Applications of Queuing Theory for Open-Pit Truck/Shovel Haulage Systems

Meredith Augusta May

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Mining & Minerals Engineering

Erik C. Westman, Chair
Gerald H. Luttrell
Kramer D. Luxbacher

19 December 2012
Blacksburg, VA

Keywords: Queuing Theory, Open Pit Mining, Haulage

Applications of Queuing Theory for Open-Pit Truck/Shovel Haulage Systems

Meredith Augusta May

Abstract

Surface mining is the most common mining method worldwide, and open pit mining accounts for more than 60% of all surface output. Haulage costs account for as much as 60% of the total operating cost for these types of mines, so it is desirable to maintain an efficient haulage system. As the size of the haulage fleet being used increases, shovel productivity increases and truck productivity decreases, so an effective fleet size must be chosen that will effectively utilize all pieces of equipment. One method of fleet selection involves the application of queuing theory to the haul cycle. Queuing theory was developed to model systems that provide service for randomly arising demands and predict the behavior of such systems. A queuing system is one in which customers arrive for service, wait for service if it is not immediately available, and move on to the next server or exit the system once they have been serviced. Most mining haul routes consist of four main components: loading, loaded hauling, dumping, and unloaded hauling to return to the loader. These components can be modeled together as servers in one cyclic queuing network, or independently as individual service channels. Data from a large open pit gold mine are analyzed and applied to a multichannel queuing model representative of the loading process of the haul cycle. The outputs of the model are compared against the actual truck data to evaluate the validity of the queuing model developed.

Acknowledgements

I would like to thank my advisor, Dr. Erik Westman, for giving me the opportunity to pursue this research and for all of the support, guidance, and assistance provided along the way. I would also like to thank Dr. Gerald Luttrell and Dr. Kray Luxbacher for being on my committee and providing valuable feedback.

I would like to thank all of the graduate students from Holden 115A for all of their encouragement, assistance, and camaraderie. Thank you for making the process of working on this project so enjoyable.

A special thanks to my industry sponsor for supporting me and my research for the past year and a half and for providing the data necessary to complete this project.

Lastly, I would like to thank my parents for their unwavering support and encouragement throughout my entire academic career.

Contents

List of Figures

List of Tables

Chapter 1: Introduction

Surface mining is the most common mining method worldwide, and open pit mining accounts for more than 60% of all surface output (Hartman & Mutmansky, 2002). Open pit mining consists primarily of the removal of topsoil and overburden, drilling and blasting of ore, and the transportation of material using a system of shovels or excavators and haul trucks. After the haul trucks have been loaded, the trucks transport the material out of the mine to a dumping location where the material will either be stored or further processed. The trucks then return into the mine and the cycle repeats itself. For most surface mines, truck haulage represents as much as 60% of their total operating cost, so it is desirable to maintain an efficient haulage system (Ercelebi & Bascetin, 2009). As the size of the haulage fleet being used increases, shovel productivity increases and truck productivity decreases, so an effective fleet size must be chosen that will effectively utilize all pieces of equipment (Najor & Hagan, 2004).

When selecting earth-moving equipment for a particular mine site, shovels and trucks must be matched based on their characteristics. The loader needs to be an appropriate size relative to the height and width of the benches being mined, and the dumping height of the loader must be sufficient to clear the side of the haul truck. The loader selected should also be able to fully load a haul truck in three to six passes without using any partially filled buckets (Alkass, El-Moslmani, & AlHussein, 2003). The number of trucks required to meet production requirements and maximize efficiency is difficult to determine, and the number of trucks necessary will change over time as mining advances and haul routes become longer.

One method of fleet selection involves the application of queuing theory to the haul cycle. Queuing theory was developed to model systems that provide service for randomly arising demands and predict the behavior of such systems. A queuing system is one in which customers arrive for service, wait for service if it is not immediately available, and move on to the next server once they have been serviced (Gross & Harris, 1998). For modeling truck-shovel systems in a mine, haul trucks are the customers in the queuing system, and they might have to wait for service to be loaded and at the dumping locations.

The scope of this project is to create a queuing model that can represent truck and shovel behavior in open pit mining operations. An (M/M/c) queuing model was created to characterize vehicle interactions within the pit and provide outputs useful for analyzing efficiency and production rates. Haul truck data from a large open pit gold mine were acquired and analyzed to provide inputs to the queuing model to provide a basis of comparison and validation to the queuing model outputs.

Chapter 2: Literature Review

2.1 Methods of Fleet Selection

Before computer systems were readily available, estimates about haul cycles were made which would approximate average times for specific activities such as loading, travelling, dumping, and delay times. The reliability of this approach varies widely based on the analyst's ability to obtain accurate average times for the cycle. This conventional method assumes that trucks make each round trip in exactly the same amount of time and that the productive capacity of a carrier is not affected by the number of carriers in the system. This method is not able to analyze variations between different cycles or different operating periods (Deshmukh, 1970).

Optimal fleet size can also be estimated based on production tonnage requirements and individual truck productive capability. In this method a truck's productive capacity is calculated based on a truck's effective payload and its estimated cycle time multiplied by a productivity factor. The number of trucks that need to be operated is then calculated by dividing the hourly tonnage required by the tons per truck per hour, based on the calculated productive capacity (Burton, 1975). This method does not provide an accurate model of truck-shovel systems, but it does provide a rough estimation of the number of trucks required to meet production needs.

Another common method for modeling fleet-loader systems involves stochastic simulation. In stochastic simulation a random number selection technique such as Monte Carlo simulation creates probability distributions from a stochastic variable based on data from time studies. This is done to obtain a sequence of variable times that might occur during actual operations. This can be used to find values for sections of the haul cycle such as loading time, dump time, or delay time. A model of a haul cycle is created based on the loading, haulage, and waiting times obtained through Monte Carlo simulation (Deshmukh, 1970). Computer simulation programs can quickly perform these simulations and the optimum number of trucks can be found by comparing models of a given haul route using different fleet sizes. Due to the stochastic and dynamic nature of shovel-truck interactions, different simulation models used to calculate fleet requirements will yield different fleet sizes for the same input parameters. This is largely due to the assumed probability distributions applied to variables in the cycle and the waiting times for haulers and loaders calculated based on those assumptions (Krause & Musingwini, 2007).

Talpac is a commonly used computer simulation program designed for evaluating haulage fleets that was developed by Runge. Users can input site specific parameters affecting fleet productivity such as material characteristics, haul route, truck and loader types, work roster, and operating limitations. Talpac can then calculate fleet productivity for long term and short term planning, equipment evaluation, optimum loading techniques, haulage costs, and other production values (Runge, 2011). Talpac is commonly used throughout the mining industry for shovel-truck analysis even though it can only fit a maximum of five probability distributions for cycle variables (Krause & Musingwini, 2007).

Another method of fleet selection involves the application of queuing theory to the haul cycle. Queuing theory was developed to model systems that provide service for randomly arising demands and predict the behavior of such systems. A queuing system is one in which customers arrive for service, wait for service if it is not immediately available, and move on to the next server once they have been serviced (Gross & Harris, 1998). For modeling truck-shovel systems in a mine, haul trucks are the customers in the queuing system, and they might have to wait for service at the loader and at the dumping location.

2.2 Applying Queuing Theory to Mining

Ernest Koenigsberg first applied queuing theory to mining practices in 1958. Koenigsberg modeled conventional, mechanized room and pillar mining operations using closed loop queuing systems with a finite number of customers based on the assumption of exponential service time distributions. The mining system being considered consists of a set of specialized machines which work in succession on a series of active mine faces. The entities involved in the cycle include a cutting machine, drilling machine, blasting crew, loading machine group – a loader and one or more shuttle car, and a roof bolting machine. Each machine proceeds to the next face when it is done with its task. The time it takes for each machine to complete its task is non-constant and subject to random time variations. Transit time and machine breakdowns also add to random time variation. This setup was translated into queuing theory notation by considering the machines to be fixed in sequence with the mining faces queuing for service in cyclic, first come-first served order. In queuing theory notation, this translates to a closed queue with N customers receiving service in order of arrival from M machines. After the M^{th} stage, the customer (mine face) rejoins the queue at stage one (Koenigsberg, 1958).

Koenigsberg adapts formulas to determine the probability that the system is in a given state, the mean number of units waiting for service at a given stage, the delay at a given stage, mean cycle time, probability that a stage is idle, and daily output. These equations can be recalculated for different numbers of servers and customers so that the results for different machine configurations can be compared. Koenigsberg finds that output increases as N, the number of working faces is increased, and the rate of change of increase decreases with increasing N. He also finds that the overall output is limited by the service rate of the slowest machine (Koenigsberg, 1958).

Queuing theory gained popularity as a method of fleet selection and haul cycle analysis in the 1970s and 1980s. Simulation models were a commonly used technique for analysis of shovel-truck systems during this time period because they could provide useful results that accounted for the variability inherent in the system (Barnes, King, & Johnson, 1979). A major drawback of computer simulation was the method's requirement of computer memory and CPU time, which was costly and time consuming. Analytical modeling methods with little to no computing requirements, such as queuing theory, were a viable alternative to computer simulation models (Billette, 1986).

In 1973 Maher and Cabrera applied cyclic queuing theory to civil engineering earthmoving projects, similar to haulage systems found in open pit mining. Queuing theory is used here to find the optimum number of trucks that should be used to minimize the cost per unit volume of earth moved. The haulage system is analyzed with the option of considering loading and transit times to be constant or variable, fitting a negative exponential distribution. This study also recognizes that with more than one excavator in operation the system can have either two separate queuing systems or one joint queue. The end result of this modeling is a set of charts for choosing the most cost-effective number of trucks based on the ratio of the loading time and haulage time and the ratio of the costs to operate the loader and the trucks (Maher & Cabrera, 1973). These charts could be applied to any earthmoving or mining operation as long as the data about cost and cycle time is known.

In 1977 Jorgen Elbrond developed a straightforward calculation technique based on queuing theory to be used as an alternative to computer simulation for evaluating open pit operation capacity. Elbrond's technique is based on queuing theory's formula for waiting time in a closed circuit with added correction factors which reflect variability in loading, travel, and dumping times. Waiting times at service stations are calculated as a function of the number of trucks in the circuit by averaging the results found through simulations for three different cases: constant travel time and constant service time, exponentially distributed travel time and exponentially distributed service time, and exponentially distributed travel time and constant service time. Correction factors are calculated using an interpolation procedure combining theoretical and simulated cases. Other data relevant to the haul cycle such as dumping time and shift composition is found using time studies. Once formulas had been completely developed, time studies made at Hamersley Iron found a correlation coefficient of 0.865 between observed and calculated wait time at shovels (Elbrond, 1977). This suggests that the technique used is a reasonably accurate method of modeling haulage systems.

