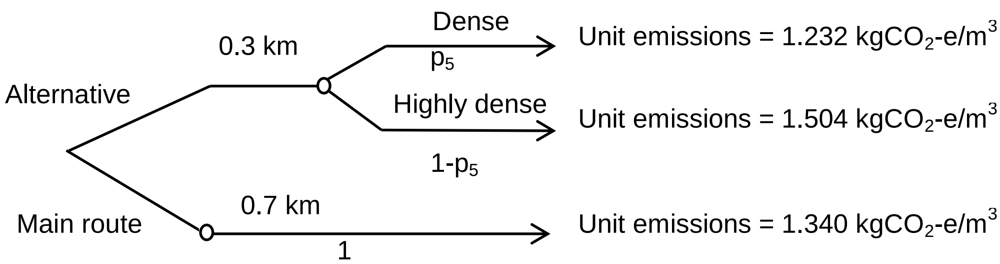
p_4	

Question 5

There are another two choices:

C1 Longer (sealed) route with dense traffic condition, or

C2 The alternative route with a shorter distance but unpredictable traffic conditions. If the traffic is denser, the travel times will be greater. If the traffic is lesser, the travel times will be shorter.



At what probability, p_5 (out of 100%) would you decide to utilize alternative route with dense traffic?

Give your answer here:

p_5	

Utility Function Scenario II: Tender submissions

This scenario is designed to evaluate non-conforming (alternative) tenders based on submitted prices and submitted technology.

A construction will be carried out on a residential development. Several contractors participated by submitting their cost proposal. Each contractor has proposed their method of construction with different technologies.

There are choices in selecting tenders based on submitted prices and submitted technology. Table A2 shows the submitted tender prices and emissions associated with each technology proposed.

There are two choices:

C1 Certain outcome – use existing technology. Price (cost) is known as tendered. The existing technology (and hence emissions) is known (from past measurement), or

C2 Uncertain outcome – Each tender uses an alternative technology. For each tender, the price is known as tendered. However, the actual emissions are unpredictable because of the alternative technologies proposed. Some tenders are cheaper, some are more expensive. But for each tender, the actual emissions are uncertain.

At what probability, p (out of 100%) would you decide to utilize alternative technology?

The preference order in Table A2 is based on lower to higher emissions/cost (kg CO_2-e/$).

Attributes	Contractor	Tender price ($)	Emissions ($kgCO_2$-e)	Emissions/cost ($kgCO_2$-e/$)
X_1	A	300000	30012	0.100
X_2	B	290400	70752	0.244
X_3	C	285000	123690	0.434
X_4	D	240000	174000	0.725
X_5	E	265000	241945	0.913
X_6	F	250000	303500	1.214
X_7	G	252000	361620	1.435

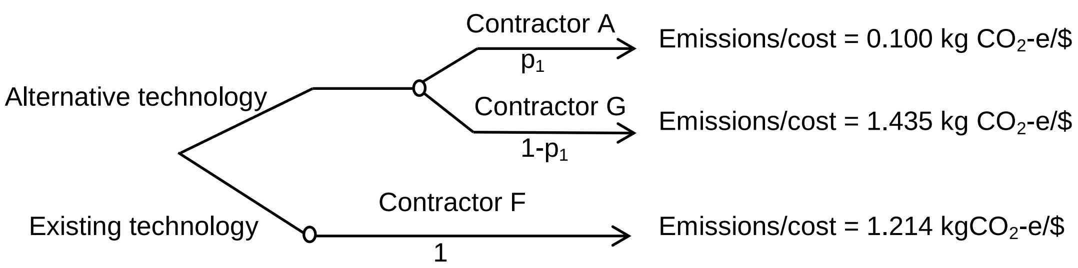
Table A2. Emissions/cost ($kgCO_2$-e/$) for submitted tenders.

Question 1

Based on the decision tree below, there are two choices:

C1 Use existing technology. Price (cost) is known as tendered. The existing technology (and hence emissions) known (from past measurement), or

C2 Each tender uses an alternative technology. For each tender, the price is known as tendered. However, the actual emissions are unpredictable because of the alternative technologies proposed. Some tenders are cheaper, some are more expensive. But for each tender, the actual emissions are uncertain.



At what probability, p_1 (out of 100%) would you decide to utilize alternative technology proposed by Contractor A?

Give your answer here:

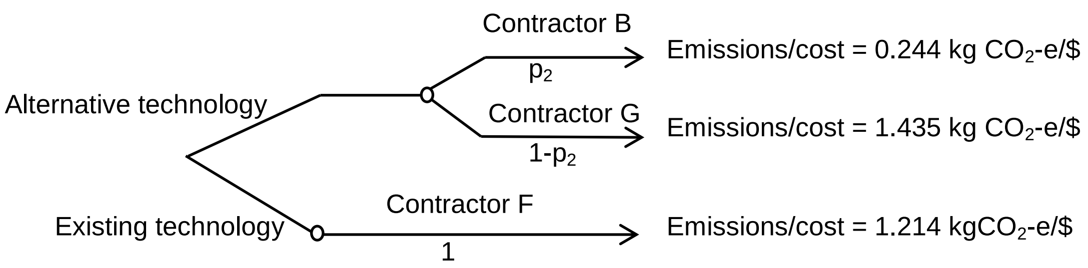
p_1	

Question 2

Much like the previous question, there are another two choices:

C1 Use existing technology. Price (cost) is known as tendered. The existing technology (and hence emissions) known (from past measurement), or

C2 Each tender uses an alternative technology. For each tender, the price is known as tendered. However, the actual emissions are unpredictable because of the alternative technologies proposed.



At what probability, p_2 (out of 100%) would you decide to utilize alternative technology proposed by Contractor B?

Give your answer here:

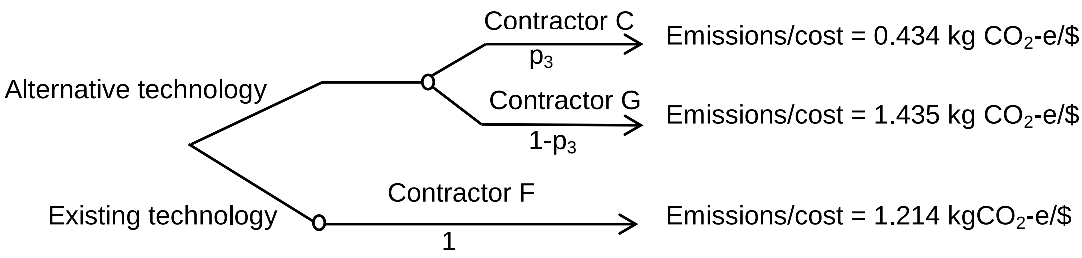
p_2	

Question 3

There are another two choices:

C1 Use existing technology. Price (cost) is known as tendered. The existing technology (and hence emissions) known (from past measurement), or

C2 Each tender uses an alternative technology. For each tender, the price is known as tendered. However, the actual emissions are unpredictable because of the alternative technologies proposed.



At what probability, p_3 (out of 100%) would you decide to utilize alternative technology proposed by Contractor C?

Give your answer here:

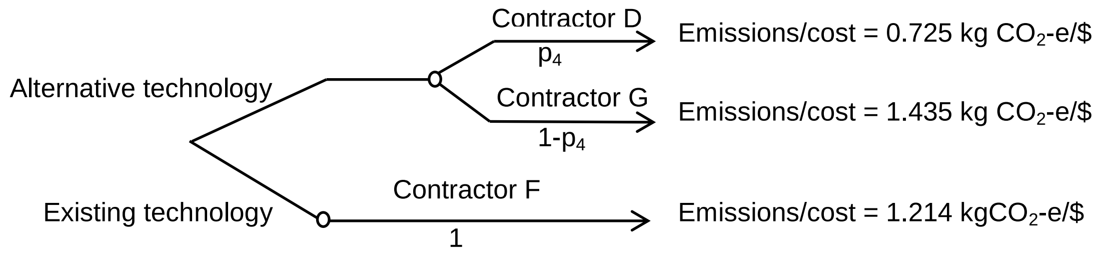
p_3	

Question 4

There are another two choices:

C1 Use existing technology. Price (cost) is known as tendered. The existing technology (and hence emissions) known (from past measurement), or

C2 Each tender uses an alternative technology. For each tender, the price is known as tendered. However, the actual emissions are unpredictable because of the alternative technologies proposed.



At what probability, p_4 (out of 100%) would you decide to utilize alternative technology proposed by Contractor D?

Give your answer here:

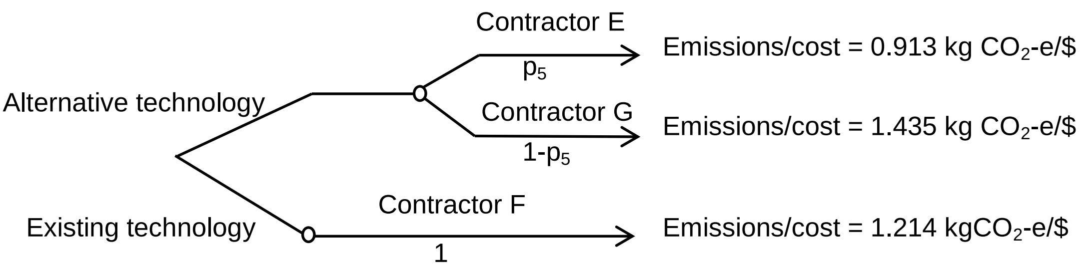
p_4	

Question 5

There are another two choices:

C1 Use existing technology. Price (cost) is known as tendered. The existing technology (and hence emissions) known (from past measurement), or

C2 Each tender uses an alternative technology. For each tender, the price is known as tendered. However, the actual emissions are unpredictable because of the alternative technologies proposed.



At what probability, p_5 (out of 100%) would you decide to utilize alternative technology proposed by Contractor E?

Give your answer here:

p_5	

Utility Function Scenario III: Service life of materials

The scenario has addressed different construction materials used in the construction. Different materials have different embodied carbon and different lifetimes. The different materials are assumed to be able to perform in the same desired way and have an equivalent appearance. Table A3 shows the embodied carbon and lifetimes for different materials.

There are two choices:

C1 Certain outcome – use existing construction material. The embodied carbon and lifetimes are known (based on past performance), or

C2 Uncertain outcome – alternative new construction materials are available. For each new material, the amount of embodied carbon is known. However, the lifetimes of each of the new materials are indefinite (until the new materials are used till their lifetimes, at which point their lifetimes can be established).

At what probability, p (out of 100%) would you decide to utilize alternative new construction material?

The preference order in Table A3 is based on lower to higher emissions/lifetimes (kg CO_2-e/year).

Attributes	Construction materials	Embodied carbon (kg CO_2-e)	Lifetimes (year)	Emissions/ lifetimes (kg CO_2-e/year)
X_1	Material B	80920	150	539
X_2	Material C	91770	130	706
X_3	Material D	117810	110	1071
X_4	Material E	101010	75	1347
X_5	Material F	133875	80	1673
X_6	Material A	125320	65	1928
X_7	Material G	107750	50	2155

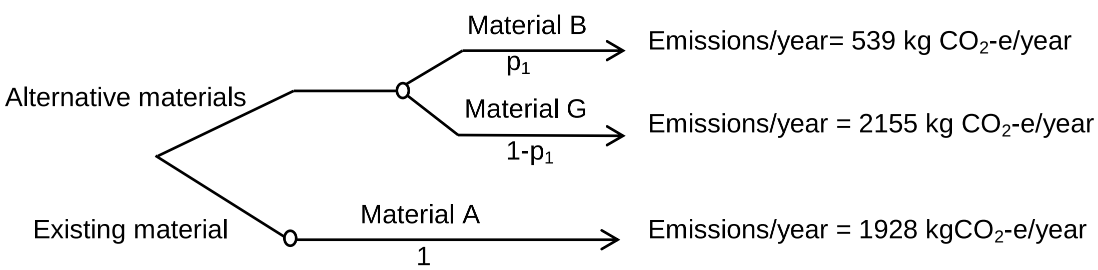
Table A3. Embodied carbon/lifetimes (kg CO_2-e/year) for different materials.

Question 1

Based on the decision tree below, there are two choices:

C1 Use existing construction material. The embodied carbon and lifetimes are known (based on past performance), or

C2 Alternative new construction materials are available. For each new material, the amount of embodied carbon is known. However, the lifetimes of each of the new materials are indefinite (until the new materials are used till their lifetimes, at which point their lifetimes can be established).



At what probability, p_1 (out of 100%) would you decide to utilize alternative new construction material B?

Give your answer here:

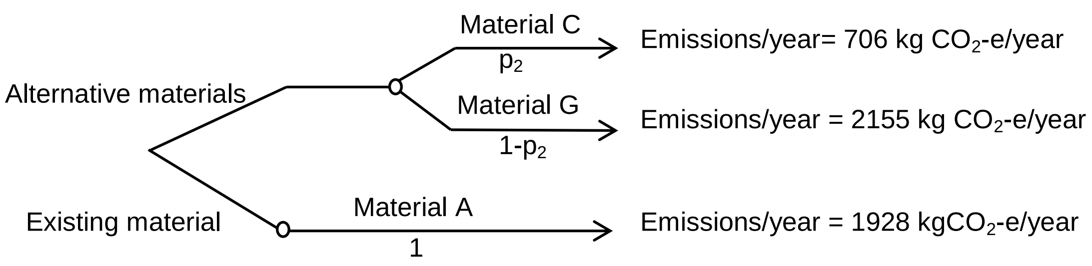
p_1	

Question 2

Much like the previous question, there are another two choices:

C1 Use existing construction material. The embodied carbon and lifetimes are known (based on past performance), or

C2 Alternative new construction materials are available. For each new material, the amount of embodied carbon is known. However, the lifetimes of each of the new materials are indefinite.



At what probability, p_2 (out of 100%) would you decide to utilize alternative new construction material C?

Give your answer here:

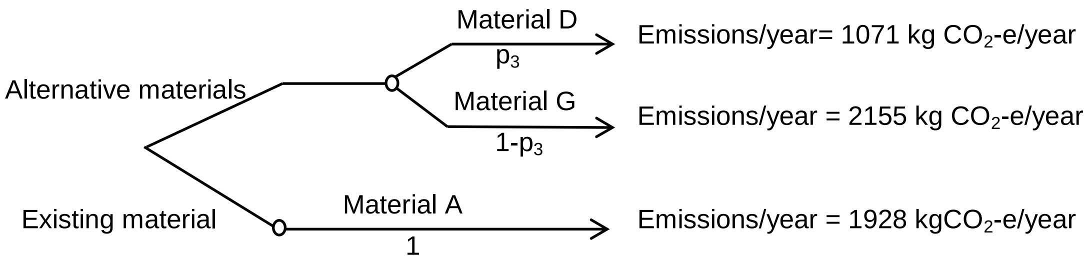
p_2	

Question 3

There are another two choices, which include C1 and C2.

C1 Use existing construction material. The embodied carbon and lifetimes are known (based on past performance), or

C2 Alternative new construction materials are available. For each new material, the amount of embodied carbon is known. However, the lifetimes of each of the new materials are indefinite.



At what probability, p_3 (out of 100%) would you decide to utilize alternative new construction material D?

Give your answer here:

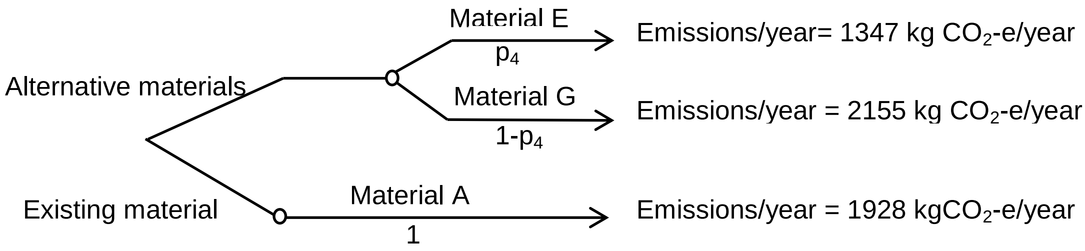
p_3	

Question 4

There are another two choices:

C1 Use existing construction material. The embodied carbon and lifetimes are known (based on past performance), or

C2 Alternative new construction materials are available. For each new material, the amount of embodied carbon is known. However, the lifetimes of each of the new materials are indefinite.



At what probability, p_4 (out of 100%) would you decide to utilize alternative new construction material E?

Give your answer here:

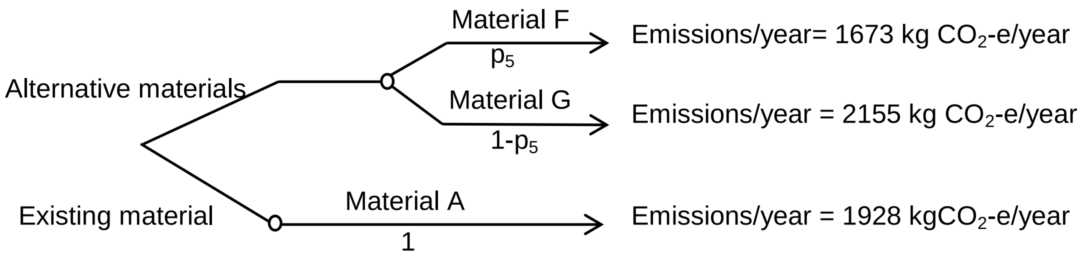
p_4	

Question 5

There are another two choices:

C1 Use existing construction material. The embodied carbon and lifetimes are known (based on past performance), or

C2 Alternative new construction materials are available. For each new material, the amount of embodied carbon is known. However, the lifetimes of each of the new materials are indefinite.



At what probability, p_5 (out of 100%) would you decide to utilize alternative new construction material F?

Give your answer here:

p_5	

Utility Function Scenario IV: Management of construction equipment

The scenario has addressed the management of multiple pieces of construction equipment used, for example in road construction- scrapers, graders, compactors, water carts. Different managers will organize the usage and interaction of equipment differently.

There are two choices:

C1 Certain outcome – an experienced manager with known practices, which may not be the optimum, but are accepted by and familiar to the equipment operators. The production and emissions are known (based on past performance), or

C2 Uncertain outcome – alternative managers. Some managers are offering new, but untried ways to do and organize the work. Production is the same, but emissions will vary depending on the efficiency with which the work is done.

At what probability, p (out of 100%) would you decide to utilize alternative managers?

The preference order in Table A4 is based on lower to higher unit emissions (kg CO_2-e/m^3).

Attributes	Manager	Work efficiency	Production (m^3/h)	Emissions (kgCO_2-e/h)	Unit emissions (kgCO_2-e/m^3)
X_1	B	Excellent	178	165.367	0.929
X_2	C	Good	178	225.517	1.267

Table A4. Unit emissions (kg CO_2-e/m^3) for the different skill of managers (continued).

Attributes	Manager	Work efficiency	Production (m^3/h)	Emissions ($kgCO_2$-e/h)	Unit emissions ($kgCO_2$-e/m^3)
X_3	D	Fair	178	278.453	1.564
X_4	E	Moderate	178	305.211	1.715
X_5	F	Slightly poor	178	345.475	1.941
X_6	A	Moderate	185	405.151	2.190
X_7	G	Very poor	178	423.677	2.380

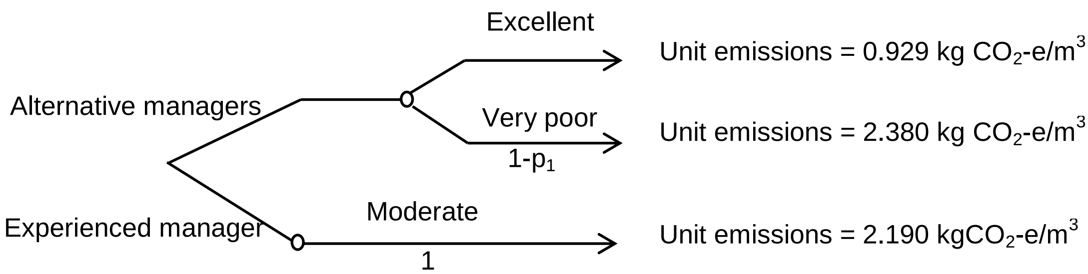
Table A4. Unit emissions (kg CO_2-e/m^3) for the different skill of managers.

Question 1

Based on the decision tree below, there are two choices:

C1 An experienced manager with known practices, which may not be the optimum, but are accepted by and familiar to the equipment operators. The production and emissions are known (based on past performance), or

C2 Alternative managers. Some managers are offering new, but untried ways to do and organize the work. Production is the same, but emissions will vary depending on the efficiency with which the work is done.



At what probability, p_1 (out of 100%) would you decide to utilize alternative manager with excellent skill?

Give your answer here:

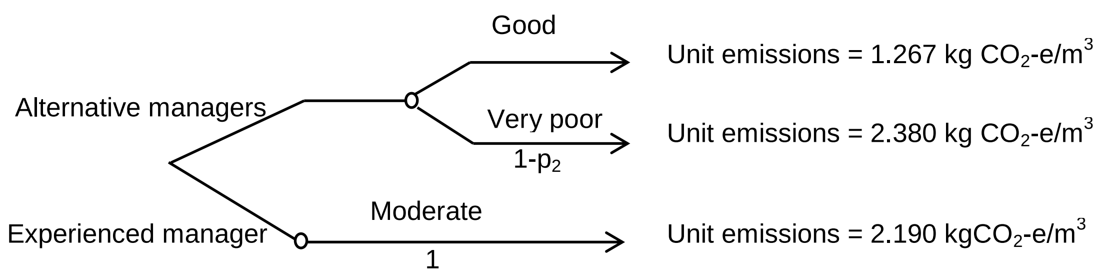
p_1	

Question 2

Much like the previous question, there are another two choices:

C1 An experienced manager with known practices, which may not be the optimum, but are accepted by and familiar to the equipment operators. The production and emissions are known (based on past performance), or

C2 Alternative managers. Some managers are offering new, but untried ways to do and organize the work. Production is the same, but emissions will vary depending on the efficiency with which the work is done.



At what probability, p_2 (out of 100%) would you decide to utilize alternative manager with good skill?

Give your answer here:

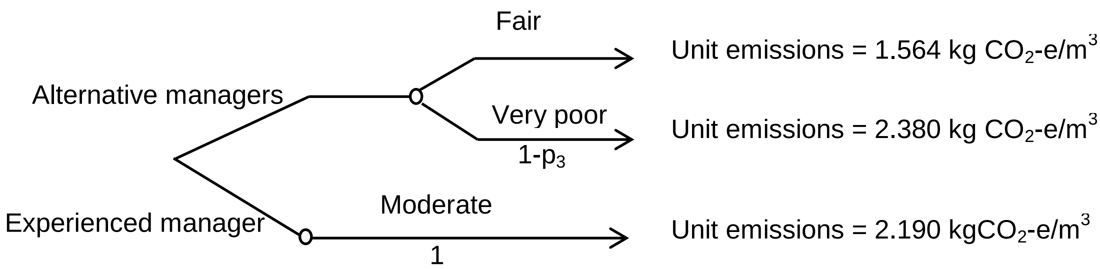
p_2	

Question 3

There are another two choices, which include C1 and C2.

C1 An experienced manager with known practices, which may not be the optimum, but are accepted by and familiar to the equipment operators. The production and emissions are known (based on past performance), or

C2 Alternative managers. Some managers are offering new, but untried ways to do and organize the work. Production is the same, but emissions will vary depending on the efficiency with which the work is done.



At what probability, p_3 (out of 100%) would you decide to utilize alternative manager with fair skill?

Give your answer here:

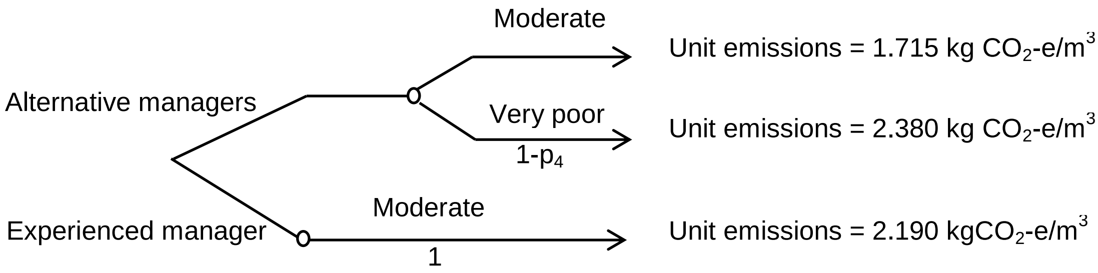
p_3	

Question 4

There are another two choices:

C1 An experienced manager with known practices, which may not be the optimum, but are accepted by and familiar to the equipment operators. The production and emissions are known (based on past performance), or

C2 Alternative managers. Some managers are offering new, but untried ways to do and organize the work. Production is the same, but emissions will vary depending on the efficiency with which the work is done.



At what probability, p_4 (out of 100%) would you decide to utilize alternative manager with moderate skill?

Give your answer here:

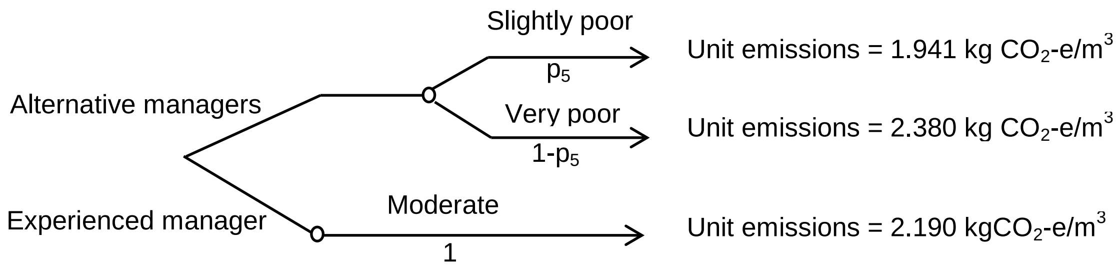
p_4	

Question 5

There are another two choices:

C1 An experienced manager with known practices, which may not be the optimum, but are accepted by and familiar to the equipment operators. The production and emissions are known (based on past performance), or

C2 Alternative managers. Some managers are offering new, but untried ways to do and organize the work. Production is the same, but emissions will vary depending on the efficiency with which the work is done.



At what probability, p_5 (out of 100%) would you decide to utilize alternative manager with slightly poor skill?

Give your answer here:

p_5	

Appendix B. Utility Function Results for Case Studies

Scenario I: Earthmoving operations

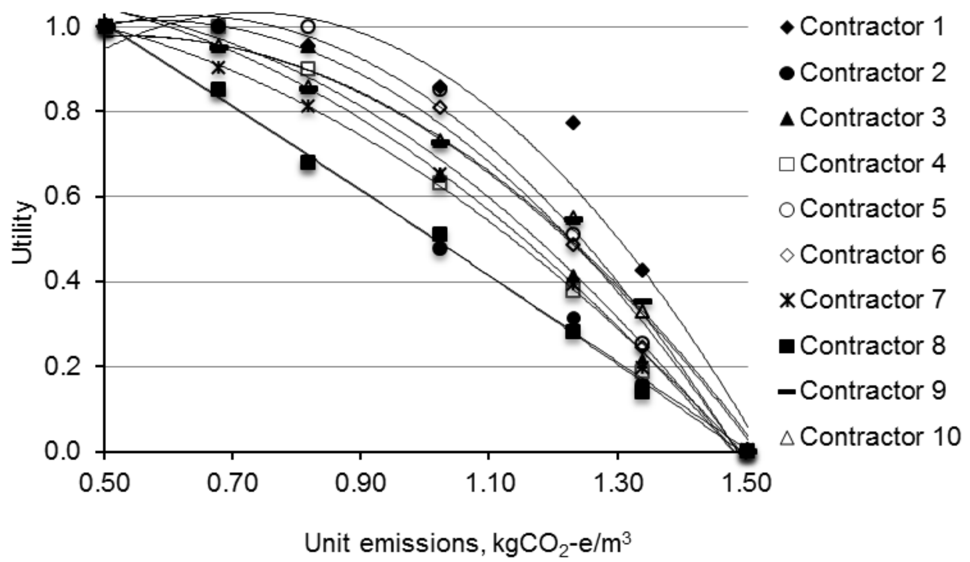


Figure B1. Utility functions for unit emissions (kgCO_2-e/m^3) for contractors.

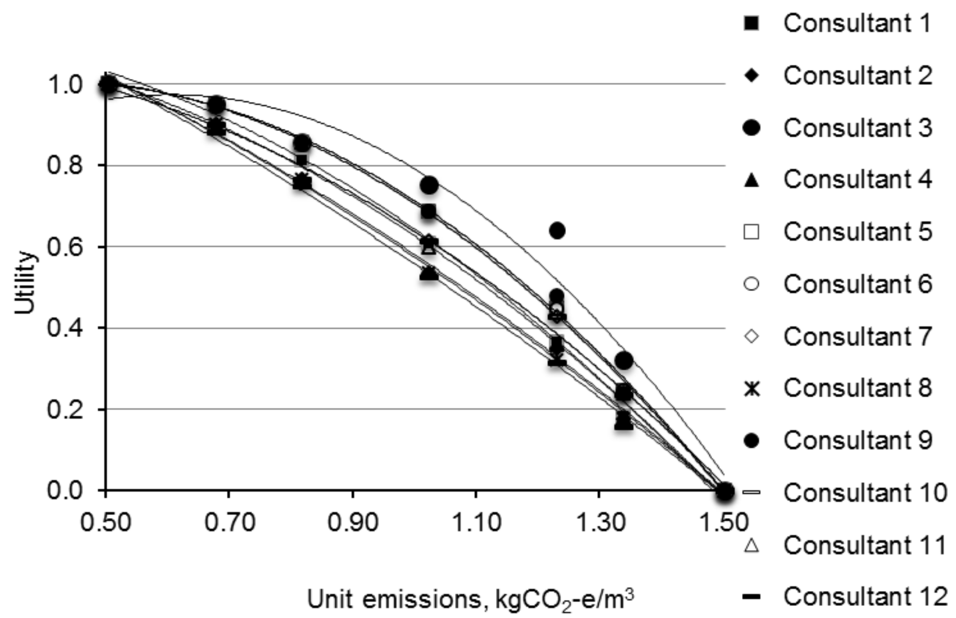


Figure B2. Utility functions for unit emissions (kgCO_2-e/m^3) for consultants.

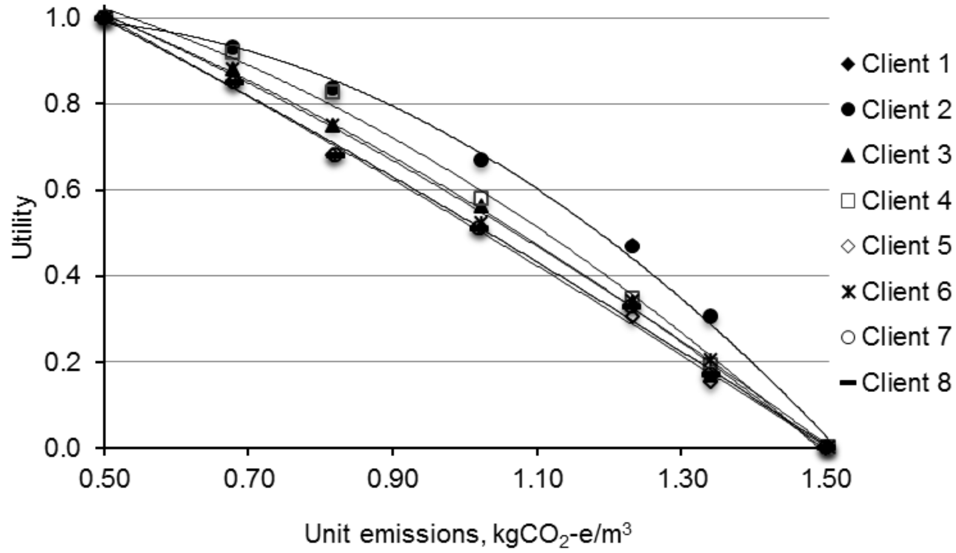


Figure B3. Utility functions for unit emissions ($kgCO_2$-e/m^3) for clients.

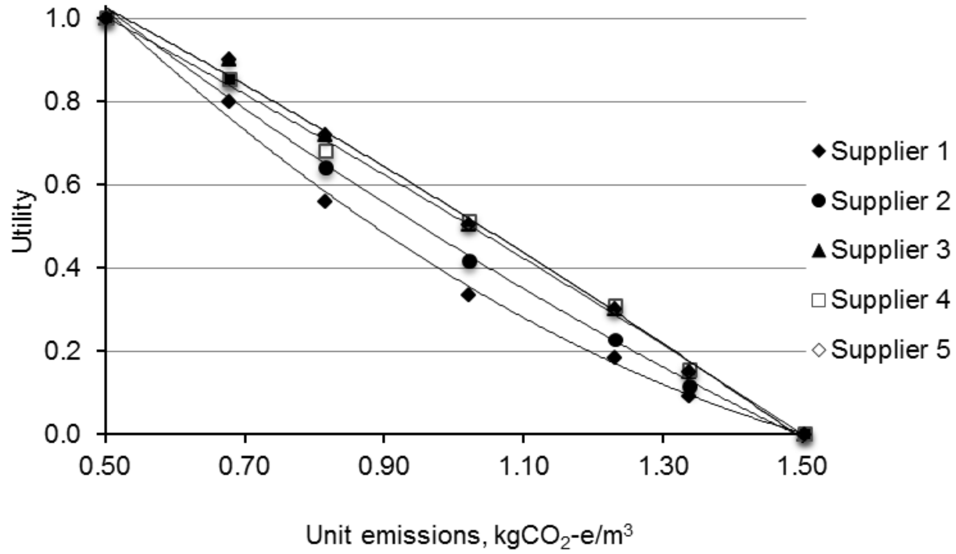


Figure B4. Utility functions for unit emissions ($kgCO_2$-e/m^3) for suppliers.