Barnes, King, and Johnson approach queuing theory as an alternative to costly computer simulation and rough-estimate match factor and efficiency factor methods of approximating production capacities of open-pit systems. In their paper Ernest Koenigsberg's approach to mine modeling using cyclic queues and Jorgen Elbrond's work with finite queues are outlined and compared to one another and to the results of stochastic simulation. The goal of this comparison is to observe any systematic relationship between the estimates found using each method (Barnes, King, & Johnson, 1979).

This comparison found that stochastic simulation is more flexible than the two queuing theory methods and provides more accurate results. Unlike the methods relying on queuing theory, simulation does not assume steady state conditions for the entirety of the cycle time; simulation is able to account for startup time and end of shift activity. The main disadvantages associated with stochastic simulation are the significant amount of time and manpower necessary to develop the simulator and the considerable amount of computer time that is used to run the simulation.

This study found that cyclic queuing as it existed at the time, such as Koenigsberg's model, is not an adequate method of estimating truck-shovel production. This is largely based on the mathematical requirement that all segment times be exponentially distributed. This causes the effects of bunching and mismatch to be greatly exaggerated, and for production to be understated. It was concluded that this method does not produce a true representation of the system's productive capacity.

Elbrond's finite queuing theory application can produce a fairly accurate estimate of production values by applying a correction factor to account for the results found using exponentially distributed activity times. Elbrond generates waiting times and subsequently production predictions which closely approximate observed values by interpolating between his three cases, which are: constant travel time and constant service time, exponentially distributed travel time and exponentially distributed service time, and exponentially distributed travel time and constant service time. Barnes, King, and Johnson conclude that while Elbrond's finite queuing theory method produces a more accurate model than Koenigsberg's cyclic queues do, modifications are needed either to the correction factors or to the method itself in order to more closely resemble actual operations output (Barnes, King, & Johnson, 1979).

In the late 1970s nearly all applications of queuing theory to mine production used exponential distributions. There were few alternatives available since the use of more-general distributions such as normal or log-normal distributions involved prohibitively complex mathematics. However, the Barnes, King, and Johnson study does address the possibility of using an Erlang K distribution with finite queues, similar to Elbrond's technique. For this proposed method only two cases would need to be analyzed: exponential arrival with Erlang K service and deterministic arrival with Erlang K service. The Erlang distribution parameters account for the effects of variability in the service rate. Correction factors need only be applied as a function of arrival rate variability. An extension of these models would be one with Erlang arrival and Erlang service times to eliminate the need for interpolation or correction factors, but the math involved with such a model would be exceptionally complex. At the time their paper was published, no solution to an Erlang/Erlang finite queuing model had been developed, but it was determined that developing such a model would provide a useful, inexpensive analytical alternative to simulation methods for open pit production calculations (Barnes, King, & Johnson, 1979).

Barbaro and Rosenshine presented a paper in 1986 which uses a cyclic queuing theory model to evaluate the productivity of a truck-shovel system. A cyclic queuing model with exponentially distributed service times is used to model an example problem and the results are compared to those from simulation to demonstrate that the assumptions of exponentially distributed service times and steady state behavior are not major problems. Barbaro and Rosenshine compare their cyclic queuing model to the methods used in the 1979 Barnes, King, and Johnson study and achieve results more favorable than those reached in the original paper. Barnes et al. consistently reported results from queuing theory-based models that exceeded the theoretical maximum capacity of the mine in question. The results of the Barbaro and Rosenshine study find that the cyclic queuing model in question is correctly coded and provides valid results. In their study, shovel utilization rates found using cyclic queuing models only differ from the results found through simulation by 0.4% and productivity values differ by 0.9%. No explanation is offered to explain the discrepancy between the different results found in the 1979 and 1986 studies (Barbaro & Rosenshine, 1987).

Engineering Queues in Construction and Mining by D. G. Carmichael contains queuing theory models based on assumptions applicable to mining and construction operations which have been validated by reference to field data records comparing theory and practice. Models for many different situations are provided, including queues with random arrivals and exponential service times; queues with alternative distributions for arrivals and servicings; cyclic queues; serial queues and storage; earthmoving, quarrying, and open-cut mining operations; and machine maintenance and repair. While there are many formulas and equations supplied for each of these topics that can easily be used as tools in scheduling, planning, productivity analysis, and cost analysis, there is little information given about how closely these models follow actual operations (Carmichael, 1987).

Muduli and Yegulalp's 1996 paper presents an analytical method of modeling truck-shovel systems as a multiple-chain closed queuing network. This allows the model to account for haulage systems which do not necessarily contain identical trucks. Prior to this, nearly all queuing theory-based models of haulage systems were based on the assumption that the fleet is composed of only one truck type. Carmichael addresses heterogeneous cases where trucks are not assumed to be identical in his book (Carmichael, 1987). Carmichael uses an approximation method to adapt the heterogeneous system into an equivalent homogeneous system, but this is not a method based on queuing theory techniques. Muduli and Yegulalp address the problem using a closed queuing network with multiple classes of customers. This allows for different classes of trucks with different capacities and operating characteristics to be included (Muduli & Yegulalp, 1996).

In queuing theory, a chain consists of a permanent categorization of jobs. As it applies to mining, a job (truck) which is part of one chain cannot switch to another. Different types of trucks can be sorted into different classes depending on their size and productivity. For this model, it is assumed that there is a single class of trucks per chain. Different classes of trucks can be given different characteristics by assigning different general service-time distributions to each one (Muduli & Yegulalp, 1996).

Often in truck-shovel modeling all trucks within the system are assumed to be identical for analytical purposes, even when it is recognized that multiple types and sizes of trucks are present in the system. This is done to simplify calculations. To calculate performance characteristics of these multiple chain queuing systems involving multiple classes of trucks a Mean Value Analysis (MVA) approach is used for conditions when all trucks of different classes have identical exponential service time distributions. For situations with generally distributed service times a method called Extended MVA can be used for multiple classes of trucks and service times (Muduli & Yegulalp, 1996).

This study compares results found using multiple chain queuing networks to the results of evaluating a system with multiple classes of trucks by assuming all trucks are identical. It is found that the maximum production rate calculated using an equivalent single-class model underestimates the maximum production rate that is possible using multiple classes of trucks by as much as 14% when two different classes of trucks are present. The relative error of maximum truck production found using equivalent single-class models increases as the number of trucks and the number of different classes of trucks involved increase. It is clear that a modeling system that accounts for different classes of trucks is essential to determine the optimal number of different sizes of trucks to maximize a mine’s production output (Muduli & Yegulalp, 1996).

In 2002 Khalil El-Moslmani created a computer model based on queuing theory to model multi-loader truck systems assuming trip times have a negative exponential distribution and service times follow an Erlang distribution with three or fewer servers. For cases with multiple types of haulers, unlike Muduli and Yegulalp's method involving multiple chain queuing systems, an approximation based on weighted averages is used to convert the heterogeneous system into a homogeneous one. This is similar to Carmichael's method of converting heterogeneous systems into homogeneous ones (Carmichael, 1987).

El-Moslmani's queuing model is solved to obtain values such as server utilization to be used in the calculation of system production. The computer module, called FLSELECTOR, is used to assist in choosing proper fleet size. FLSELECTOR is implemented using Visual Basic for Application (VBA) and Microsoft Excel and allows for an optimum fleet to be selected based on least cost, maximum production, or minimum project duration (El-Moslmani, 2002). FLSELECTOR also allows the user to compare the different production outputs that would be achieved using different haul routes from the loading area to the dumping area (Alkass, El-Moslmani, & AlHussein, 2003). Charts for the ten best fleets for a particular set of requirements can be viewed and printed. Arrival rate, service rate, utilization, production, cost, duration, and cost per unit are calculated for each fleet. Calculation may take only a few seconds for situations with one server and one type of truck or as long as ten minutes for more complex systems such as those with three servers with more than two types of haulers (El-Moslmani, 2002).

The performance of FLSELECTOR is compared to the results of simulation and deterministic methods. When comparing results to those from deterministic models, FLSELECTOR gives smaller production values than the deterministic model does. This is consistent with studies which have found that deterministic models tend to overestimate production values. FLSELECTOR gives output relatively in line with that of the simulation system SimEarth. Comparison indicates that the two methods' outputs differ by an average of 14% (El-Moslmani, 2002).

Limitations of FLSELECTOR include the fact that it can only handle a maximum of three servers and its assumption that no queues will form at the dumping point. Despite this, FLSELECTOR provides a user-friendly method of applying queuing theory to fleet selection and offers multiple configurations of fleet components that can meet the needs of individual project requirements. The paper does not specify whether predicted FLSELECTOR output has been compared to the data obtained from actual fleet performances (El-Moslmani, 2002).

Najor and Hagan present an approach to mine scheduling that incorporates a heuristic model based on queuing theory. The goal in developing this model is to reduce financial expenditure in the mine production system by efficiently managing the fleet, maximizing the use of equipment while minimizing the resources necessary to support this equipment, and ensuring that fleet size matches targets for material movement. To develop this model, queuing theory is applied to a capacity-constrained model based on truck productivity (Najor & Hagan, 2004).

Queuing formulas for values such as expected wait time and expected number of trucks being serviced are incorporated into a spreadsheet which calculates production values and the estimated cost per tonne of material moved. Comparison between the capacity constrained model and a conventional, mechanistic approach shows that the capacity-constrained model offers more conservative production values than the conventional approach, which tends to overestimate mining capacity. On average, the conventional approach underestimates the amount of time it would take to complete a project by 8% compared to the amount of time found using the capacity-constrained method (Najor & Hagan, 2004).

It is recommended that the capacity constrained method be used in mines with relatively short haul distances. As haul distance increases the productivity values found for haul trucks become very similar regardless of what method is used to calculate them. In this study, the capacity-constrained, queuing theory based model is applied to a situation requiring relatively few trucks to meet production needs. The optimum fleet size found to minimize the cost per tonne of material moved for the model in question consists of only three or four trucks (Najor & Hagan, 2004). This is significantly smaller than fleet sizes for large open-pit mines which can require more than 100 trucks to meet production needs.