Scenario II: Tender submission

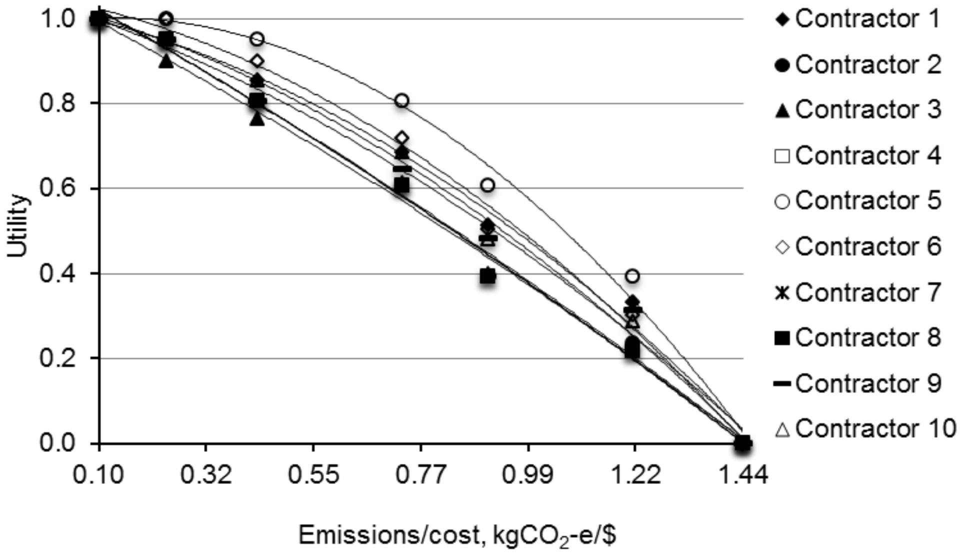


Figure B5. Utility functions for emissions/cost ($kgCO_2$-e/$) for contractors.

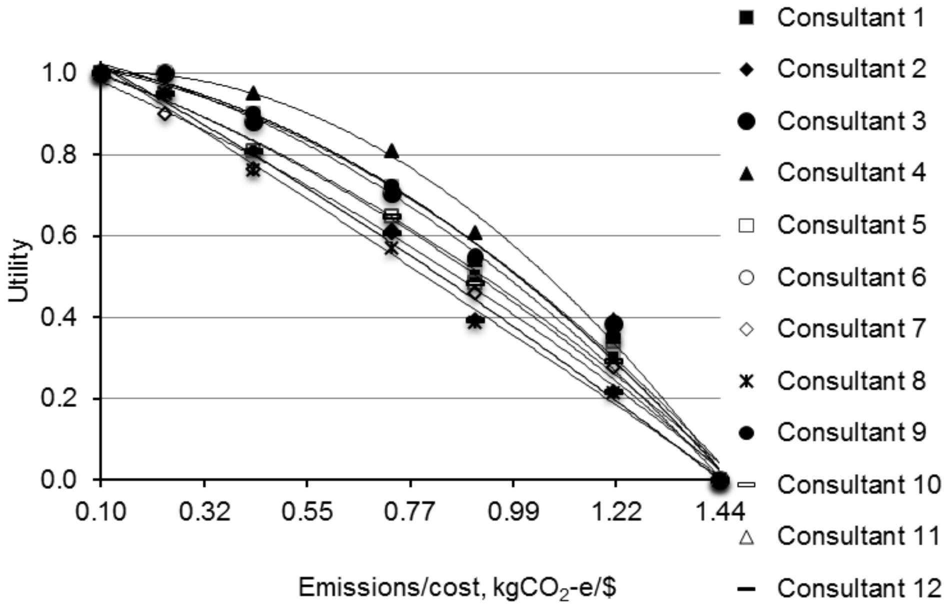


Figure B6. Utility functions for emissions/cost ($kgCO_2$-e/$) for consultants.

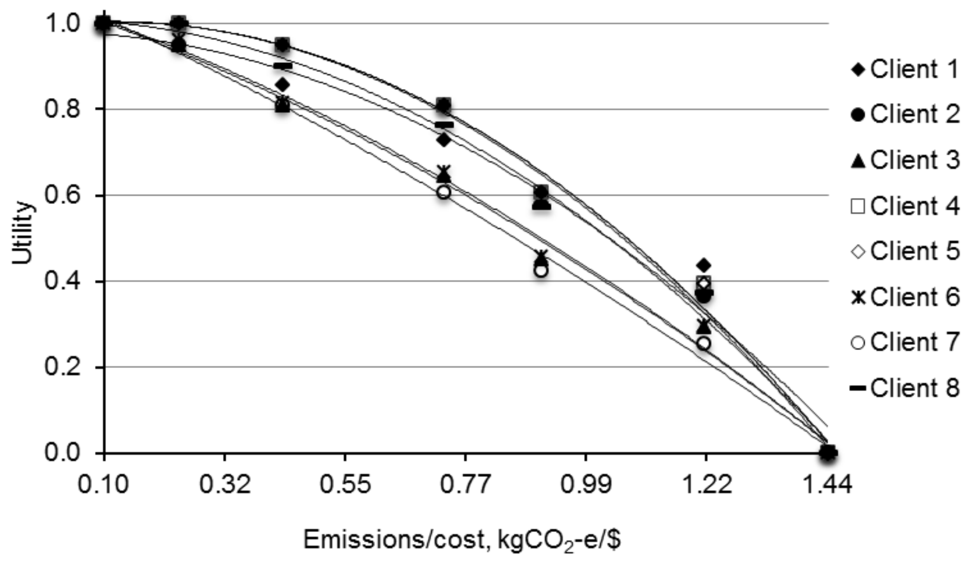


Figure B7. Utility functions for emissions/cost (kgCO_2-e/$) for clients.

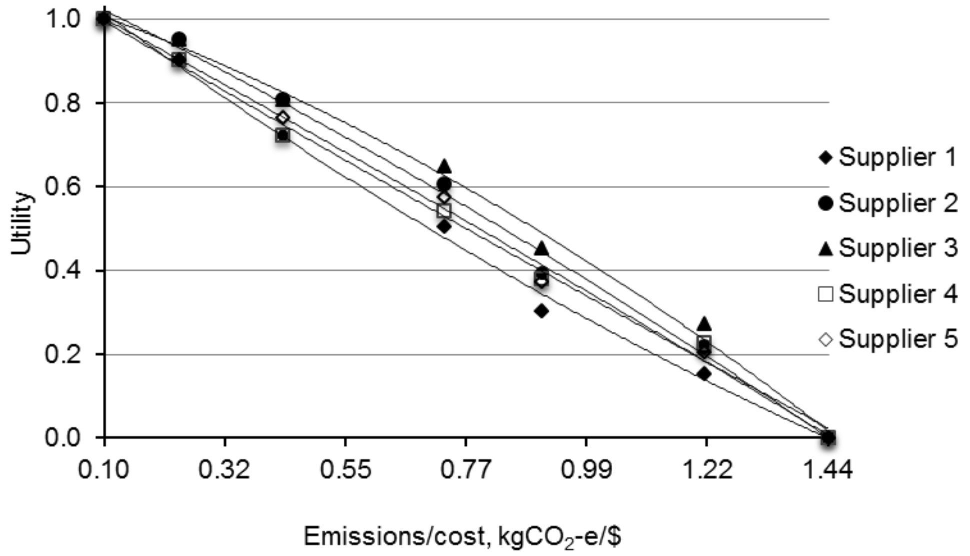


Figure B8. Utility functions for emissions/cost (kgCO_2-e/$) for suppliers.

Scenario III: Service life of material

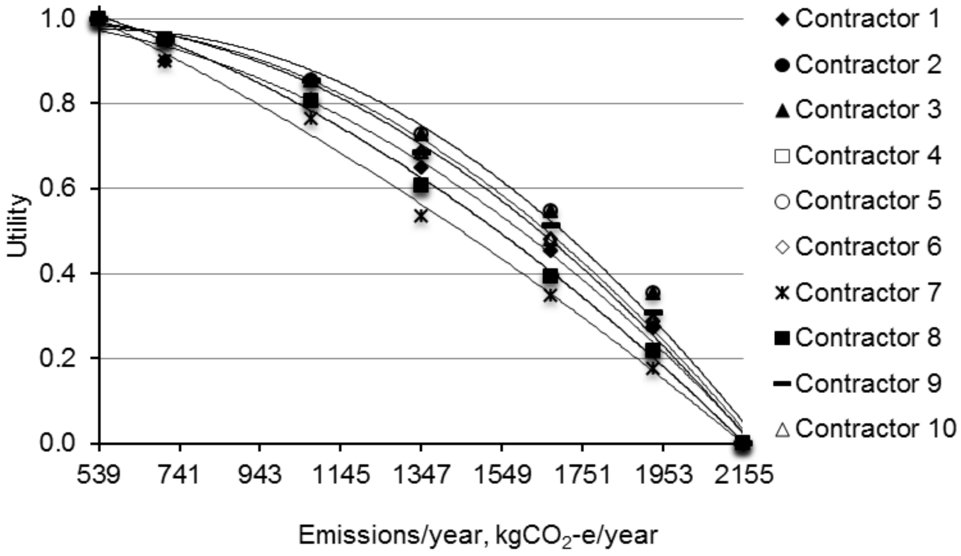


Figure B9. Utility functions for emissions/year (kgCO_2-e/year) for contractors.

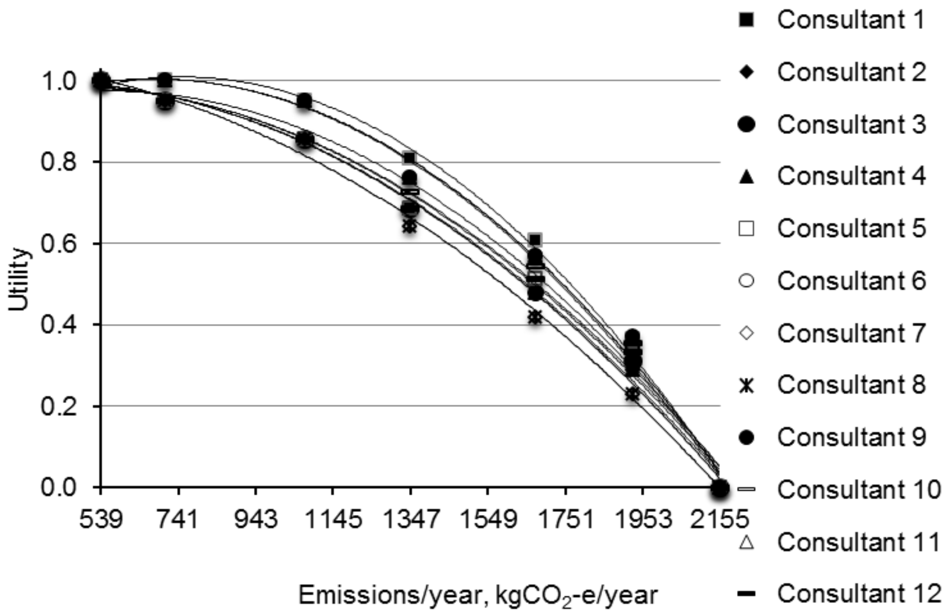


Figure B10. Utility functions for emissions/year (kgCO_2-e/year) for consultants.

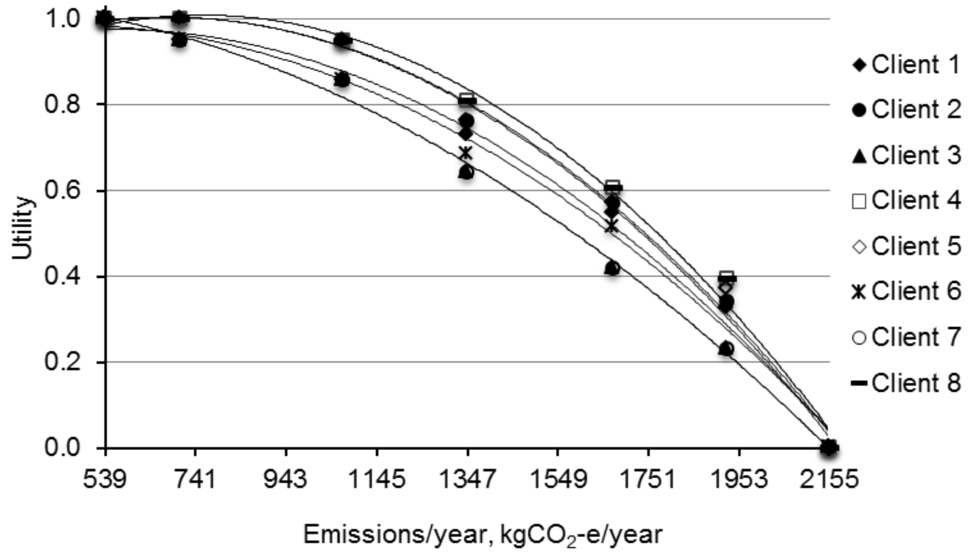


Figure B11. Utility functions for emissions/year (kgCO_2-e/year) for clients.

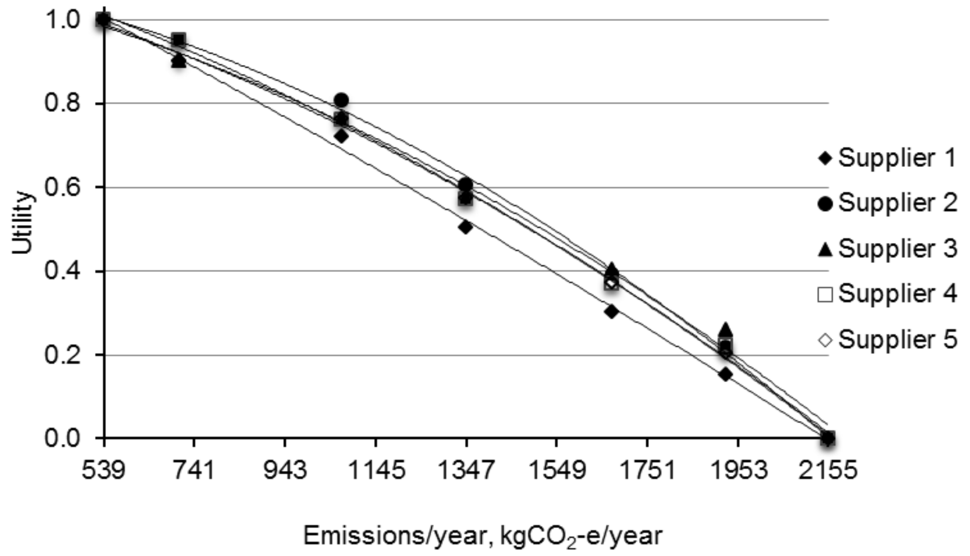


Figure B12. Utility functions for emissions/year (kgCO_2-e/year) for suppliers.

Scenario IV: Management of equipment

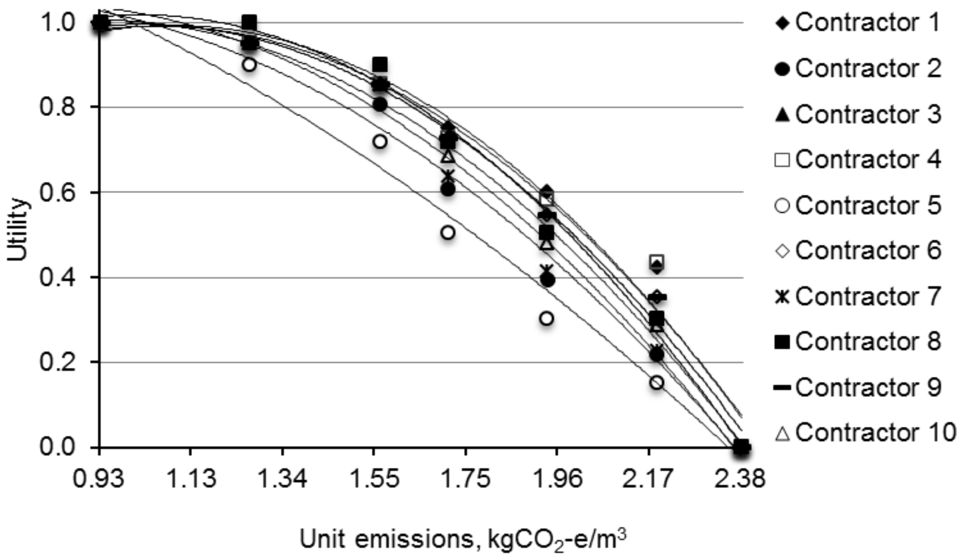


Figure B13. Utility functions for unit emissions ($kgCO_2$-e/m^3) for contractors.

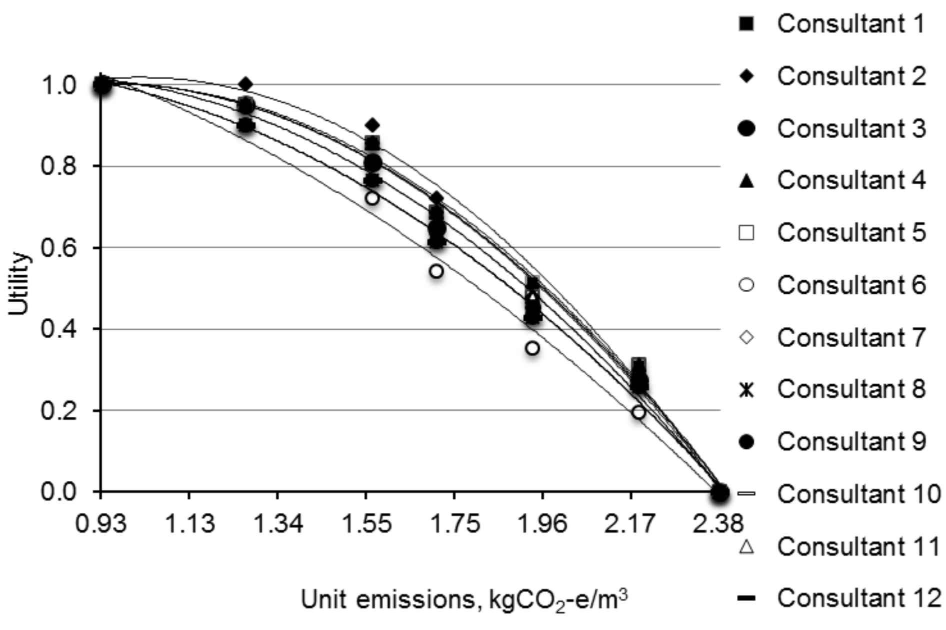


Figure B14. Utility functions for unit emissions ($kgCO_2$-e/m^3) for consultants.

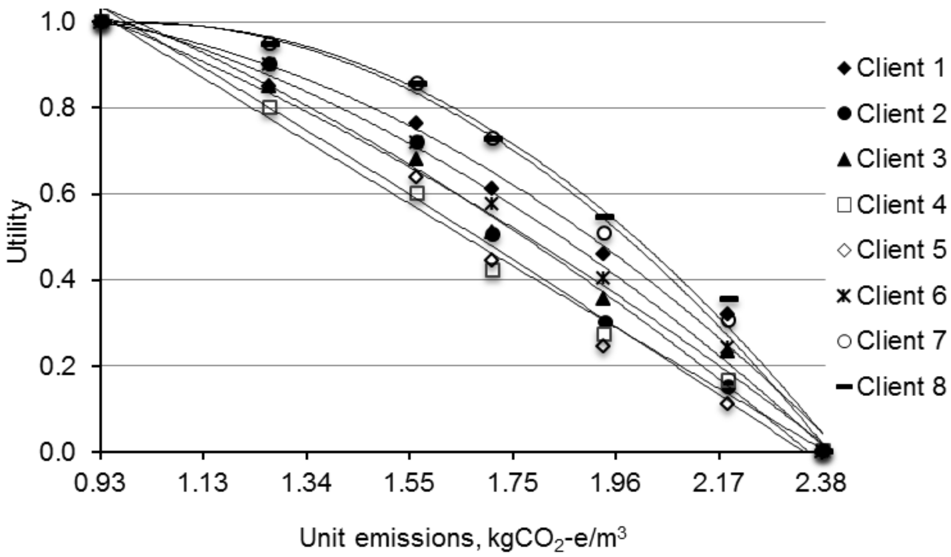


Figure B15. Utility functions for unit emissions (kgCO_2-e/m^3) for clients.

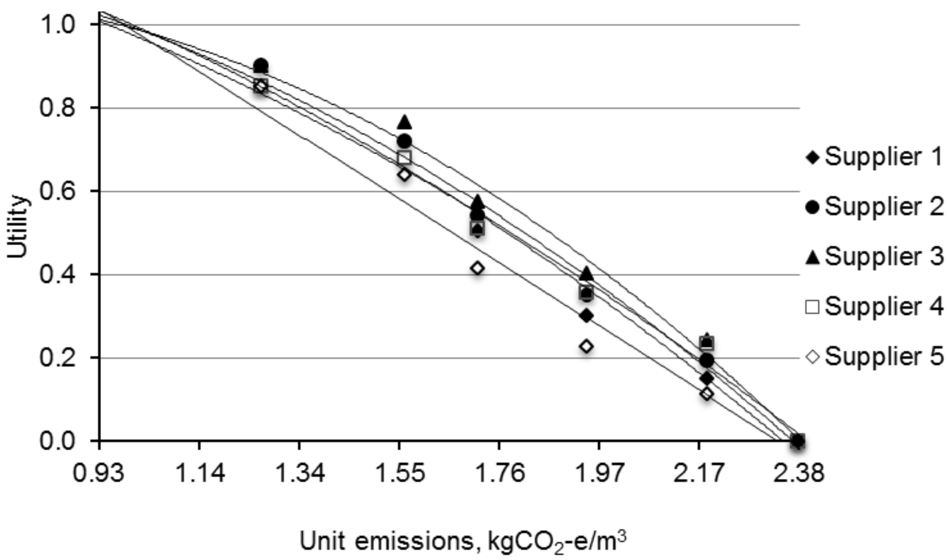


Figure B16. Utility functions for unit emissions (kgCO_2-e/m^3) for suppliers.

Appendix C. Utility Simulation – Earthmoving Operation Analysis

The following applies to a single excavator (server) and a fleet of trucks (Carmichael, 1988 extended to include emissions).

A. Notation

B	backcycle time
C_L	cost per unit time of a loader/excavator
C_T	cost per unit time of a truck
CP	cost per production
DUR	duration
EM	emissions
EP	emissions per production
E[ ]	expected value, mean, average
CUM	cumulative time
I	idling emissions/unit time
K	truck fleet size
L, T	subscripts for loader/excavator and truck
n	cycle count, n = 1, 2, …, ζ
N	non-idling emissions/unit time
PROD	production
S	service time
Var[ ]	variance
W	waiting time
ζ	total number of truck cycles

B. Calculation loop

The following is repeated for varying fleet sizes, K = 1, 2, ...

For each n, n = 1, 2, …, ζ, generate S(n), B(n). Choose ζ reasonably large.

Set CUM(n), n = 1, 2, …, K+1, to some reasonable values to start the algorithm off. For example,

$CUM(1) = S(1)$

$CUM(n) = CUM(n-1) + S(n)$ n = 2, 3, …, K+1

The statistics are compiled for each truck cycle, n. For n = K+2, K+3, …, ζ,

$W(n) = \max\{CUM(n-1)-[CUM(n-K) + B(n-K)], 0\}$

$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$

$PROD(n) = CAP$

$$EM_L(n) = I_L[CUM(n) - CUM(n-1) - S(n)] + N_L S(n)$$

$$EM_T(n) = I_T[W(n) + S(n)] + N_T B(n)$$

$DUR(n) = CUM(n) – CUM(n-1)$

Emissions per production,

$$EP(n) = \frac{EM_L(n) + EM_T(n)}{PROD(n)}$$

Cost per unit time,

$C(n) = C_L + KC_T$

Cost per production,

$$CP(n) = \frac{C_L + KC_T}{PROD(n)} DUR(n)$$

C. Statistics, expected utility

From EP(n) and CP(n) for all n, their means (E[EP], E[CP]) and variances (Var[EP], Var[CP]) are calculated. For a given utility function, expected utility follows for unit emissions and unit costs from Equation (3).

Appendix D. Underlying Modeling Loading Policies

A. Notation

The following notation is used:

B	backcycle time; the sum of haul, maneuver, dump and return times for each truck cycle
C	owning and operating cost per unit time
CAP	capacity of a truck
CUM	a cumulative time measure for each truck cycle
E	emissions
K	truck fleet size
L, T	subscripts for excavator (loader) and truck respectively
LT	load time
M	maneuver time
n	truck numbering according to consecutive cycles, and not a particular truck identity; n = 1, 2, …., ζ
N, I	subscripts for non-idling emissions per unit time and idling emissions per unit time respectively
NC	number of truck cycles
PROD	production
S	service time; the sum of maneuver time M and load time LT for each truck for each loading; S = M + LT
S_s	service time corresponding to constrained minimum waiting time.
TC	total cost
TD	total duration
TE	total emissions
TP	total production
W	waiting time; the time between a truck arriving at the load point and the time maneuvering to load starts
α	a fraction, $0 \leq \alpha \leq 1$

ζ total number of truck cycles considered in the calculations

B. Fractional loading, single-sided loading, zero waiting time policies

The loading policy adjusts the service time such that waiting times are minimized, min W(n) subject to $\alpha S(n) \leq S_s(n) \leq S(n)$, where $0 \leq \alpha \leq 1$ is the constraining minimum fraction of a full load. α = 1 and α = 0 correspond, respectively, to single-sided loading and zero waiting time policies.

For any given α, and for each n, n = 1, 2, …, ζ, generate S(n), B(n) and M(n) by sampling from their distributions. Choose ζ reasonably large.

Set CUM(n), n = 1, 2, …, K+1, to some reasonable values to start the calculations.

For n = K+2, K+3, … there are four cases to consider. In each case, the arrival time of n at the server adjusts (retrospectively) if necessary the service time of n-1. Linear load-growth is used as an approximation in order to simplify the calculations, but more complicated logic expressions could be used to reflect a stepped load growth (Kaboli and Carmichael, 2014).

(i) If truck n arrives after the service of truck n-1 is complete or at the completion of truck n-1 servicing (that is, if CUM(n-K) + B(n-K) $\geq$ CUM(n-1-K) + B(n-1-K) + W(n-1) + S(n-1)), then,

$$S_s(n-1) = S(n-1)$$

$$CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + S_s(n-1)$$

$$W(n) = 0$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

(ii) If truck n arrives after servicing starts but before the service of truck n-1 is complete (that is, if CUM(n-1-K) + B(n-1-K) + W(n-1) $\leq$ CUM(n-K) + B(n-K) $\leq$ CUM(n-1-K) + B(n-1-K) + W(n-1) + S(n-1)), then, as an approximation that gets better with larger α

(it is exact at α = 1), smaller maneuver time relative to load time, and the closer n arrives to n-1 completing service,

$S_s(n-1)$ = the larger of {CUM(n-K) + B(n-K) - CUM(n-1-K) - B(n-1-K) – W(n-1)}or { $M(n-1)+\alpha[S(n-1)-M(n-1)]$ }

CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + $S_s(n-1)$

W(n) = respectively, 0 or CUM(n-1-K) +B(n-1-K) +W(n-1) +{ $M(n-1)+\alpha[S(n-1)-M(n-1)]$ – CUM(n-K) – B(n-K)}

CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)

(iii) If truck n arrives during the truck n-1 waiting period (that is, CUM(n-1-K)+B(n-1-K) ≤ CUM(n-K) + B(n-K) ≤ CUM(n-1-K) + B(n-1-K) + W(n-1)), then

$S_s(n-1)=M(n-1)+\alpha[S(n-1)-M(n-1)]$

CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + $S_s(n-1)$

W(n) = CUM(n-1-K) + B(n-1-K) + W(n-1) + $M(n-1)+\alpha[S(n-1)-M(n-1)]$ - CUM(n-K) - B(n-K)

CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)

(iv) If truck n arrives before truck n-1 (that is CUM(n-K) + B(n-K) ≤ CUM(n-1-K) + B(n-1-K)), then, ignoring trucks prior to n-1,

W(n-1) = 0

S_s(n-1) = 0

CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + $S_s(n-1)$

W(n) = 0

CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)

And approximately,

$$PROD(n)=\frac{S_s(n)-M(n)}{S(n)-M(n)}CAP$$

or 0 where the numerator is negative.

with,

$$E_L(n)=I_L[CUM(n)-CUM(n-1)-S_S(n)]+N_L S_S(n)$$

$$E_T(n) = I_T[W(n) + S_S(n)] + N_T B(n)$$

C. Double-sided loading policy

For each truck cycle n, n = 1, 2, …, ζ, generate M(n), LT(n) and B(n) by sampling from their distributions. S(n) = M(n) + LT(n). Choose ζ reasonably large.

Set CUM(n), n = 1, 2, …, K+1, to some reasonable values to start the calculations.

For n = K+2, K+3, … there are three cases to consider:

(i) Truck n arrives and completes its maneuver before truck n-1 completes loading. That is, if CUM(n-K) + B(n-K) + M(n) $\leq$ CUM(n-1) , then,

W(n) = CUM(n-1) - [CUM(n-K) + B(n-K) + M(n)]

CUM(n) = CUM(n-K) + B(n-K) + M(n) + W(n) + LT(n)

(ii) Truck n arrives before truck n-1 completes loading, and n completes its maneuver after truck n-1 completes loading. That is, if CUM(n-K) + B(n-K) $\leq$ CUM(n-1) $\leq$ CUM(n-K) + B(n-K) + M(n), then,

W(n) = 0

CUM(n) = CUM(n-K) + B(n-K) + M(n) +LT(n)

(iii) Truck n arrives after truck n-1 completes loading. That is, if CUM(n-K) + B(n-K) $\geq$ CUM(n-1), then,

W(n) = 0

CUM(n) = CUM(n-K) + B(n-K) + M(n) + LT(n)

Then,

PROD(n) = CAP

$$E_L(n) = I_L[CUM(n) - CUM(n-1) - LT(n)] + N_L LT(n)$$

$$E_T(n) = I_T[W(n) + S(n)] + N_T B(n)$$

D. Production, unit emissions, unit cost

Production

Removing the start-up K+1 cycles from the calculations,

Number of truck cycles, NC = $\zeta - (K + 1)$

Total duration, TD = $CUM(\zeta) + B(\zeta)$ - CUM(K+1)

Total production, TP = $\sum_{NC} PROD(n)$

Total production/unit time = $\dfrac{TP}{TD}$

Unit Emissions

Total excavator emissions, $TE_L = \sum_{NC} E_L(n)$

Total truck emissions, $TE_T = \sum_{NC} E_T(n)$

Total emissions/unit time = $\dfrac{TE_L + TE_T}{TD}$

Emissions/ production = Total emissions per unit time/Total production per unit time

Unit Cost

Total cost/unit time = $C_L + KC_T$

Cost/production = Total cost per unit time/Total production per unit time

Appendix E. Field Data Set 1 - Cut-and-Fill Operation

Cycle no.	Queue time	Maneuver time at cut	Load time	Haul time	Maneuver time at fill	Dump time	Return time
1-1	0.00	0.42	2.15	0.82	0.50	0.35	2.63
1-2	0.93	0.52	1.95	1.17	1.17	0.47	3.33
1-3	2.35	0.28	2.12	1.47	0.77	0.47	2.78
1-4	3.13	0.47	1.62	1.12	0.27	0.45	2.65
1-5	3.62	0.32	1.73	1.15	0.20	0.47	3.75
2-1	4.22	0.72	1.72	1.00	0.83	0.35	1.80
2-4	2.85	0.48	1.67	1.57	0.30	0.37	2.22
2-2	3.32	0.30	1.88	1.10	0.32	0.42	1.73
2-3	3.92	0.63	1.88	1.83	0.30	0.42	1.25
2-4	3.47	0.38	1.63	1.03	0.67	0.22	1.05
3-1	5.75	0.37	1.40	1.05	0.27	0.38	1.47
3-2	5.05	0.30	1.57	1.43	0.50	0.40	1.05
3-3	5.92	0.32	1.45	1.18	0.27	0.38	0.77
3-4	5.95	0.65	1.97	1.32	0.22	0.38	1.03
3-5	5.93	0.73	1.83	1.33	0.17	0.40	1.77
4-1	5.93	0.60	1.38	0.98	0.45	0.38	1.22
4-2	5.60	0.47	1.75	1.52	0.67	0.37	3.33
4-3	6.12	0.75	1.75	1.88	0.23	0.38	2.22
4-4	6.30	0.35	1.62	2.22	0.30	0.43	2.00
4-5	5.20	0.78	1.82	1.25	0.35	0.37	2.65
5-1	5.47	0.38	1.47	1.37	0.58	0.37	1.73
5-2	3.48	1.00	1.62	2.02	0.20	0.40	1.25
5-3	4.27	0.15	1.65	1.80	0.33	0.40	1.33

Table E1. Summarised event time data for the truck cycles. Times in minutes (continued).