Krause and Musingwini demonstrate that a modified Machine Repair Model, an example of a finite source queuing model, can be applied to mining projects to accurately estimate required fleet size. Based on the Machine Repair Model, a truck is sent for loading (repair) every cycle and there is a set number of shovels (repair bays). Interarrival time and service time are both assumed to be exponentially distributed. Since trucks are drawn from a finite population, their arrival pattern depends on the state of the system. Equations for situations in the Machine Repair Model are easily adjusted to fit loading and hauling situations. For example, the average time a truck spends waiting for repair becomes the average amount of time a truck queues at the loading unit or dump site (Krause & Musingwini, 2007).

The modified Machine Repair Model and four common methods of analyzing shovel-truck systems are applied to a virtual mine. These common methods include Elbrond's cyclic queuing model, a regressive model developed by Caterpillar called Fleet Production and Cost model (FPC), Talpac, and a stochastic simulation model called Arena. Loading cycle times of three, four, and five minutes are simulated and dumping and maneuvering times are kept constant, assuming consistent operator ability. Using these assumptions, the five models are run to produce estimates of achievable shift production. The Arena model is used as a benchmark for comparing the accuracy of the other estimation methods. The Arena model is used as a benchmark because its ability to be programmed with any number of probability distribution models fitted to an unlimited number of cycles makes it very flexible and capable of closely imitating real mining systems (Krause & Musingwini, 2007).

All of the models used produce estimates of loads per shift that are within 97%-99.7% of the Arena estimates. Arena reports slightly more loads per shift than the other models do, which can indicate that the other models are slightly more conservative. Overall, the results indicate that the modified Machine Repair Model is capable of producing productivity estimates that closely resemble those of other common truck-shovel analysis methods. When used to calculate fleet size necessary to meet increased production requirements at a surface coal mine in South Africa, the modified Machine Repair Model again produces results that are comparable to the other models. Arena, the modified Machine Repair Model, and Elbrond's model all calculate an optimum fleet size of nine trucks. FPC and Talpac calculate that an additional truck is necessary, for a fleet size of ten trucks. Based on this, it is concluded that the modified Machine Repair Method produces production values and fleet sizes that are comparable to other commonly used models. The modified Machine Repair Model also has the advantage of being relatively inexpensive, since it can be modeled using Microsoft Excel, a program which most mining companies already use (Krause & Musingwini, 2007).

Czaplicki's goal in his 2009 book is to allow operations to get the maximum profit from their loading and hauling systems by reducing losses in production time and having high utilization of the machines involved. Czaplicki applies queuing theory to shovel-truck systems using a modification of the Maryanovitch queuing model for truck reliability and repair. This involves using cyclic queues with two phases, service and travel, where service consists of loading the trucks and travel consists of haulage, dumping, and returning. Normal distributions are used to represent service and travel times and it is assumed that no queuing occurs at the dump site. Czaplicki presents formulas determining parameters such as truck fleet size, reserve fleet size, probability distributions for numbers of trucks and shovels in work state, and system productivity based on equipment reliability, the numbers of various pieces of equipment involved, and cycle time distributions (Czaplicki, 2009).

Czaplicki applies his formulas to two case studies to see how accurately an example machinery system can be modeled. One case study involves five loaders and trucks with a high availability, and the other involves seven loaders and trucks with low availability that will require repair more frequently and thus have less time available for haulage. For both system parameters, the equations determine an appropriate number of trucks and repair stands. Both systems yield an average queue length of approximately 1.4 trucks per loader. This means that the loader is able to achieve near-continuous production and relatively little truck cycle time is lost due to waiting (Czaplicki, 2009).

Ercelebi and Bascetin present a method of assigning trucks to shovels using closed queuing network theory for systems using only one type of truck. For truck-shovel systems where minimizing cost per amount of material moved is the primary goal, a balance must be achieved between the cost of idle time for the shovel and the cost associated with providing extra trucks. Loading, hauling, and dumping times are assumed to fit exponential distributions. Production costs are determined by incorporating the hourly cost to run each piece of equipment into the equations calculating the number of trucks to be used. Cost predictions for the system found using queuing theory are compared to the results found using a linear programming model and a case study for overburden removal at an open pit coal mine. Queuing theory provides the minimum loading and hauling costs for the system, along with an optimal number of trucks assigned to the shovels. When this system is implemented on the mine in question, the overburden removal target for the year is exceeded and average production costs are reduced (Ercelebi & Bascetin, 2009).

Ta, Ingolfsson, and Doucette present a paper based on truck and shovel behavior in oil sands mining. Their goal is to use queuing theory to capture the nonlinear relationship between average mine throughput and the number of trucks in use and then develop this relationship into a manageable optimization model. The model includes options for only a single truck size or multiple truck sizes, and individual trucks are assigned a readiness parameter so that the model can indicate both how many trucks are necessary and which individual trucks ought to be used. Shovel service times and truck back-cycle times are represented with an Erlang distribution. The probability that a shovel is idle is linearized so that shovel throughput can be expressed as a linear function. This model is compared to simulation results and it is shown that the optimization model accurately predicts shovel utilization and idle time. Information about truck utilization and idle time is not calculated, but the optimization model provides valuable information about how many trucks should be used to meet necessary production targets (Ta, Ingolfsson, & Doucette, 2010).

2.3 Conclusion

Most surface mines use truck and shovel systems to transport ore and waste material. It can be difficult to determine the proper number of trucks that should be used in these systems due to the dynamic nature of fleets of equipment and the fact that the length of the haul road is continually increasing as mining progresses. There are many different methods to model and simulate truck and shovel behavior, and companies are constantly looking for ways to quickly and more accurately predict equipment performance. Queuing theory presents a promising method to account for idle time caused by trucks waiting to be serviced at either the loading or dumping point. When trucks and shovels are represented as servers and customers in a queuing network, the proper number of machines that should be implemented in a mine can be determined, ensuring that production needs can be met while still maintaining efficient use of equipment.

Queuing theory formulas can represent multiple shovels, any size fleet consisting of multiple types of trucks, and various haul routes as mining progresses, and it can account for idle time that occurs when trucks must wait either at loading or dumping locations. Queuing theory is a viable option for fleet selection and modeling pit behavior for truck-shovel systems.

Chapter 3: Applications of Queuing Theory for Open-Pit Truck/Shovel Haulage Systems

3.1 Abstract

Surface mining is the most common mining method worldwide, and open pit mining accounts for more than 60% of all surface output. Haulage costs account for as much as 60% of the total operating cost for these types of mines, so it is desirable to maintain an efficient haulage system. As the size of the haulage fleet being used increases, shovel productivity increases and truck productivity decreases, so an effective fleet size must be chosen that will effectively utilize all pieces of equipment. One method of fleet selection involves the application of queuing theory to the haul cycle. Queuing theory was developed to model systems that provide service for randomly arising demands and predict the behavior of such systems. A queuing system is one in which customers arrive for service, wait for service if it is not immediately available, and move on to the next server or exit the system once they have been serviced. Most mining haul routes consist of four main components: loading, loaded hauling, dumping, and unloaded hauling to return to the loader. These components can be modeled together as servers in one cyclic queuing network, or independently as individual service channels. Data from a large open pit gold mine are analyzed and applied to a multichannel queuing model representative of the loading process of the haul cycle. The outputs of the model are compared against the actual truck data to evaluate the validity of the queuing model developed.

3.2 Introduction

Surface mining is the most common mining method worldwide, and open pit mining accounts for more than 60% of all surface output (Hartman & Mutmansky, 2002). For most surface mines, truck haulage represents as much as 60% of their total operating cost, so it is desirable to maintain an efficient haulage system (Ercelebi & Bascetin, 2009). As the size of the haulage fleet being used increases, shovel productivity increases and truck productivity decreases, so an effective fleet size must be chosen that will efficiently utilize all pieces of equipment (Najor & Hagan, 2004). Having more trucks in service than necessary wastes fuel, as trucks must spend time idling while waiting for service, and the company must pay the vehicle operators to drive a truck that is not actually needed. Alternately, having too few trucks causes idle time for the loaders, which causes a drop in production.

By applying queuing theory to mining haulage systems, the inherent stochastic nature of haul truck and loader behavior can be accounted for and the model created can be used to adjust fleet sizes to better serve loading needs. In this project a queuing model was generated that can be used to model truck and loader behavior in an open pit mine. The model is then applied to actual haulage data from an active mining operation.

3.3 Queuing Theory Background

Queuing theory was developed to provide models capable of predicting the behavior of systems that provide service for randomly arising demands. A queuing system is defined as one in which customers arrive for service, wait for service if it is not immediately available, and move on to the next server or exit the system once service is complete. Queuing theory was originally developed to model telephone traffic. Randomly arising calls would arrive and need to be handled by the switchboard, which had a finite maximum capacity. There are six basic characteristics that are used to describe a queuing system: arrival distribution of customers, service distribution of servers, queue discipline, system capacity, number of service channels, and number of service stages (Gross & Harris, 1998).

3.3.1 Customer Arrivals

In most queuing situations the arrival process of new customers to the system is stochastic. In these cases it is necessary to know the distribution of the times between successive customer arrivals, or the interarrival times. It is also important to understand the behavior of customers upon entering the system. Some customers may wait for service no matter how long the queue is, while others may see that a queue is too long and decide not to enter the system. When this happens the customer is described as having balked. Other customers may enter the system, but lose patience after waiting in the queue and decide to leave the system. These customers are said to have reneged. In situations with two or more parallel waiting lines a customer who switches from one line to the other is said to have jockeyed for position. Any or all of these behaviors may be present when a queuing system has what are classified as impatient customers. Impatient customers cause state-dependent arrival distributions, since the arrival pattern of new customers depends on the amount of congestion in the system at the time of their entry.

3.3.2 Service Distributions

A probability distribution is also necessary to describe customer service times, since it will not always take the same amount of time for each customer to receive service. Single service, where one customer is serviced at a time, or batch service, where multiple customers receive simultaneous service from a single server are both service options. A common example of a queuing system utilizing batch service involves waiting in line for a roller coaster. In this scenario, the people waiting in line are the customers and the roller coaster car is the server. A single line is formed to wait, and when the roller coaster car arrives the first four people in line who get into the car receive simultaneous batch service.