Cycle no.	Queue time	Maneuver time at cut	Load time	Haul time	Maneuver time at fill	Dump time	Return time
5-4	3.57	0.43	1.73	1.72	0.35	0.38	1.52
5-5	4.02	0.47	1.20	1.63	0.28	0.38	1.25
6-1	3.95	0.40	1.68	1.22	0.33	0.40	1.47
6-2	3.95	0.30	1.50	1.77	0.58	0.42	1.73
6-3	3.92	0.78	1.82	1.37	1.33	0.38	2.22
6-4	3.92	1.05	1.83	2.38	0.30	0.42	1.80
6-5	4.73	0.34	1.88	1.53	0.25	0.42	2.78
Mean	**4.227**	**0.504**	**1.709**	**1.440**	**0.443**	**0.394**	**1.926**
Variance	**2.266**	**0.048**	**0.046**	**0.146**	**0.079**	**0.002**	**0.594**
Standard deviation	**1.505**	**0.220**	**0.214**	**0.382**	**0.282**	**0.046**	**0.771**

Table E1. Summarised event time data for the truck cycles. Times in minutes.

Cumulative distributions for each of the truck cycle component times are given in Figures E1 to E7.

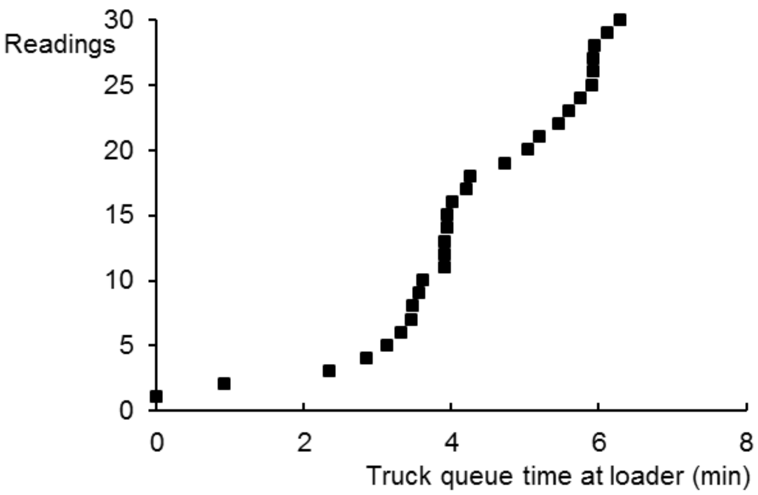


Figure E1. Cumulative distribution, truck queue time at loader.

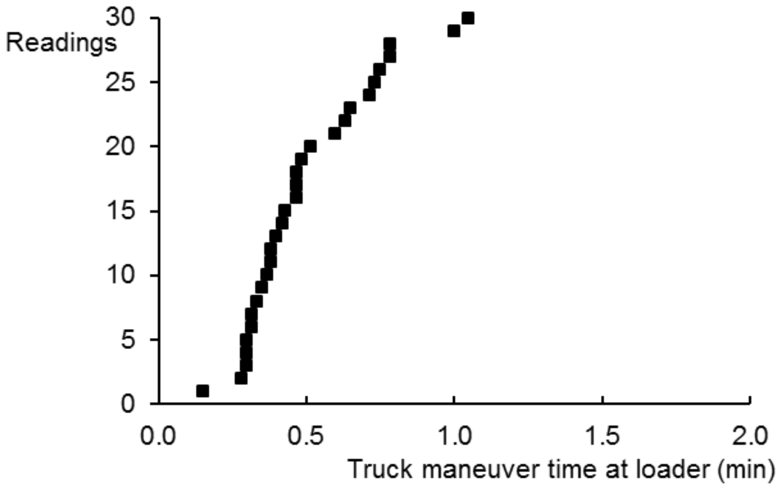


Figure E2. Cumulative distribution, truck maneuver time at loader.

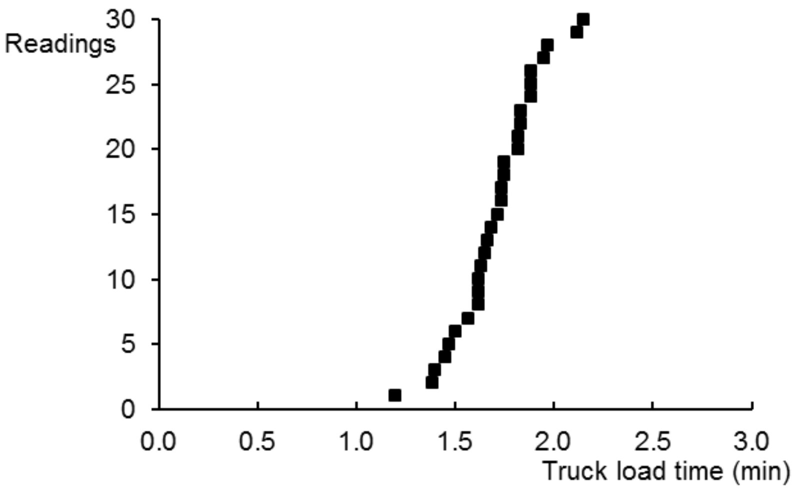


Figure E3. Cumulative distribution, truck load time.

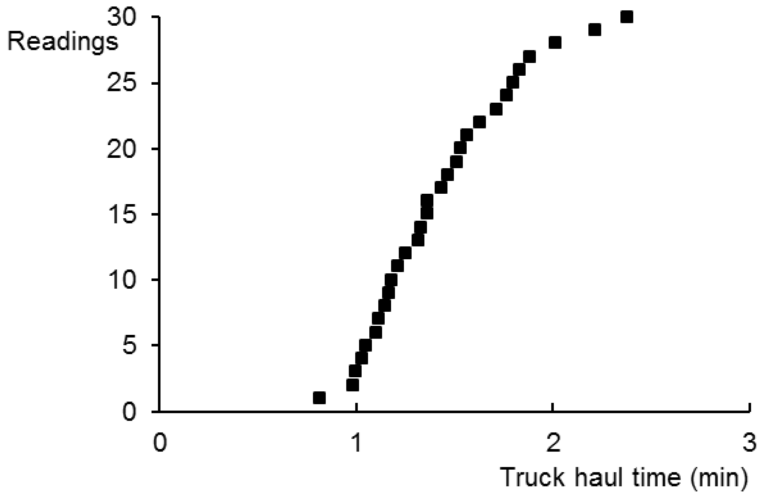


Figure E4. Cumulative distribution, truck loaded haul time.

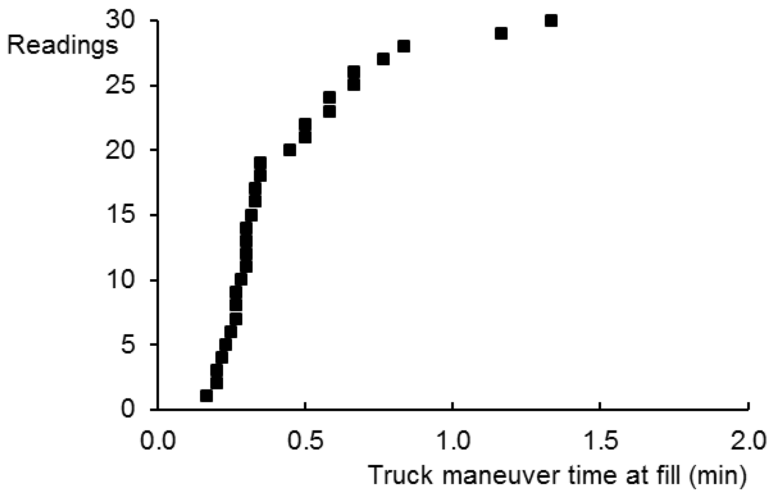


Figure E5. Cumulative distribution, truck maneuver time at fill.

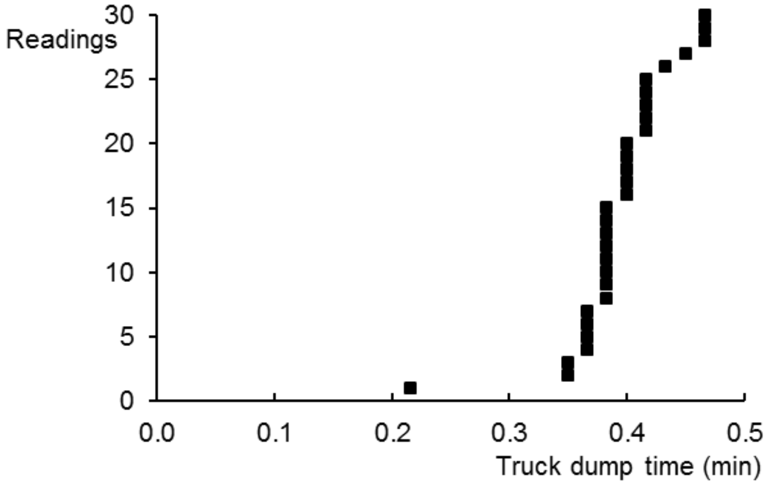


Figure E6. Cumulative distribution, truck dump time.

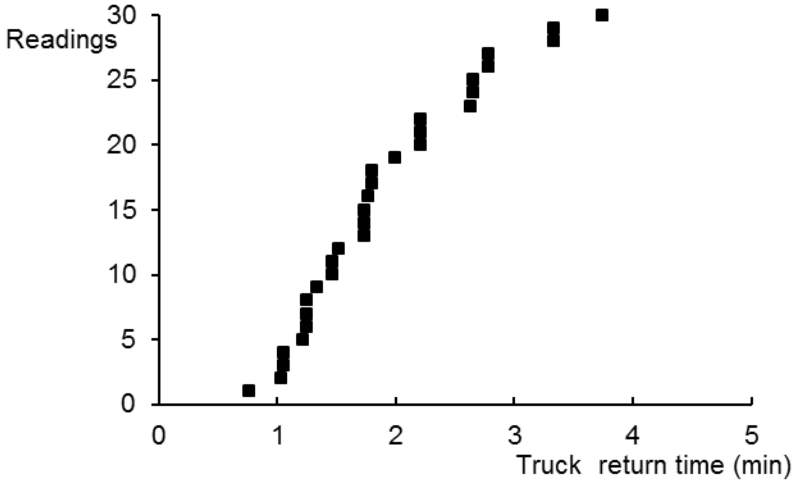


Figure E7. Cumulative distribution, truck return time.

Appendix F. Underlying Modeling – Multiplier Loading, Single-Sided Loading

The loading policy adjusts the loading time such that loading of at least $S(n)-M(n)$ occurs, but can load to $\alpha[S(n)-M(n)]$ if time is available, where $\alpha \geq 1$ is a (constraining) maximum multiplier of a full load. α = 1 corresponds to single-sided loading.

For any given α, and for each n, n = 1, 2, …, ζ, generate S(n), B(n) and M(n) by sampling from their distributions. Choose ζ reasonably large.

Set CUM(n), n = 1, 2, …, K+1, to some reasonable values to start the calculations.

For n = K+2, K+3, … there are five cases to consider. In each case, the arrival time of n at the server adjusts (retrospectively) if necessary the service time of n-1. Linear load-growth is used as an approximation in order to simplify the calculations, but more complicated logic expressions could be used to reflect a stepped load growth (Kaboli and Carmichael, 2014).

(i) If truck n arrives after the service of truck n-1 multiplier load is complete or at the completion of truck n-1 multiplier load (that is, if CUM(n-K) + B(n-K) $\geq$ CUM(n-1-K) + B(n-1-K) + W(n-1) + M(n-1) + $\alpha[S(n-1)-M(n-1)]$), then,

$$S_s(n-1) = M(n-1) + \alpha[S(n-1)-M(n-1)]$$

$$CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + S_s(n-1)$$

$$W(n) = 0$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

(ii) If truck n arrives between time of single load and multiplier load (that is, if CUM(n-1-K) + B(n-1-K) + W(n-1) + S(n-1) $\leq$ CUM(n-K) + B(n-K) $\leq$ CUM(n-1-K) + B(n-1-K) + W(n-1) + M(n-1) + $\alpha[S(n-1)-M(n-1)]$), then,

$$S_s(n-1) = M(n-1) + \alpha[S(n-1)-M(n-1)]$$

$$CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + S_s(n-1)$$

$$W(n) = CUM(n-1) - CUM(n-K) - B(n-K)$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

(iii) If truck n arrives after n-1 starts loading but before single load of truck n-1 is complete (that is, if $CUM(n-1-K) + B(n-1-K) + W(n-1) \leq CUM(n-K) + B(n-K) \leq CUM(n-1-K) + B(n-1-K) + W(n-1) + S(n-1)$), then,

$$S_s(n-1) = S(n-1)$$

$$CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + S_s(n-1)$$

$$W(n) = CUM(n-1) - CUM(n-K) - B(n-K)$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

(iv) If truck n arrives during the truck n-1 waiting period (that is, $CUM(n-1-K)+B(n-1-K) \leq CUM(n-K) + B(n-K) \leq CUM(n-1-K) + B(n-1-K) + W(n-1)$), then

$$S_s(n-1) = S(n-1)$$

$$CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + S_s(n-1)$$

$$W(n) = CUM(n-1) - CUM(n-K) - B(n-K)$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

(v) If truck n arrives before truck n-1 (that is $CUM(n-K) + B(n-K) \leq CUM(n-1-K) + B(n-1-K)$), then, ignoring trucks prior to n-1,

$$W(n-1) = 0$$

$$S_s(n-1) = 0$$

$$CUM(n-1) = CUM(n-1-K) + B(n-1-K) + W(n-1) + S_s(n-1)$$

$$W(n) = 0$$

$$CUM(n) = CUM(n-K) + B(n-K) + W(n) + S(n)$$

And approximately,

$$PROD(n) = \frac{S_s(n) - M(n)}{S(n) - M(n)} CAP$$

or 0 where the numerator is negative.

with,

$$E_L(n) = I_L[CUM(n) - CUM(n-1) - S_S(n)] + N_L S_S(n)$$

$$E_T(n) = I_T[W(n) + S_S(n)] + N_T B(n)$$

Appendix G. Field Data Set 2 - Cut-and-Fill Operation

Cycle no.	Queue time	Maneuver time at cut	Load time	Haul time	Maneuver time at fill	Dump time	Return time
1-1	0.00	0.27	1.93	2.88	0.38	0.37	3.78
1-2	1.73	0.40	3.10	3.18	0.17	0.27	2.32
1-3	2.48	0.43	2.23	2.93	0.35	0.28	2.67
1-4	5.55	0.52	1.50	3.50	0.10	0.13	3.68
1-5	3.33	0.47	1.37	2.97	0.53	0.33	2.57
2-1	3.30	0.50	1.55	2.73	0.37	0.33	2.58
2-2	3.20	0.42	2.97	3.10	0.38	0.25	3.85
2-3	3.33	0.42	1.33	3.67	0.10	0.20	2.43
2-4	3.47	0.52	1.98	2.37	0.23	0.28	3.38
2-5	4.83	0.32	1.47	1.73	0.15	0.15	3.90
3-1	4.83	0.40	2.53	2.57	0.87	0.23	2.17
3-2	1.55	0.37	2.67	2.55	0.65	0.22	3.27
3-3	3.57	0.40	0.97	3.33	0.92	0.38	2.03
3-4	4.13	0.43	1.43	1.97	0.67	0.17	2.13
3-5	4.50	0.43	1.57	2.75	0.67	0.18	2.52
4-1	3.73	0.42	1.80	2.48	0.67	0.20	2.30
4-2	2.15	0.32	2.97	2.75	0.13	0.27	3.60
4-3	1.77	0.47	1.37	2.78	0.53	0.27	2.53
4-4	4.72	0.43	1.58	2.53	0.38	0.20	3.58
4-5	4.95	0.33	1.00	2.77	0.40	0.28	3.43
5-1	5.45	0.43	3.07	2.53	0.23	0.18	2.10
5-2	3.50	0.45	3.17	2.80	0.22	0.17	3.68
5-3	5.52	0.42	1.62	2.77	0.22	0.35	2.92

Table G1. Summarised event time data for the truck cycles. Times in minutes (continued).