In some cases the service process may be dependent upon the number of customers waiting in the queue. The server may work more quickly due to the lengthening queue, or alternately the server may become flustered by the large number of customers waiting and the service rate may slow as a result. Situations in which the service rate depends on the number of customers in the queue for service are referred to as state-dependent services.

3.3.3 Queue Discipline

The manner in which customers in a queue are selected for service is referred to as the queue discipline. The most common queue discipline is first come, first served, or FCFS, where customers receive service in the order in which they arrived. This discipline is also commonly referred to as FIFO, or first in, first out. Another common queue discipline is LCFS, or last come, first served. This is commonly used in inventory situations where the most recently placed items waiting to be used are the most easily reached to be selected. RSS is a service discipline in which customers are selected for service in random order, independent of their order arriving to the queue.

There are a variety of different priority queue disciplines where different classes of customers are given higher priorities than other classes. In these disciplines the customer with the highest priority will be selected for service ahead of lower priority customers, regardless of how long each customer has been in the queue. If the queue discipline is preemptive, a customer with the highest priority is allowed to receive service immediately upon arrival at the server, even if a lower priority customer is already in service. The lower priority customer whose service is preempted resumes service after the higher priority customer has left. In nonpreemptive cases the highest priority customer that arrives at the server moves to the head of the queue, but must wait until the customer currently being serviced has left (Cooper, 1972).

3.3.4 System Capacity

If a queue has a physical limitation to the number of customers that can be waiting in the system at one time, the maximum number of customers who can be receiving service and waiting is referred to as the system capacity. These are called finite queues since there is a finite limit to the maximum system size. If capacity is reached, no additional customers are allowed to enter the system.

3.3.5 Number of Service Stations

The number of service stations in a queuing system refers to the number of servers operating in parallel that can service customers simultaneously. In a single channel service station, there is only one path that customers can take through the system. Figure 3.1 below shows the path customers, represented by circles, take through a single service channel queuing network. The customers arrive at the server, represented by the rectangle, and form a queue to wait for service if it is not immediately available, and then proceed through the system once service has been completed.

Figure 3.1: Single Channel Queuing System

When there are multiple servers available operating in parallel, incoming customers can either wait for service by forming multiple queues at each server, as shown in (a) of Figure 3.2, or they can form a single queue where the first customer in line goes to the next available server, depicted in (b). Both of these types of queues are commonly found in day-to-day life. At the grocery store individual lines are formed at each cashier, but a single line is generally formed when customers are waiting in line at the bank. The first customer in line then proceeds to the next available teller. A single queue waiting for multiple servers is generally the preferred method, as it is more efficient at providing service to the incoming customers.

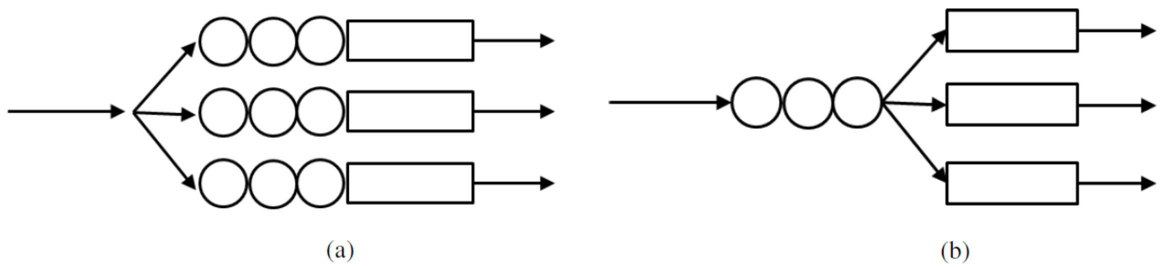

Figure 3.2 Multichannel Queuing Systems

3.4 Notation

Queuing processes are frequently referred to by using a set of shorthand notation in the form of (a/b/c/):(d/e/f) where the symbols a through f stand for the characteristics shown below in Table 3.1.

Table 3.1: Queuing Notation Abbreviations

Symbol	Characteristic
a	arrival distribution
b	service distribution
c	number of parallel servers
d	service discipline
e	maximum number of units that can be in the system at one time
f	source population size

The symbols a through f will take different abbreviations depending on what type of queuing process is being described. Symbols a and b both represent types of distributions, and may contain codes representing any of the common distributions listed in Table 3.2.

Table 3.2: Distribution Abbreviations

Symbol	Explanation
M	Markovian: exponentially distributed interarrival or service times
D	Deterministic: constant distribution
E_l	Erlang distribution with parameter l
G	General Distribution

Symbols c, e, and f all represent discrete values and are represented with the appropriate number or ∞ if there is no limit to the system size or population source. The service discipline, d, may be represented by any of the abbreviations explained below in Table 3.3.

Table 3.3: Service Disciplines

Symbol	Explanation
FCFS	First come, first served
FIFO	First in, first out (same as FCFS)
LCFS	Last come, first served
RSS	Random selection for service
PR	Priority
SIRO	Service in random order

The (*d/e/f*) term is often omitted, and in such cases the default assumptions are (FCFS/∞/∞). For example, an (M/D/3) queue would have exponential interarrival times, deterministic service rates, and three servers working in parallel. While not explicitly stated, a service discipline of first come, first served and infinite queue capacity and an infinite calling population are generally implied.

3.5 Queuing Systems in Mining

In mining operations, queues frequently form during the haulage process as trucks arrive at loaders, crushers, and dump locations and have to wait their turn in line. This process can be represented using queuing networks where the haul trucks represent the customers in the system and the servers are the loaders or crushers that the trucks are waiting for. When representing loading operations with queuing systems, the time a truck spends positioning and spotting at the loader can be included either as part of the loading cycle time or as part of the time the truck was waiting in the queue for service. Figure 3.3 below depicts a basic mining queuing system composed of haul trucks and excavators.

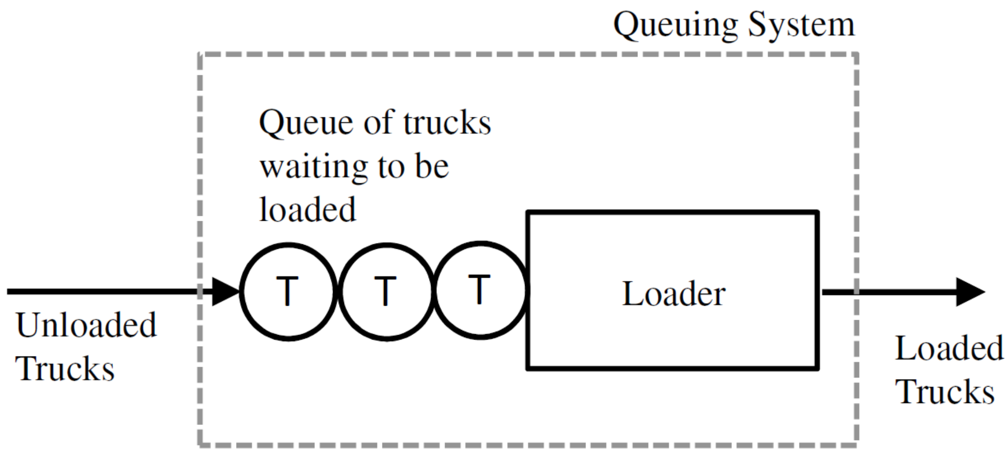

Figure 3.3: Truck and Loader Queuing System

Most basic haul routes have four main components: loading, loaded travel time, dumping of material, and unloaded travel time. These stages are repeated in sequence throughout the haulage system, and are easily represented by a cyclic queue, as shown below in Figure 3.4. In some cases the haul routes can be classified as servers in addition to the loader and the crusher, since the haul routes are necessary steps in the production cycle, and the amount of time it will take individual trucks to complete the trip is not constant throughout the production shift, so it is possible to assign a service distribution to the haul routes and treat them as servers, even though no queues will form since multiple trucks can be on the haul roads at the same time.

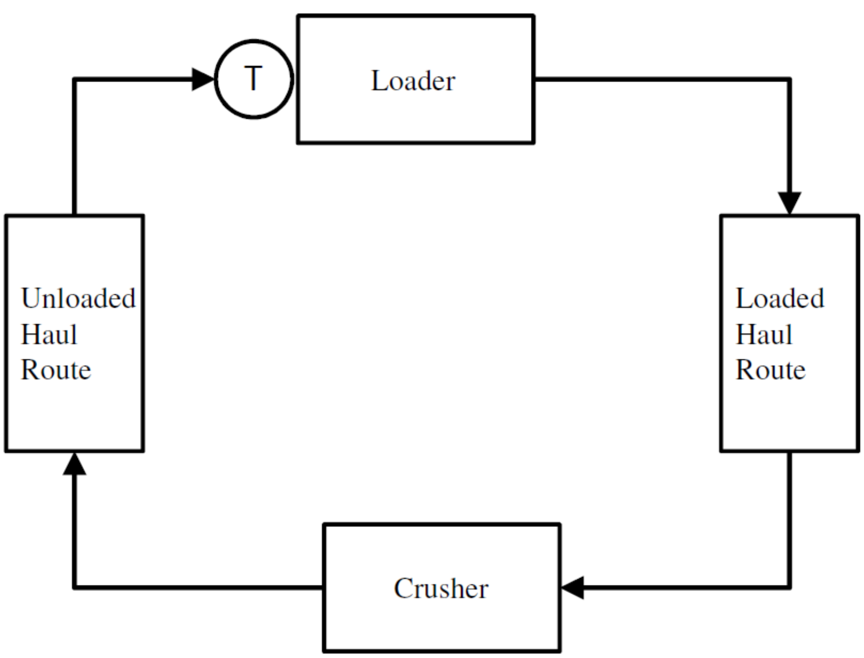

Figure 3.4: Cyclic Queuing System

The above cyclic queuing model can be adjusted to include multiple loaders, operating in parallel. Figure 3.5 below shows a possible configuration with three loaders with a single queue formed for trucks to wait to be loaded, but any number of loaders could be used.

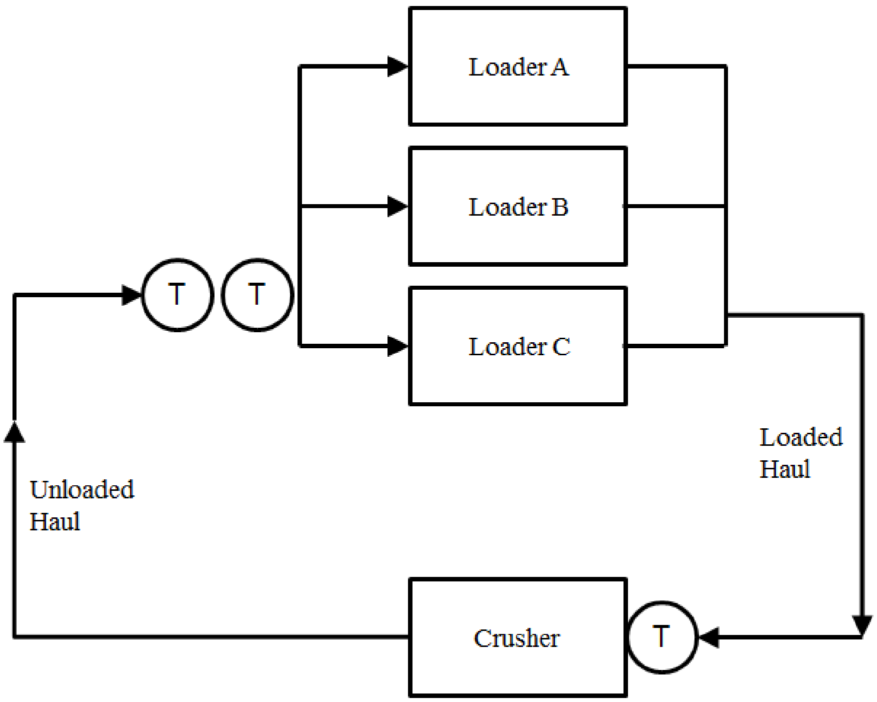

Figure 3.5: Cyclic Queuing System with Parallel Loaders

The cyclic queues represented above model the haulage systems for basic mine layouts. As the complexity of mining operations increases more intricate queuing systems must be used to represent operations. A network queue, such as the one depicted below in Figure 3.6 can be used when there are multiple paths available to the haul trucks. For this type of queuing model to work, metrics are necessary to determine the likelihood of each path being taken throughout the haul cycle. This could depend on the congestion of part of the system, the characteristics of each individual server, the contents of the truck's load, or a myriad of other factors.

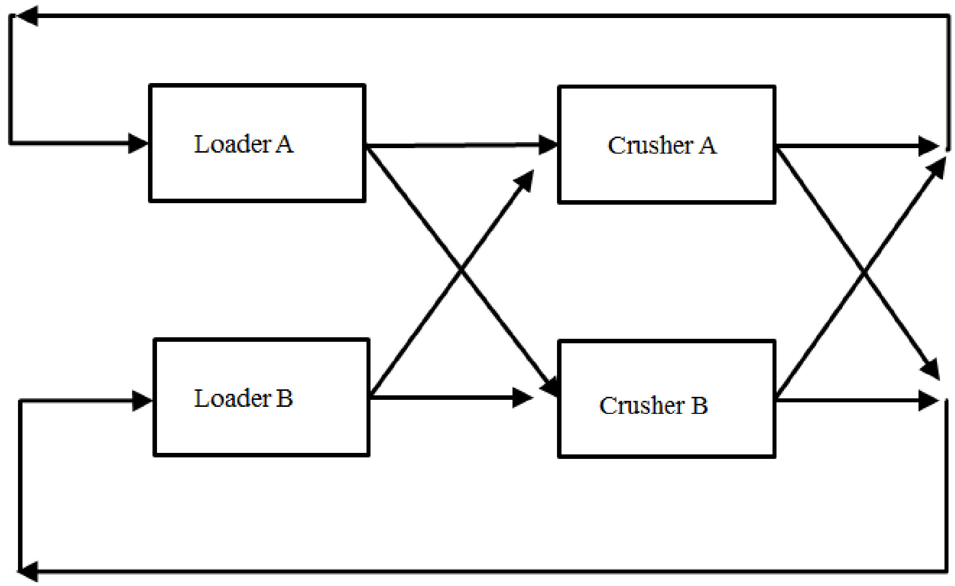

Figure 3.6: Network Queuing System

Mines that are simultaneously operating from more than one pit can treat each pit as separate, independent queuing networks provided they do not share any resources. If they do share resources, for example two separate pits sharing a single crusher, the operation must be treated as one queuing network with subsystems for each pit. An example of this type of configuration is shown on the following page in Figure 3.7.

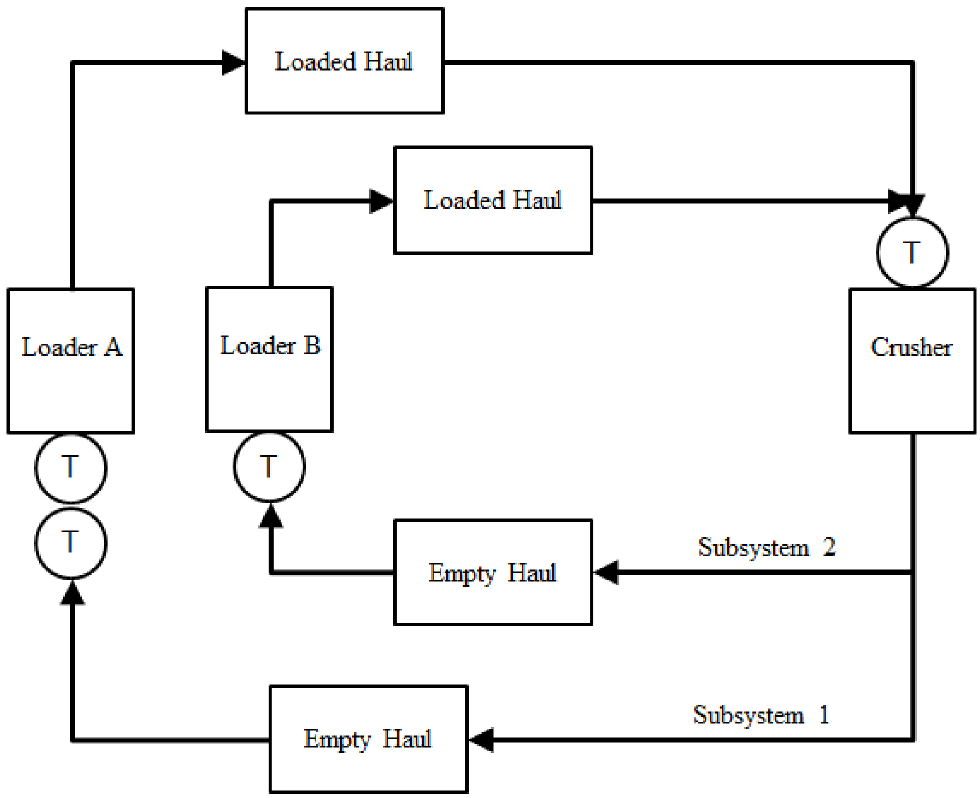

Figure 3.7: Queuing Schematic with Multiple Pits

3.6 Recent Applications of Queuing Theory to Mining

One recent mining application of queuing theory involves a closed queuing theory network assuming exponential distributions for loading, hauling, and dumping times. This model was developed to minimize production costs per amount of material moved. Production costs are incorporated by applying hourly costs to run each piece of equipment. Cost predictions for the system found using queuing theory were compared to the results found using a linear programming model and a case study for overburden removal at an open pit coal mine. Queuing theory provides the minimum loading and hauling costs for the system, along with an optimal number of trucks assigned to the shovels. When this system is implemented on the mine in question, the overburden removal target for the year is exceeded and average production costs are reduced (Ercelebi & Bascetin, 2009).

Another recent queuing mining project uses queuing theory to capture the nonlinear relationship between average mine throughput and the number of trucks in use, and then develops this relationship into an optimization model. The model includes options for single truck sizes or multiple truck sizes, and individual trucks are assigned a readiness parameter so that the model can indicate both how many trucks are necessary and which individual trucks ought to be used. Shovel service times and truck back-cycle times are represented with an Erlang distribution. The probability that a shovel is idle is linearized so that shovel throughput can be expressed as a linear function. This model is compared to simulation results and it is shown that the optimization model accurately predicts shovel utilization and idle time. Information about truck utilization and idle time is not calculated, but the optimization model provides valuable information about how many trucks should be used to meet necessary production targets (Ta, Ingolfsson, & Doucette, 2010).

3.7 Queuing Model

A model of a truck and shovel system for an open pit mine with multiple loaders operating within the pit was constructed using Microsoft Excel. This was done with the goal of providing a middle ground between very simplistic deterministic methods of analyzing haul truck fleet performance and complex, full-blown simulations that incorporate every aspect of mine activity. The rate of new haul truck arrivals and the loading rates of the excavators were both assumed to be exponential. An (M/M/c) queuing model was selected to follow this assumption of exponential service and interarrival times and to allow for various numbers of loaders to be selected. An (M/M/c) model is one in which each server has an independent and identically distributed exponential service-time distribution and an exponential arrival process. This model of pit behavior is versatile and can be used to model pit behavior for a variety of different haulage configurations and mine layouts. The service discipline used is first come first served, with the assumption that there are no special classes of trucks.

3.7.1 Inputs

To use this model, the values for the number of loaders operating, the arrival rate of new trucks, and the service rate per loader must be known to be used as inputs to the model. The necessary inputs are outlined on the following page in Table 3.4.

Table 3.4: Queuing Model Inputs

Symbol	Explanation
λ	Average arrival rate of new trucks
μ	Average service rate per loader
c	Number of loaders operating in parallel

The arrival rate, λ, is the average rate at which new trucks arrive at the loader. The service rate, μ, is the service rate of an individual loader. In cases with more than one loader in operation, all loaders are assumed to be equivalent, so μ would be the average service rate of the loaders. The arrival rate, λ, and service rate, μ, should both be input in the form of trucks per hour. Both the arrival rate and the service rate are independent of queue length. The queue will not have impatient customers, since it would be unrealistic for haul trucks to not join the line to be loaded, regardless of how many trucks are already waiting. There would also be no jockeying for position since trucks form a single line to wait to be loaded, with the first truck going to the next available loader. The model uses this information to calculate a variety of outputs about the truck and shovel system.