Cycle no.	Queue time	Maneuver time at cut	Load time	Haul time	Maneuver time at fill	Dump time	Return time
5-4	6.08	0.42	1.53	2.27	0.38	0.28	2.65
5-5	5.87	0.43	1.62	2.62	0.22	0.20	2.88
6-1	5.13	0.37	1.27	2.58	0.22	0.22	2.52
6-2	1.83	0.37	2.65	2.75	0.72	0.33	2.30
6-3	4.48	0.33	1.93	2.78	0.45	0.23	3.60
6-4	5.52	0.32	1.70	2.55	0.42	0.20	2.53
6-5	4.75	0.42	1.48	2.42	0.63	0.15	2.25
Mean	**3.842**	**0.407**	**1.912**	**2.721**	**0.411**	**0.244**	**2.872**
Variance	**2.300**	**0.040**	**0.439**	**0.158**	**0.052**	**0.005**	**0.383**
Standard deviation	**1.517**	**0.200**	**0.663**	**0.398**	**0.228**	**0.069**	**0.619**

Table G1. Summarised event time data for the truck cycles. Times in minutes.

Cumulative distributions for each of the cycle component times are given in Figures G1 to G7.

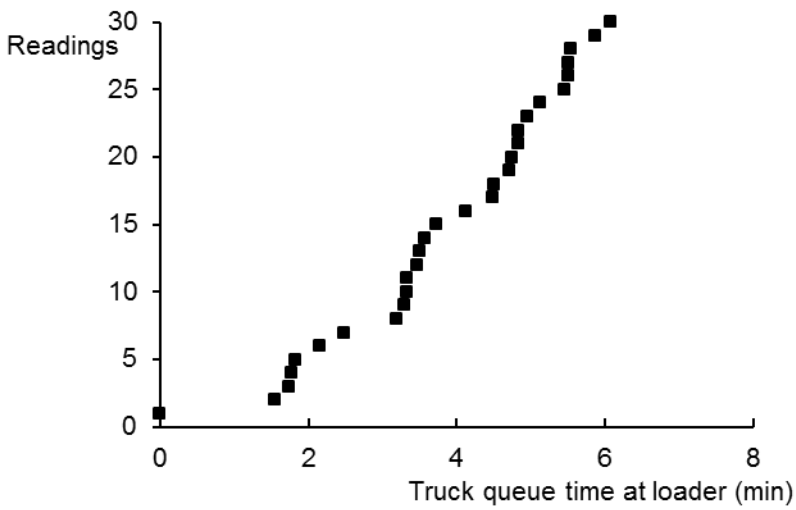


Figure G1. Cumulative distribution, truck queue time at loader.

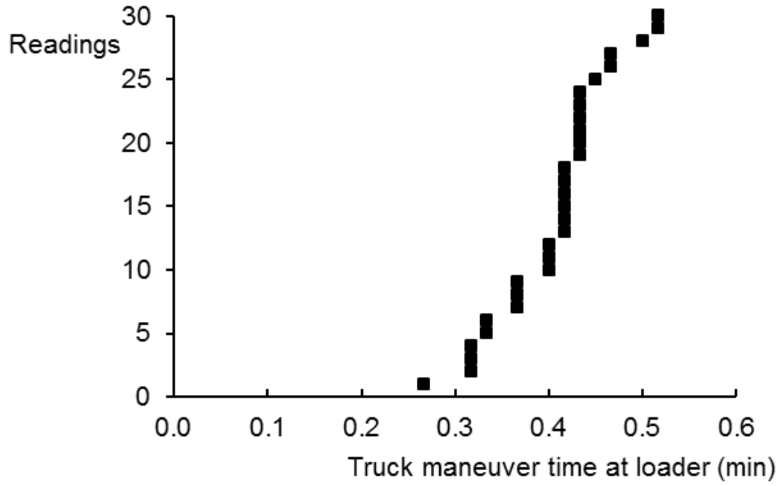


Figure G2. Cumulative distribution, truck maneuver time at loader.

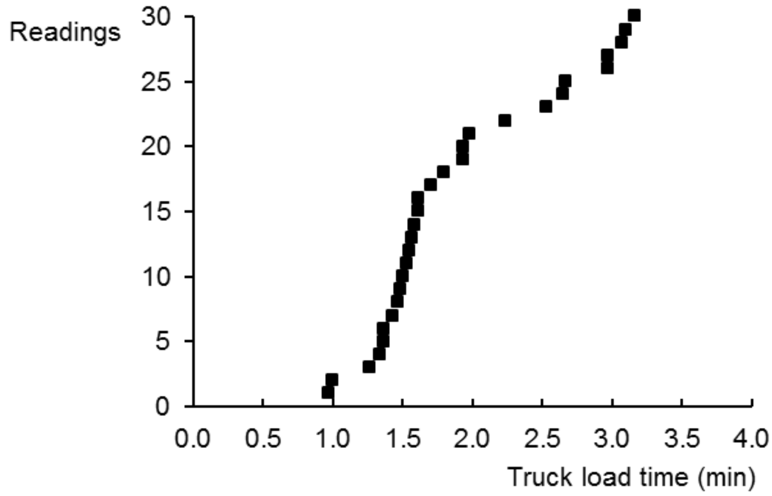


Figure G3. Cumulative distribution, truck load time.

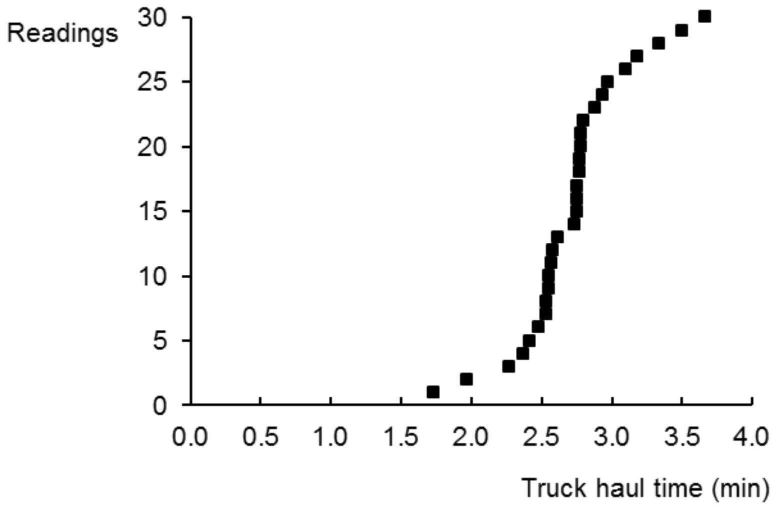


Figure G4. Cumulative distribution, truck loaded haul time.

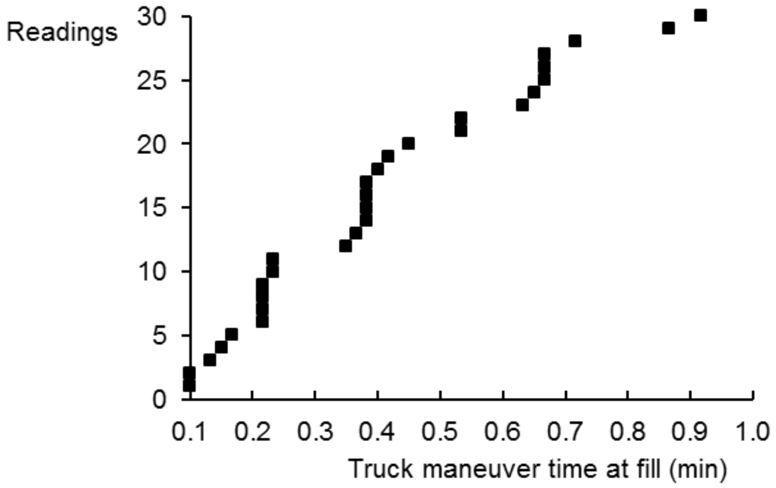


Figure G5. Cumulative distribution, truck maneuver time at fill.

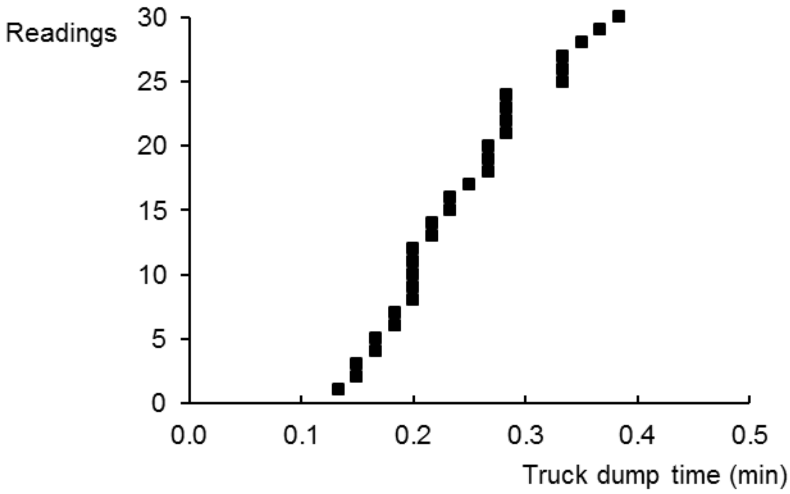


Figure G6. Cumulative distribution, truck dump time.

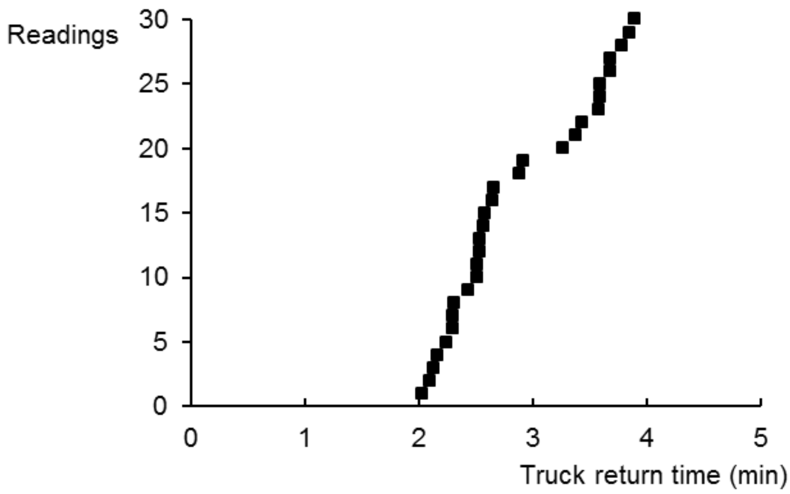


Figure G7. Cumulative distribution, truck return time.

Appendix H. Estimation of Emissions Using Peralta et al. (2016) Approach

The approach developed by Peralta et al. (2016) was adopted in Chapter 5 to examine the overloading and underloading cases in which the loaded haul time, loaded haul speed and fuel use for fractional loading and single-sided loading with extra or less bucket cases were adjusted in line with the lesser and greater load being carried. The formulations employed in the analysis of this study are provided as below.

The calculation of gross vehicle weight (GVW) is expressed in Equation (1):

$$GVW = PW + EW \tag{1}$$

Where PW is payload weight and EW is empty weight of truck.

The velocity of a truck is determined using the rimpull-speed gradeability curves or retarder curves (Catterpillar Inc, 2015). Alternatively, Phelps (1977) equations can also be used to calculate the speeds for haul and return trucks. However, it is important to take note that the adjustment of emissions in Chapter 5 only involves the loaded haul, while its return haul is independent of the changes of load. The retarding power demand when truck ascending a grade is given in Equation (2) (Catterpillar Inc., 2015).

$$\text{Retarding power, } P = \frac{GW.TR.V}{273.75}0.7457 \tag{2}$$

The total resistance is also known as the total effective grade, when a truck travels downhill is given in Equation (3):

$$TR = \text{Grade resistance} - \text{Rolling resistance} \tag{3}$$

The fuel consumption of a truck while travelling is estimated based on the engine load factor and rated engine power using Equation (4) (Runge, 1998):

$$FC = P.0.3.LF \tag{4}$$

Where FC is the fuel consumption; P is the power demand and LF is the load factor.

The travel time from a loader to dump is given in Equation (5):

$$\text{Travel time from a loader to dump, } t_{ld} = \frac{d_{ld}}{V_{ld}} \tag{5}$$

Truck cycle time (t_{cycle}) is the sum of the maneuver time at loader, load time, loaded haul time, maneuver at dump time, dump time, empty return time and queue waiting time. The truck cycle time is expressed in Equation (6):

$$t_{cycle} = t_{maneuveratloader} + t_{load} + t_{loadedhaul} + t_{maneuveratdump} + t_{dump} + t_{emptyreturn} + t_{wait} \tag{6}$$

Truck cycle time can be broken into idling and non-idling components. The service and queuing times are considered to be idling time, while the backcycle time is regarded as non-idling time. The fuel consumption for a truck in terms of litres per trip (VF) is given in Equation (7):

$$VF = FC_{nonidle}(t_{loadedhaul} + t_{maneuveratdump} + t_{dump} + t_{emptyreturn}) + FC_{idle}(t_{wait} + t_{maneuveratloader} + t_{load}) \tag{7}$$

Where $FC_{nonidle}$ and FC_{idle} are the fuel consumptions for truck non-idle and idle times, respectively. $FC_{nonidle}$ is estimated based on Equation (4) while FC_{idle} is calculated based on the equation given in Kaboli and Carmichael (2014).

The number of trips (N_{trips}) per hour is given in Equation (8):

$$N_{trips} = \frac{1}{t_{cycle}} \tag{8}$$

The fuel consumption for a truck in terms of litres per hour (VF_h) is given in Equation (9):

$$VF_h = VF.N_{trips} \tag{9}$$

The CO_2 emissions for a truck is expressed in Equation (10) (Kecojevic and Komljenovic, 2010) as:

$$CO_2 = FC.CF \tag{10}$$

Where FC is the fuel consumption and CF is the conversion factor for emissions. The conversion factor for CO_2 emissions can be estimated using Equation (11):

$$CF = CC.10_{-6}.0.99.(44/12) \tag{11}$$

Where CC is carbon content for the diesel fuel (g/L) and 0.99 is the oxidation factor. The carbon content for the diesel is given as CC = 733 g/L (EPA, 2005b).

Appendix I. Field Data Set 3 - Concreting Operation using Pump

Cycle no.	Queue time at batching plant	Maneuver time at batching plant	Load time	Haul time
1-1	0.00	1.28	9.18	9.62
1-2	7.30	1.35	9.75	8.32
1-3	12.67	1.33	9.72	9.20
1-4	21.57	1.50	10.13	7.15
1-5	29.18	1.05	10.18	8.25
1-6	36.13	1.17	9.12	8.47
1-7	40.45	1.30	9.87	8.13
2-1	32.40	1.32	7.00	7.03
2-2	19.08	1.37	9.38	9.33
2-3	14.27	0.63	8.75	10.60
2-4	10.90	1.45	11.08	9.57
2-5	23.03	1.67	10.25	9.83
2-6	20.57	1.62	10.17	11.27
2-7	16.78	2.32	9.60	9.90
3-1	20.05	2.40	11.10	10.43
3-2	17.07	1.67	11.12	9.27
3-3	18.30	0.80	11.30	10.65
3-4	19.23	2.05	11.10	10.28
3-5	17.10	2.48	9.13	10.18
3-6	18.15	1.75	10.48	9.45
3-7	21.57	1.37	9.92	11.27
4-1	20.05	1.67	9.72	8.87
4-2	18.30	1.63	10.02	9.02

Table I1a. Summarised event time data for the truck cycles. Times in minutes (continued).

Cycle no.	Queue time at batching plant	Maneuver time at batching plant	Load time	Haul time
4-3	19.42	1.44	10.14	8.84
4-4	19.23	1.51	9.82	8.74
Mean	**19.712**	**1.525**	**9.921**	**9.347**
Variance	**70.775**	**0.195**	**0.848**	**1.240**
Standard deviation	**8.413**	**0.441**	**0.921**	**1.113**

Table I1a. Summarised event time data for the truck cycles. Times in minutes.