3.7.2 Equations

Based on this queuing system and input variables, the variables r and ρ are defined as,

$$r = \lambda/\mu \qquad \text{Equation 3.1}$$

and

$$\rho = r/c = \lambda/c\mu \qquad \text{Equation 3.2}$$

Where r is the expected number of trucks in service, or the offered workload rate, and ρ is defined as the traffic intensity or the service rate factor (Giffin, 1978). This is a measure of traffic congestion. When ρ > 1, or alternately λ > cμ where c is the number of loaders, the average number of truck arrivals into the system exceeds the maximum average service rate of the system and traffic will continue back up. For situations when ρ > 1, p_0, the probability that there are zero trucks in the queuing system is defined as

$$p_0 = \left(\sum_{n=0}^{c-1} \frac{r^n}{n!} + \frac{r^c}{c!\,(1-\rho)} \right)^{-1} \quad \text{Equation 3.3}$$

Where n is the number of trucks available in the haulage system. Even in situations with high loading rates, it is extremely likely that trucks will be delayed by waiting in line to be loaded. The queue length will have no definitive pattern when arrival and service rates are not deterministic, so the probability distribution of queue length is based on both the arrival rate and the loading rate (Gross & Harris, 1998). The expected number of trucks waiting to be loaded, L_q, can be calculated based on $p_0$using the following equation.

$$L_q = \left(\frac{r^c \rho}{c!(1-\rho)^2}\right) p_0 \quad \text{Equation 3.4}$$

The average number of trucks in the queuing system, L, and the average time a truck spends waiting in line, W_q, can be found by applying Little's formula which states that the long term average number of customers in a stable system, L, is equal to the long term average effective arrival rate, λ, multiplied by the average time a customer spends in the system, W (Gross & Harris, 1998). Algebraically, this is expressed as

$$L = \lambda W \quad \text{Equation 3.5}$$

and can also be applied in the form

$$L_q = \lambda W_q \quad \text{Equation 3.6}$$

Using these equations, the average time a truck spends waiting to be loaded, W_q can be calculated as follows.

$$W_q = \frac{L_q}{\lambda} = \left(\frac{r^c}{c!(c\mu)(1-\rho)^2}\right) p_0 \quad \text{Equation 3.7}$$

The average time a truck spends in the system, W, is defined as

$$W = W_q + \frac{1}{\mu} = \frac{1}{\mu} + \left(\frac{r^c}{c!(c\mu)(1-\rho)^2}\right) p_0$$ Equation 3.8

The model currently supports up to seven loaders operating in parallel, but could easily be adjusted to include more. There is no limit on haul truck fleet size, provided the arrival rate of trucks to the loading system does not increase to the point of overwhelming the loading capacity. This model is only valid for values of ρ, the traffic intensity per server, that are less than one. If ρ were to increase above one, the system would back up indefinitely, as the arrival rate of empty trucks would be greater than the loaders are capable of handling.

3.7.3 Outputs

When given the appropriate inputs, the model calculates and outputs values for various aspects of pit activity. These include loader utilization, the average time a truck spends in the system, the average time a truck spends waiting to be loaded, the average number of trucks waiting in line, the average number of trucks in the system, and the system output in trucks per hour. Table 3.5 below lists the outputs created by the model and the appropriate units for each variable.

Table 3.5: Queuing Model Outputs

Variable	Units	Description
ρ	%	Loader Utilization
W	hours	Time spent in system
W_q	hours	Time spent in queue
L	Number of trucks	Number of trucks in system
L_q	Number of trucks	Number of trucks in queue
θ	Trucks per hour	System output

Figure 3.8 on the following page shows a screenshot of the model. The values the user inputs are highlighted in yellow, and the intermediate calculations and final outputs are highlighted in green.

	A	B	C	D	E	F	G	H	I	J	K	L
1	M/M/c		Exponential service times									
2			Exponential interarrival times									
3			c servers									
4	Number of Servers, c	3			r =	1.71755		is = λ/μ, traffic intensity, aka service rate factor				
5	Arrival Rate, λ	23.1667	cars/hour		ρ =	0.57252		is = r/c, traffic intensity per server				
6	Service Rate (per server), μ	13.4882	cars/hour		Q =	0.74667						
7												
8												
9			n	n	n	n						
10	r	1.71755	0	1	2	3	4	5	6			
11	ρ	0.57252	2.97542	3.69297	3.45041	2.81987	2.33801	2.09997	2.01107			
12	p_0	0.09883										
13	number waiting, Lq	0.26146	Pn									
14	Time waiting in line, Wq	0.01129	0.00872	0.02371	0.03223	0.02921	0.02647	0.02399	0.02174			
15	Time in system, W	0.08542	0.02616	0.04741	0.03223	0	-0.02647	-0.04799	-0.06523			
16	Number in system, L	1.97901										
17	System Output (trucks/hour), θ	39.0376										

Figure 3.8: Screenshot of Model

3.8 Example Application

While this queuing model provides information about the system being modeled that is correct based on the equations of queuing theory, it is necessary to see if the actual behavior of trucks in a mine are consistent with the model. Haul truck data were obtained from a large surface gold mine located outside of the United States. Information about the haul trucks in this mine was obtained in the form of Global Positioning System (GPS) data. Each truck is equipped with a GPS unit that records the easting, northing, elevation, and speed at regular time intervals. This information, combined with the contour map of the mine, allows the complete haul route to be examined.

3.8.1 Data

Haul truck GPS information was obtained in the form of .dat files containing thousands of data points, each with a time stamp, truck number, truck speed, and location based on easting northing and elevation. Truck speed is reported in kilometers per hour, and all of the time stamps are in the format of seconds beginning January 1, 1970. When this information is imported into AutoCad along with the mine map it is possible to determine information about loading locations, haul routes, dumping locations, and areas where trucks are waiting. The data files were formatted so that AutoCAD Civil 3D could plot each haul truck location on a contour map of the mine property and store the truck ID number, time stamp, and corresponding velocity for each point.

This mine, shown below as a contour map in Figure 3.9 has four separate pits, three of which were in operation at the time of the study. Only the northernmost and southernmost pits will be examined, since the third operational pit was only minimally active during the time of study.

Figure 3.9: Contour Map of Entire Mine Property

This mine operates 24 hours per day with a total of approximately 30 haul trucks in use. While it is unclear whether or not all of the trucks in operation have the same loading capacity, none of the trucks are assigned a higher priority than the other. In all cases, the first trucks are handled on a first come, first served basis. The northernmost pit, shown below in Figure 3.10, is in the beginning stages of mining and operates with one loader and between five and eight trucks. This pit currently only reaches a depth of approximately 30 feet.

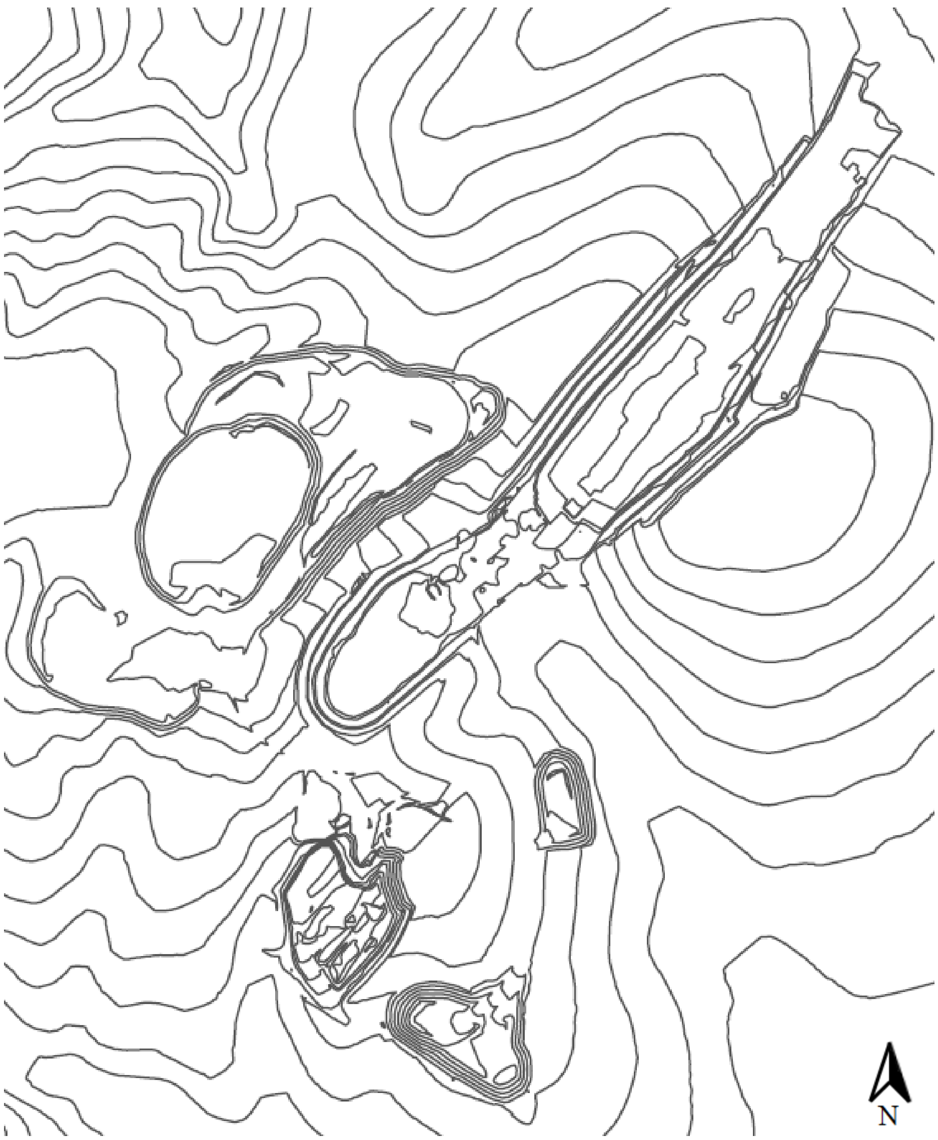

Figure 3.10: Contour Map of North Pit

The south pit, shown on the following page in Figure 3.11, has a depth of 130 feet and operates with between 22 and 27 trucks and alternates between having two loaders and three loaders in operation. The large waste dump location northwest of the pit is no longer in use, so waste material is now being dumped at the smaller mound located west of the pit. The trucks also carry material to a crusher, which is located southwest of the pit, at the end of the haul ramp.

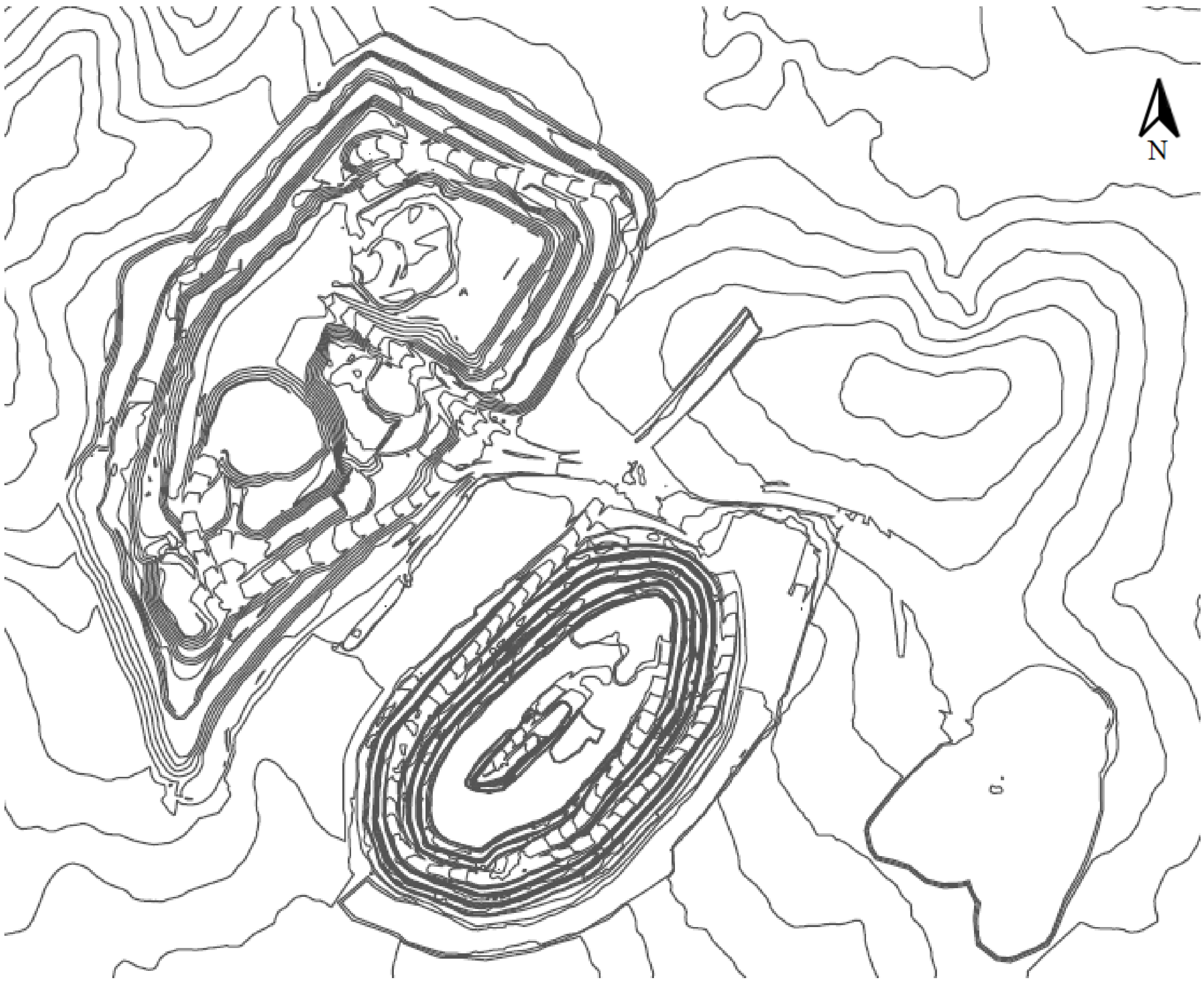

Figure 3.11: South Pit Contour Map

3.8.2 Haul Routes

Both ore and waste material are mined in the pits, so loaded trucks will travel to either the crusher to dump ore or to the spoils pile to dump waste material. The route trucks take to dump waste material from the south pit onto the waste pile is shown on the following page in Figure 3.12 with the route highlighted in red.

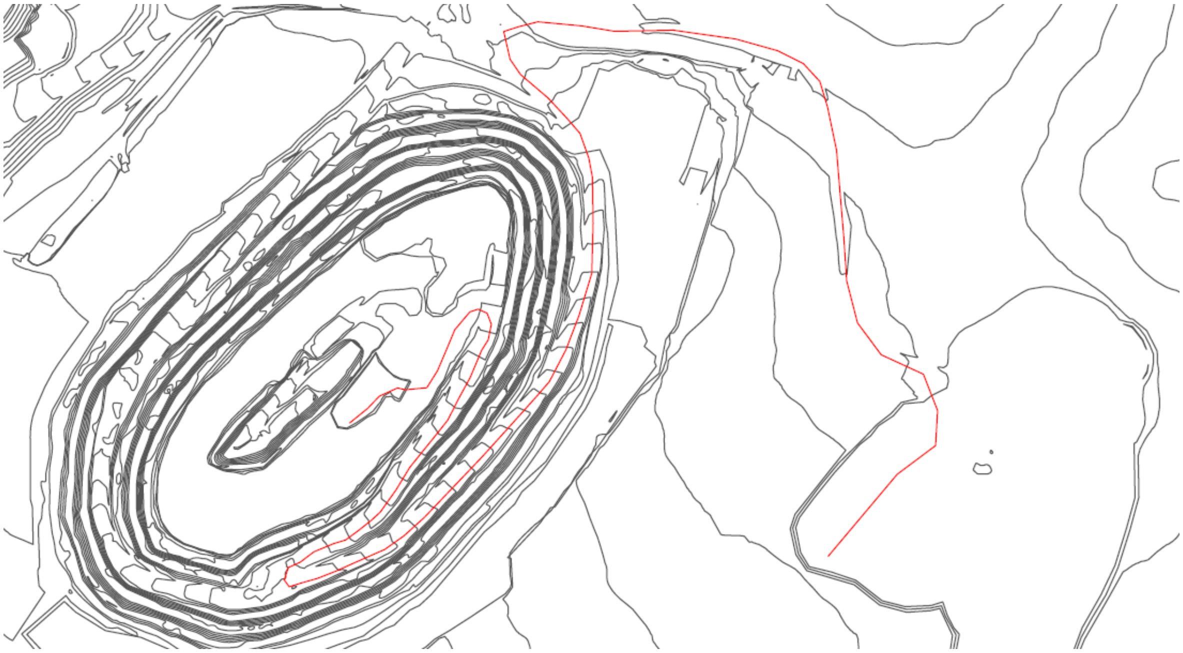

Figure 3.12: Haul Route from Pit to Waste Dump Location

The route trucks loaded with ore take to the crusher is shown below in Figure 3.13, highlighted in red.

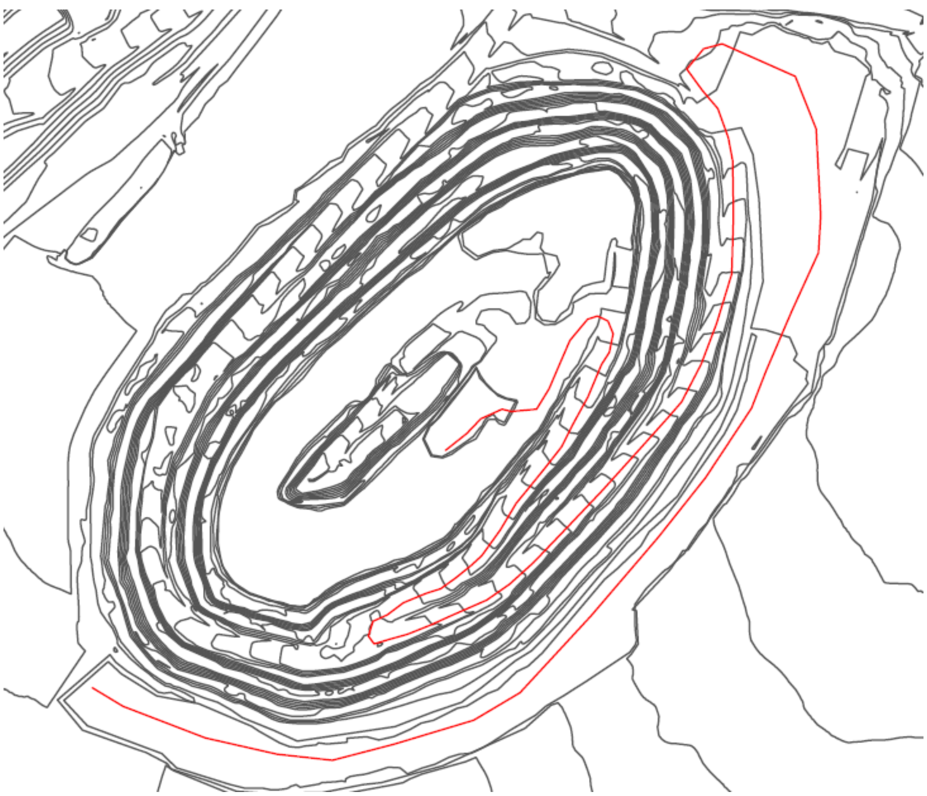

Figure 3.13: Haul Route from Pit to Crusher

3.8.3 Loading

Loading areas are identified based on the locations where haul trucks are stopped in the pit. This was accomplished by importing the data from a particular shift into Microsoft Excel and filtering the points based on truck velocity. Points where trucks had a velocity of zero were selected and imported onto an AutoCAD contour drawing of the mine to show locations where vehicles were stopped. The trucks could be stopped either to wait for service or while receiving service at the loaders or dumping locations. As shown below in Figure 3.14 with points representing locations where haul trucks are stopped, the locations where the three loaders were operating are clearly identifiable by the clusters of points representing stopped trucks throughout the shift.