Cycle no.	Queue time at site	Maneuver time at site	Unloading time	Wash-out time	Return time
1-1	0.00	0.63	15.25	1.70	8.27
1-2	6.05	1.53	16.25	2.20	10.97
1-3	11.92	2.23	15.30	1.83	9.40
1-4	20.52	1.25	16.30	2.02	9.52
1-5	27.02	1.13	15.93	1.88	10.13
1-6	33.70	1.28	15.30	2.02	10.73
1-7	39.33	1.40	15.33	2.17	10.00
2-1	50.03	1.25	16.17	2.03	8.30
2-2	54.57	1.42	16.12	2.00	8.20
2-3	47.60	1.32	17.63	1.98	8.22
2-4	42.97	1.53	16.27	2.13	8.28
2-5	46.83	1.53	16.47	1.83	8.30
2-6	49.68	1.70	14.03	1.93	8.30

Table I1b. Summarised event time data for the truck cycles. Times in minutes (continued).

Cycle no.	**Queue time at site**	**Maneuver time at site**	**Unloading time**	**Wash-out time**	**Return time**
2-7	47.93	1.22	16.18	2.05	8.30
3-1	51.05	1.93	15.38	2.17	10.73
3-2	49.73	1.60	13.60	2.08	8.22
3-3	45.02	1.38	15.70	2.02	10.00
3-4	47.97	0.47	15.00	1.93	10.13
3-5	47.20	0.57	14.00	1.94	8.30
3-6	50.97	2.65	14.25	2.00	8.20
3-7	45.61	1.51	16.12	1.93	8.56
4-1	41.22	1.42	16.25	1.95	8.92
4-2	40.01	1.53	15.81	2.00	9.52
4-3	35.43	0.97	15.12	1.97	9.43
4-4	30.25	1.58	14.32	2.12	9.18
Mean	**38.504**	**1.402**	**15.523**	**1.996**	**9.124**
Variance	**220.123**	**0.221**	**0.890**	**0.013**	**0.883**
Standard deviation	**14.837**	**0.470**	**0.944**	**0.115**	**0.939**

Table I1b. Summarised event time data for the truck cycles. Times in minutes.

Cumulative distributions for each of the truck cycle component times are given in Figures I1 to I9.

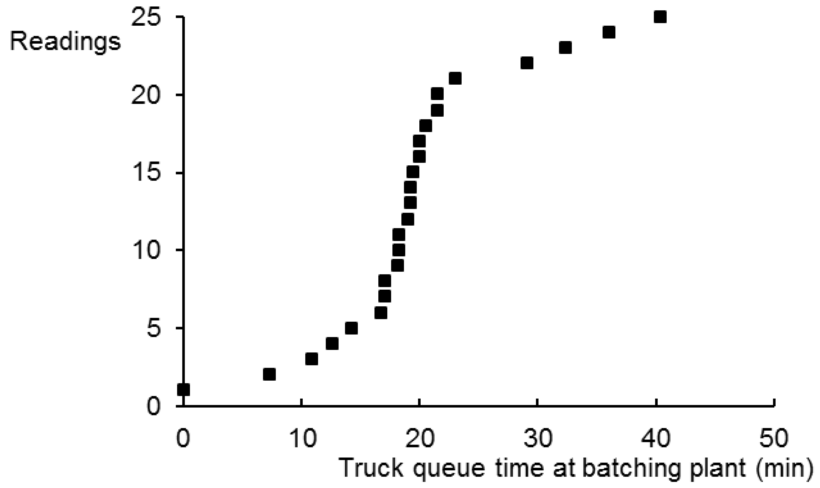


Figure I1. Cumulative distribution, truck queue time at batching plant.

Figure I2. Cumulative distribution, truck maneuver time at batching plant.

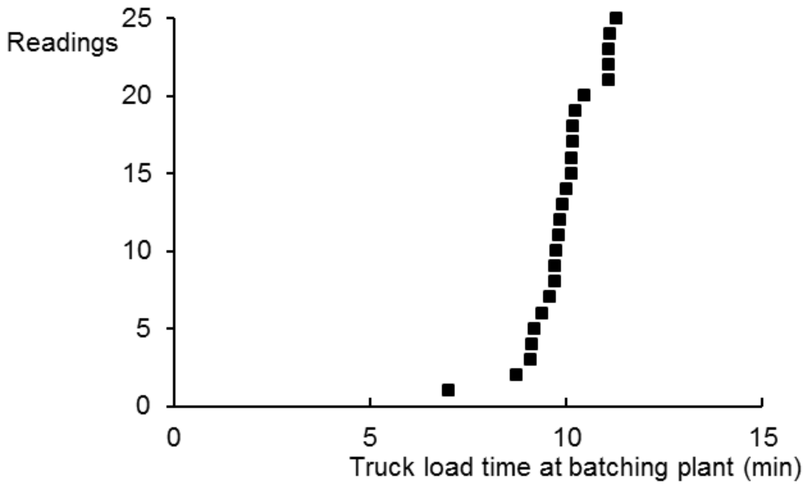


Figure I3. Cumulative distribution, truck load time at batching plant.

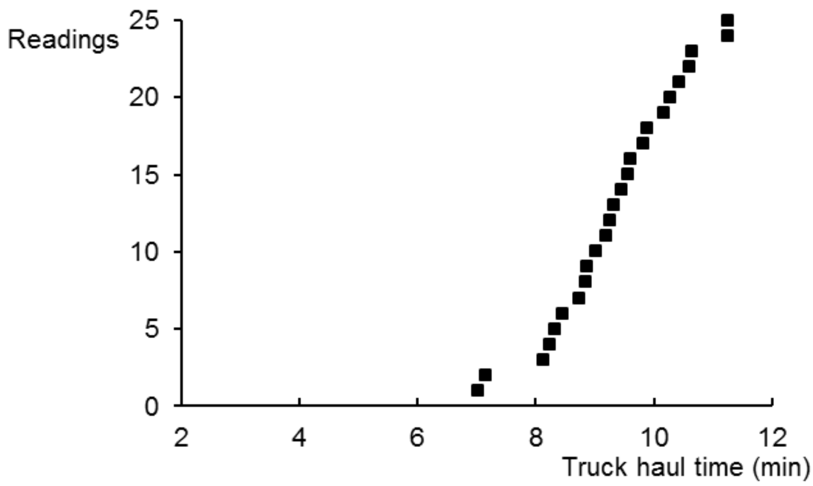


Figure I4. Cumulative distribution, truck loaded haul time.

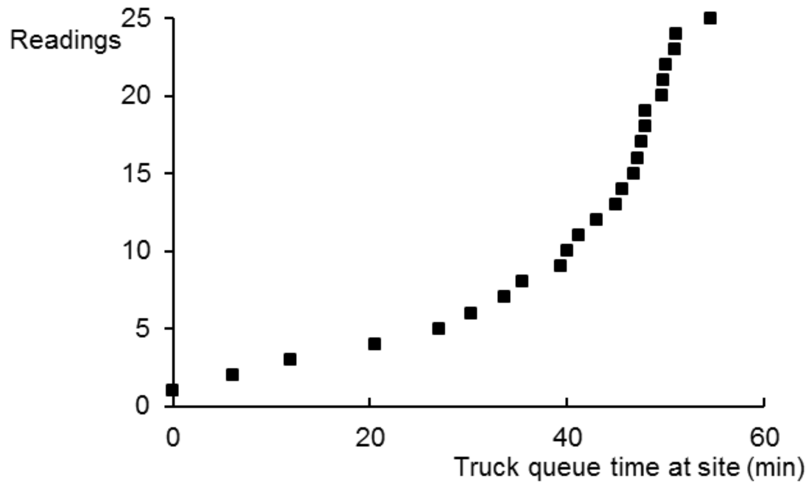


Figure I5. Cumulative distribution, truck queue time at site.

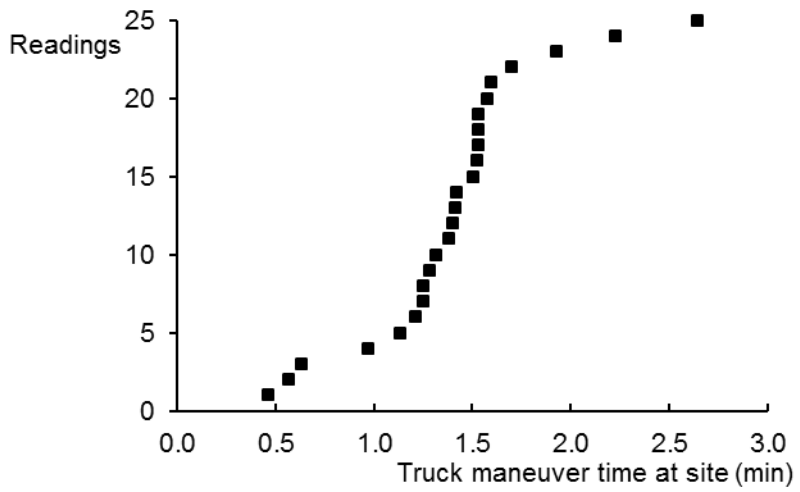


Figure I6. Cumulative distribution, truck maneuver time at site.

Figure I7. Cumulative distribution, truck unloading time at site.

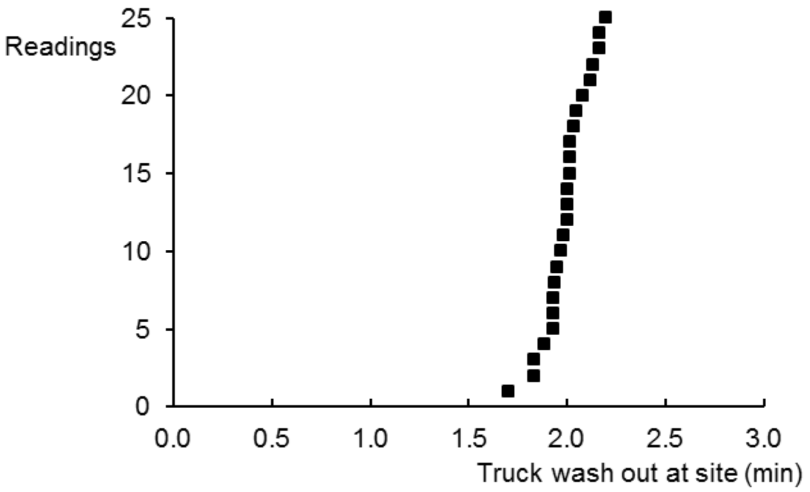


Figure I8. Cumulative distribution, truck wash-out at site.

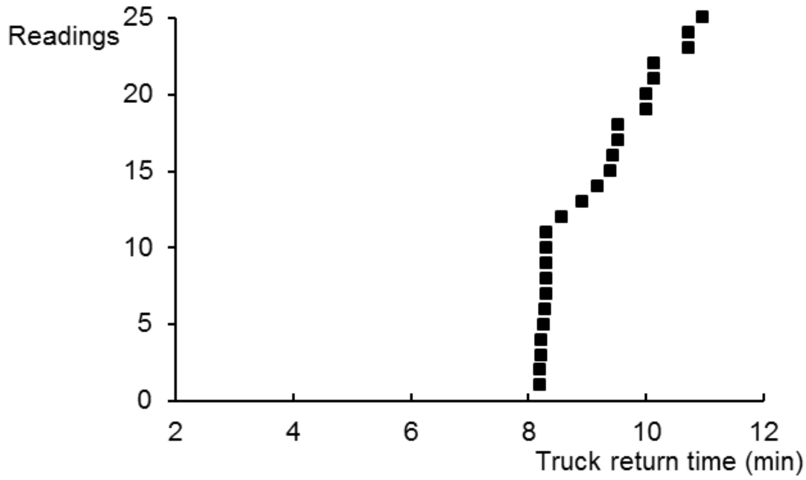


Figure I9. Cumulative distribution, truck return time.

Appendix J. **Field Data Set 4 - Concreting Operation using Crane and Bucket**

Two different truck capacities, each of 6 m^3 and 8m^3 were observed during the field study and the event time data are presented as below:

Cycle no. and CAP	Queue time at batching plant	Maneuver time at batching plant	Load time	Haul time
1-6	0.00	1.42	7.90	10.00
1-6	12.00	1.51	7.03	10.28
1-6	35.21	1.64	7.65	10.00
2-6	44.00	1.73	7.58	10.17
2-6	45.00	1.53	7.08	10.08
2-6	46.92	1.56	7.10	10.15
3-6	48.82	1.55	7.73	10.20
3-6	46.77	1.38	7.25	10.30
3-6	47.13	1.51	7.20	10.13
4-6	47.88	1.62	7.17	10.15
4-6	46.68	1.30	7.30	10.35
4-6	46.82	1.57	7.17	10.17
Mean	**38.936**	**1.527**	**7.347**	**10.165**
Variance	**255.443**	**0.014**	**0.085**	**0.012**
Standard deviation	**15.983**	**0.117**	**0.291**	**0.109**

Table J1a. Summarised event time data for the truck cycles. Times in minutes (continued).

Cycle no. and CAP	**Queue time at site**	**Maneuver time at site**	**Unloading time**	**Wash-out time**	**Return time**
1-6	0.00	0.67	41.42	2.50	10.37
1-6	10.85	0.63	44.02	2.17	10.35
1-6	31.83	0.72	46.13	2.20	10.33
2-6	24.05	0.63	47.85	2.17	10.08
2-6	30.07	0.57	43.47	2.52	10.38
2-6	35.00	0.55	42.45	2.40	10.03
3-6	22.57	0.58	43.43	2.75	10.67
3-6	20.10	0.50	47.95	2.37	10.48
3-6	26.67	0.53	44.93	1.97	9.97
4-6	28.17	0.67	40.10	2.35	10.50
4-6	31.47	0.58	40.10	2.55	10.72
4-6	25.10	0.53	40.65	2.45	10.32
Mean	**23.822**	**0.597**	**43.542**	**2.365**	**10.350**
Variance	**96.946**	**0.004**	**7.696**	**0.045**	**0.054**
Standard deviation	**9.846**	**0.066**	**2.774**	**0.213**	**0.233**

Table J1a. Summarised event time data for the truck cycles. Times in minutes.

Cycle no. and CAP	Queue time at batching plant	Maneuver time at batching plant	Load time	Haul time
1-8	0.00	1.46	7.02	10.28
1-8	7.03	1.48	7.15	12.28
2-8	28.02	1.67	7.07	11.67
2-8	24.74	1.59	7.07	11.27
3-8	24.90	1.72	7.25	11.40
3-8	27.30	1.64	7.08	11.38
4-8	27.00	1.66	7.07	12.50
4-8	29.00	1.75	7.07	12.50
Mean	**26.826**	**1.621**	**7.096**	**11.660**
Variance	**2.892**	**0.011**	**0.005**	**0.571**
Standard deviation	**1.701**	**0.105**	**0.072**	**0.755**

Table J1b. Summarised event time data for the truck cycles. Times in minutes (continued).

Cycle no. and CAP	Queue time at site	Maneuver time at site	Unloading time	Wash-out time	Return time
1-8	0.00	0.40	58.72	2.52	12.38
1-8	5.45	0.42	60.17	2.45	11.99
2-8	9.90	0.43	60.77	2.80	11.37
2-8	7.53	0.48	60.30	2.53	13.17
3-8	6.33	0.45	60.78	1.98	13.25
3-8	10.52	0.38	60.17	2.35	12.03
4-8	6.62	0.42	60.53	2.50	11.20
4-8	4.58	0.35	56.72	2.20	12.07
Mean	**6.367**	**0.417**	**59.769**	**2.417**	**12.181**
Variance	**10.812**	**0.002**	**1.947**	**0.060**	**0.550**
Standard deviation	**3.288**	**0.041**	**1.395**	**0.244**	**0.742**

Table J1b. Summarised event time data for the truck cycles. Times in minutes.

Cumulative distributions for each of the truck cycle component times are given in Figures J1 to J9.

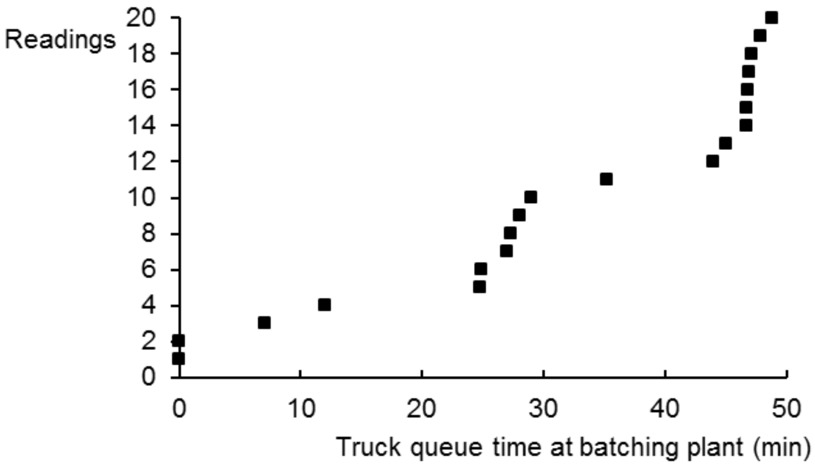


Figure J1. Cumulative distribution, truck queue time at batching plant.

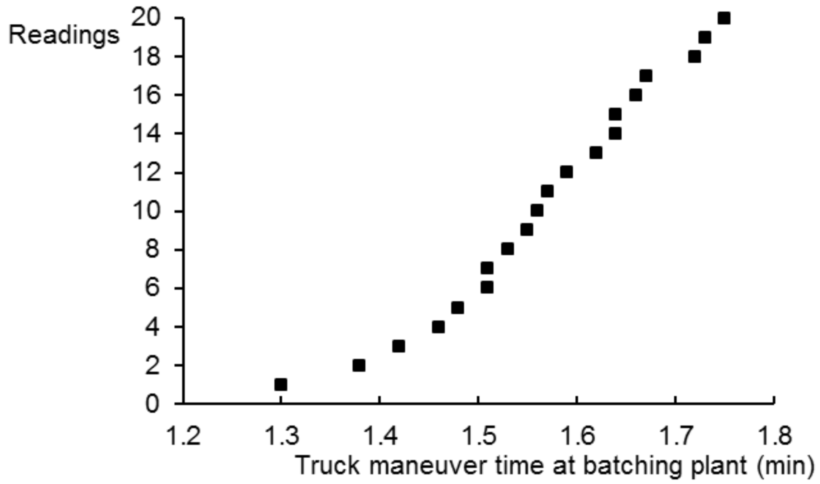


Figure J2. Cumulative distribution, truck maneuver time at batching plant.

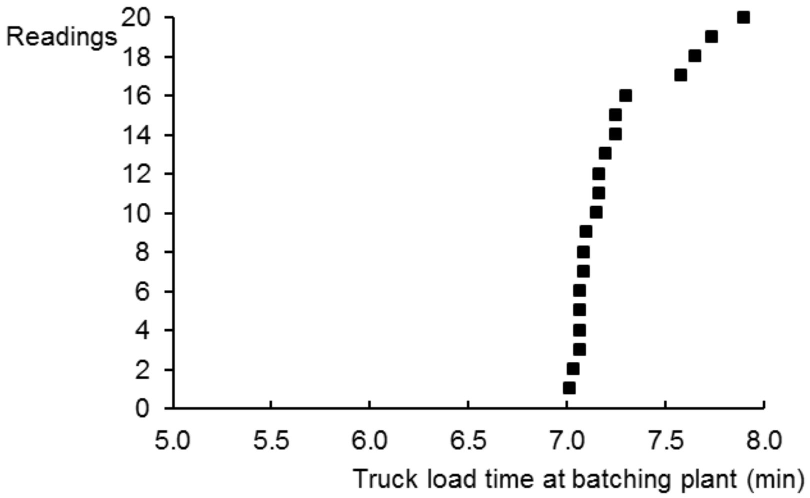


Figure J3. Cumulative distribution, truck load time at batching plant.

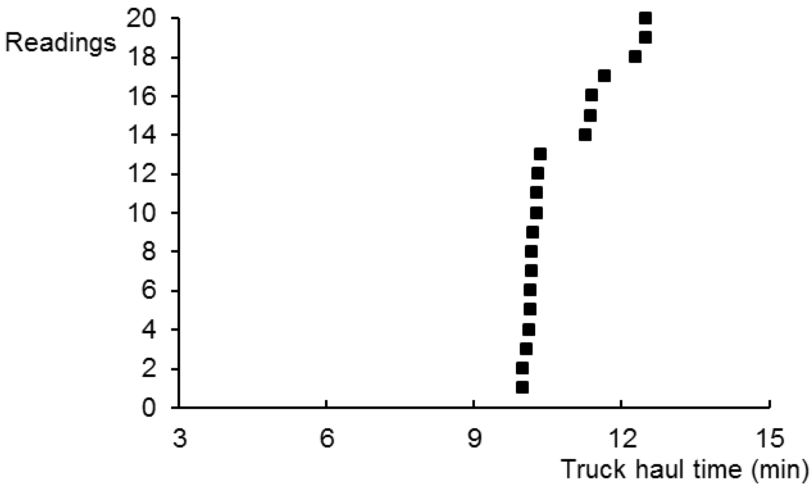


Figure J4. Cumulative distribution, truck loaded haul time.

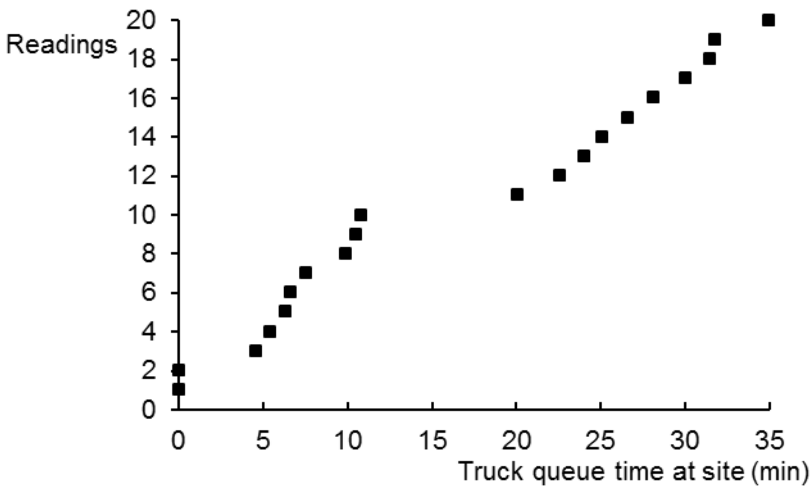


Figure J5. Cumulative distribution, truck queue time at site.

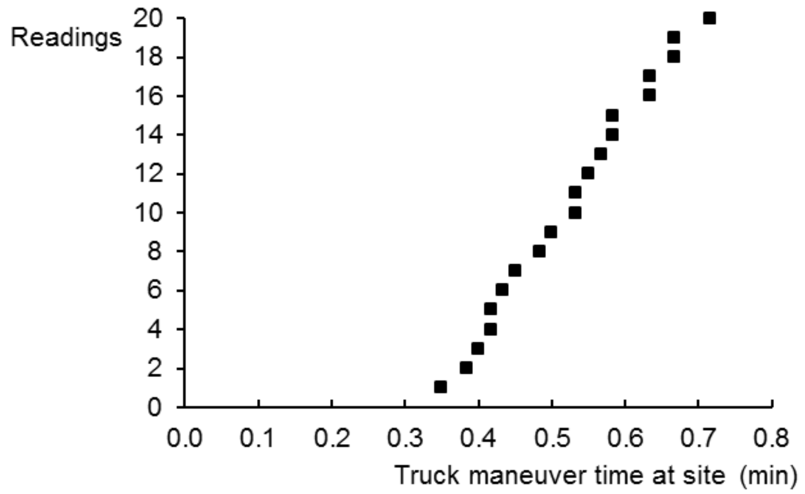


Figure J6. Cumulative distribution, truck maneuver time at site.

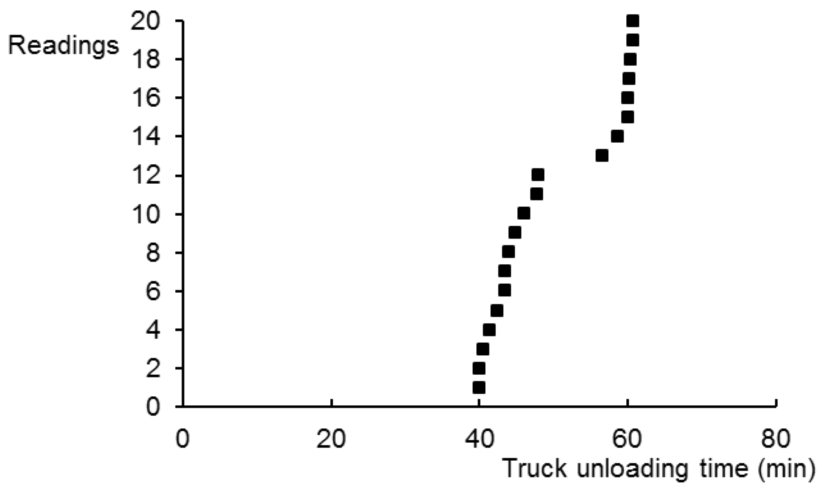


Figure J7. Cumulative distribution, truck unloading time at site.

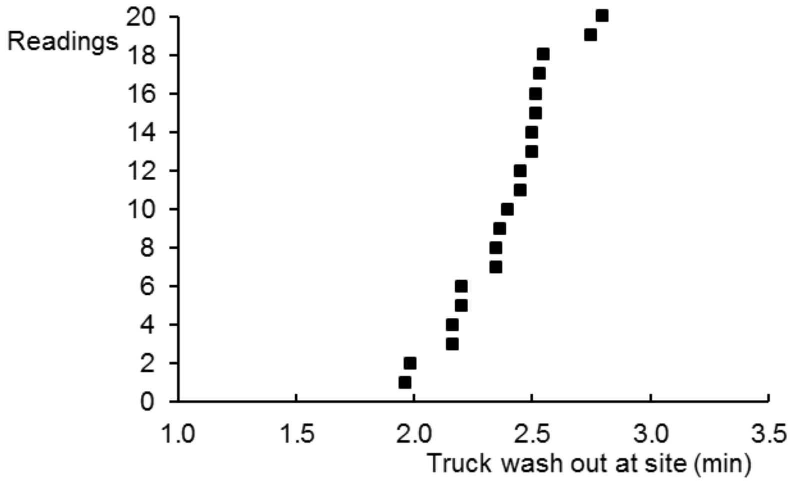


Figure J8. Cumulative distribution, truck wash-out at site.

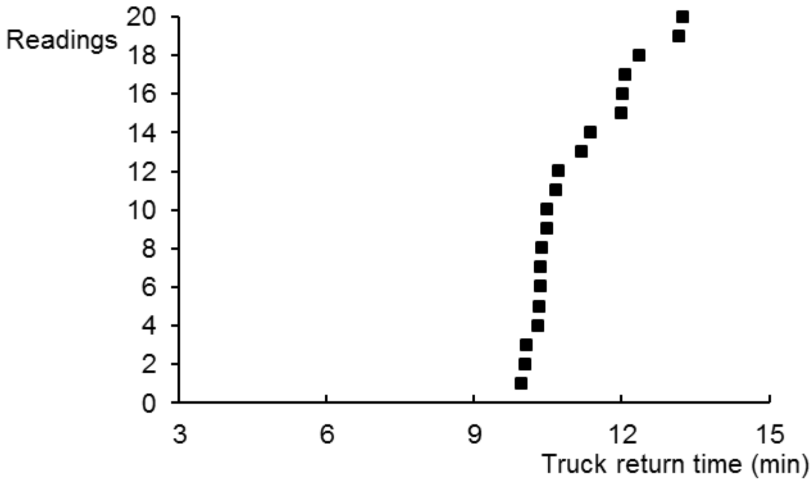


Figure J9. Cumulative distribution, truck return time.

Cumulative distributions for each of the crane cycle component times are given in Figures J10 to J13.

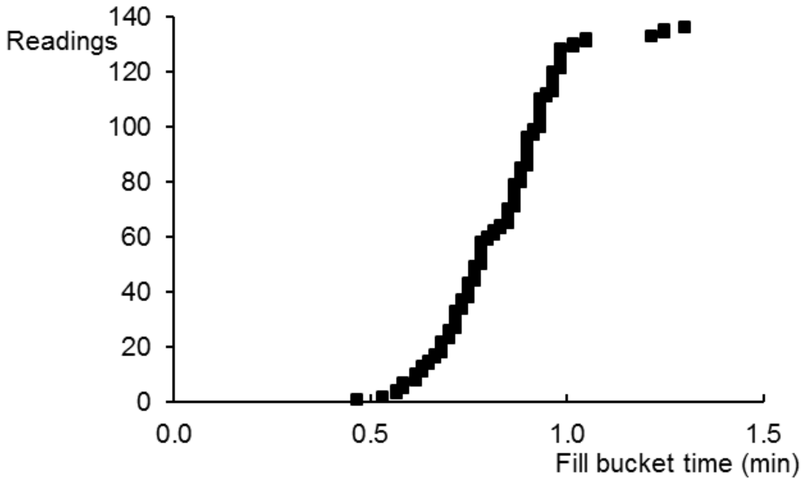


Figure J10. Cumulative distribution, fill bucket time for crane.

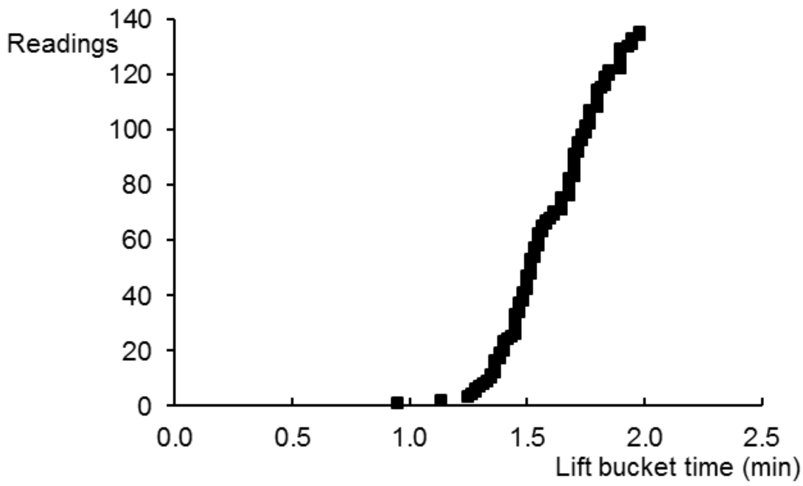


Figure J11. Cumulative distribution, lift bucket time for crane.

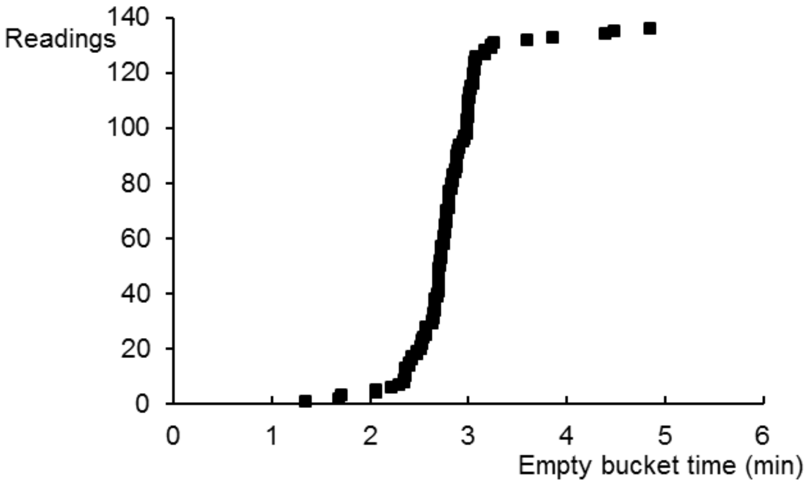


Figure J12. Cumulative distribution, empty bucket time for crane.

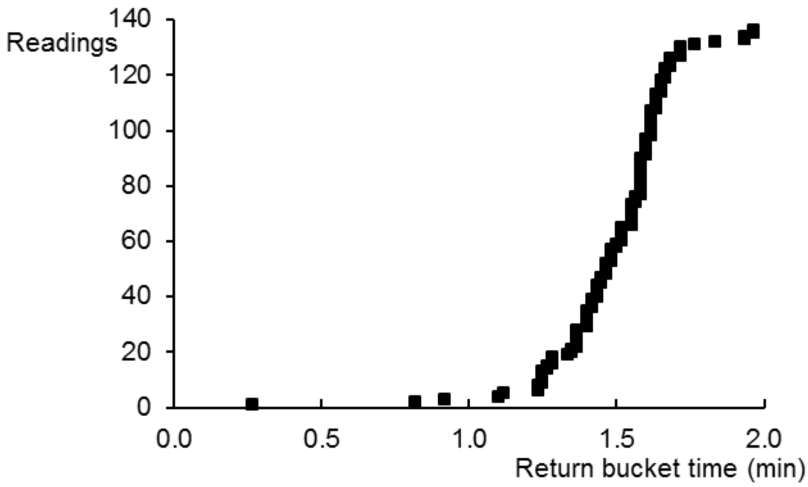


Figure J13. Cumulative distribution, return bucket time for crane.