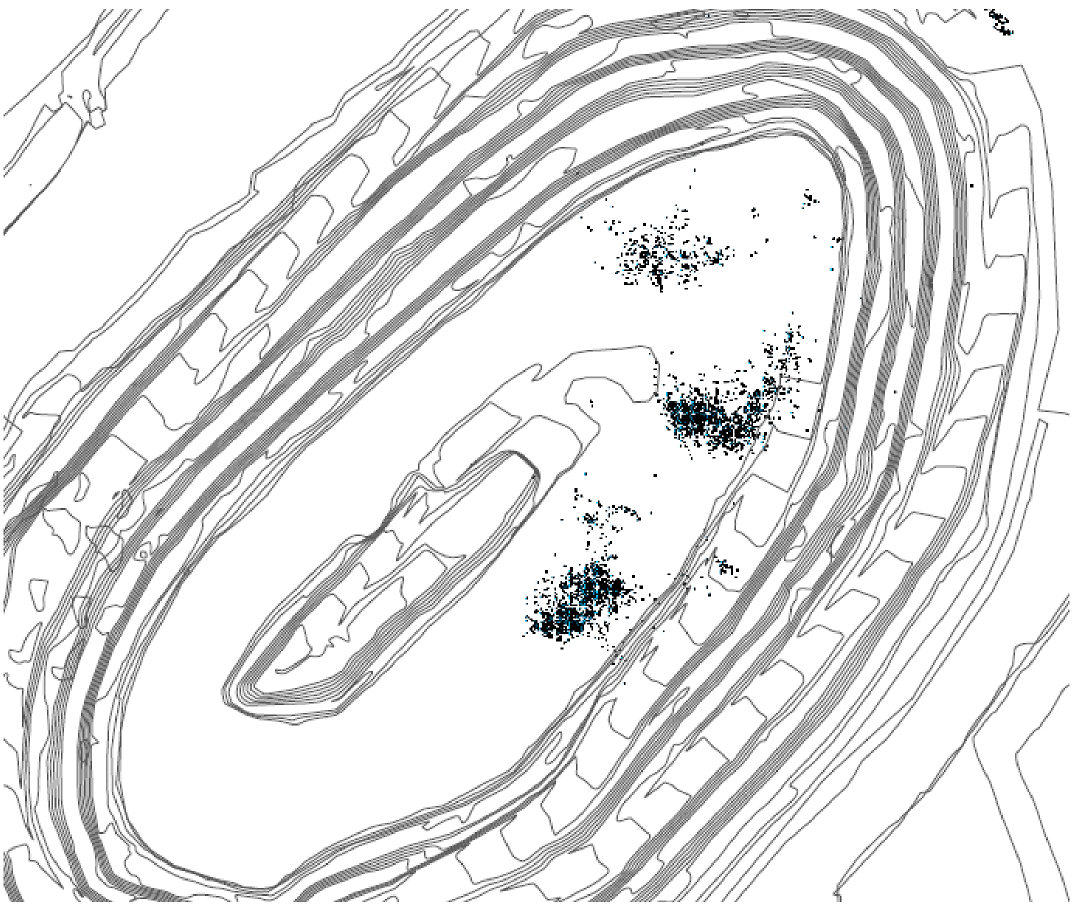

Figure 3.14: South Pit Loading Locations

The data points of haul trucks stopped in the loading areas were isolated from the rest of the data. These points were sorted based on truck number, and for each truck the time stamp for when a new loading cycle began was recorded. This was determined based on the amount of time that had passed between data points for an individual truck. Since only data points located within the loading area were being considered, a large time gap meant that the truck had left the loading area during that interval, so the next data point represents a new arrival.

Once the new arrival time stamps for all of the trucks active during this time period had been recorded they were combined to form a list of all of the new truck arrivals for that shift. These times were then used to calculate the distribution of arrival times of haul trucks to be loaded. The amount of time between each new arrival was calculated by subtracting the difference between each successive time stamp of arriving haul trucks. For these purposes, a new arrival is defined as when the haul truck first comes to a stop within the pit limits. The times between arrivals were sorted into bins and used to create a graph of frequency vs. time between new arrivals. Frequency is represented as a percentage of the total number of arrivals that occurred during the shift. Figure 3.15 below shows an example of this type of plot, created using data from twelve hours of production in the south pit with twenty two trucks in operation.

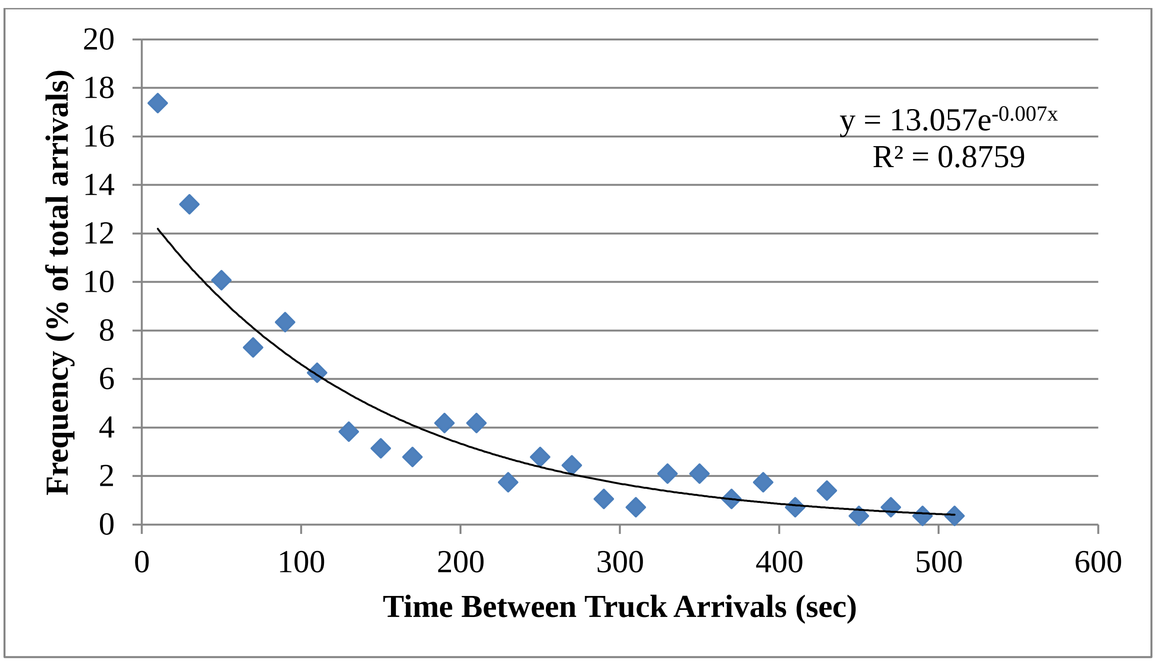

Figure 3.15: South Pit Arrival Distribution

Various equations were applied to the data and it was found that the exponential equation is an adequate fit for the interarrival times of haul trucks in the south pit. The same process was applied to trucks operating in the north pit, but there were not enough trucks operating in that pit to yield any discernible distribution of arrival times. Figure 3.16 on the following page shows the frequency of interarrival times for that pit over a full shift. It is clear that the data do not form a distribution. Haulage operations such as this one cannot be modeled using queuing theory, since a distribution could not adequately represent interarrival times in the system.

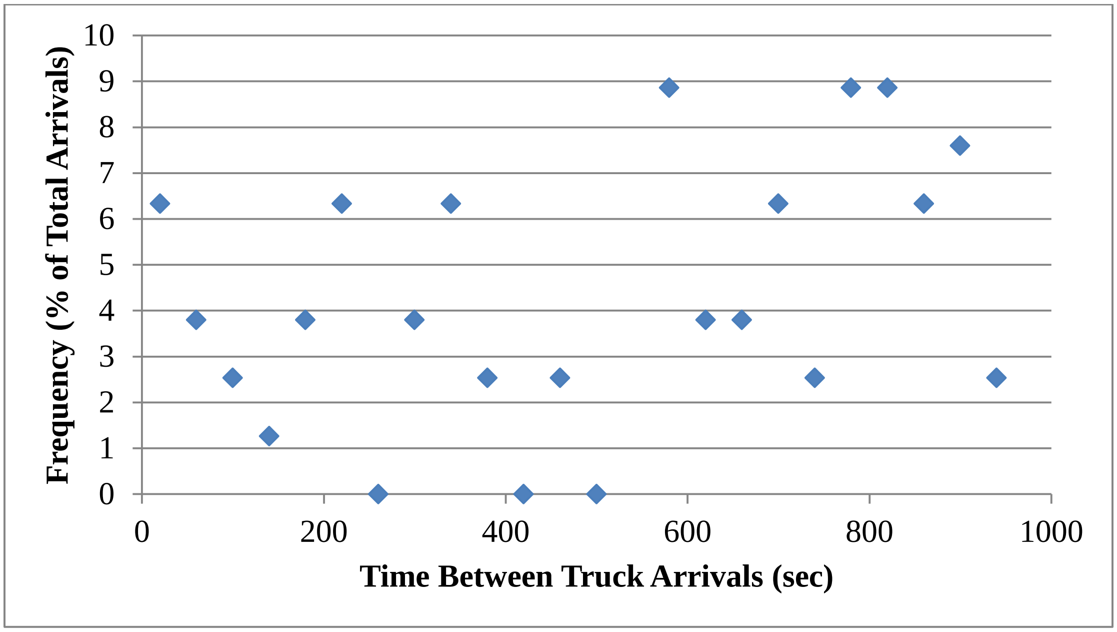

Figure 3.16: North Pit Interarrival Times

<u>3.8.4 Service Times</u>

The loading service time distributions were more difficult to obtain, since the GPS information does not differentiate between times when a truck is stopped because it is waiting to be loaded and times when a truck is stopped while being loaded. The service times for individual loaders were determined by isolating the data points corresponding to each loader operating in the pit and identifying the time stamp that corresponds to each time the truck left that specific loading area. Similar to how arrival times were determined, the departure times were identified as the last time a particular truck was in the loading area before a large time gap.

Once all of the time stamps corresponding to trucks departing from the loader had been recorded, they were combined to form a list of all of the truck departures for that loader during that work shift. These times were then used to calculate the distribution of service times for the loader. The amount of time between each departure was calculated by subtracting the difference between each successive time stamp of departing loaded haul trucks. This difference in times between successive truck departures represents the amount of time it takes for a loader to service one haul truck. This method includes the truck’s spotting time as part of the service time. The times between departures were sorted into bins and used to create a graph of frequency vs. time between new arrivals. Frequency is represented as a percentage of the total number of departure times calculated for the shift. Figure 3.17 below shows an example of this type of plot for one loader, created using data from twelve hours of production in the south pit with twenty two trucks in operation.

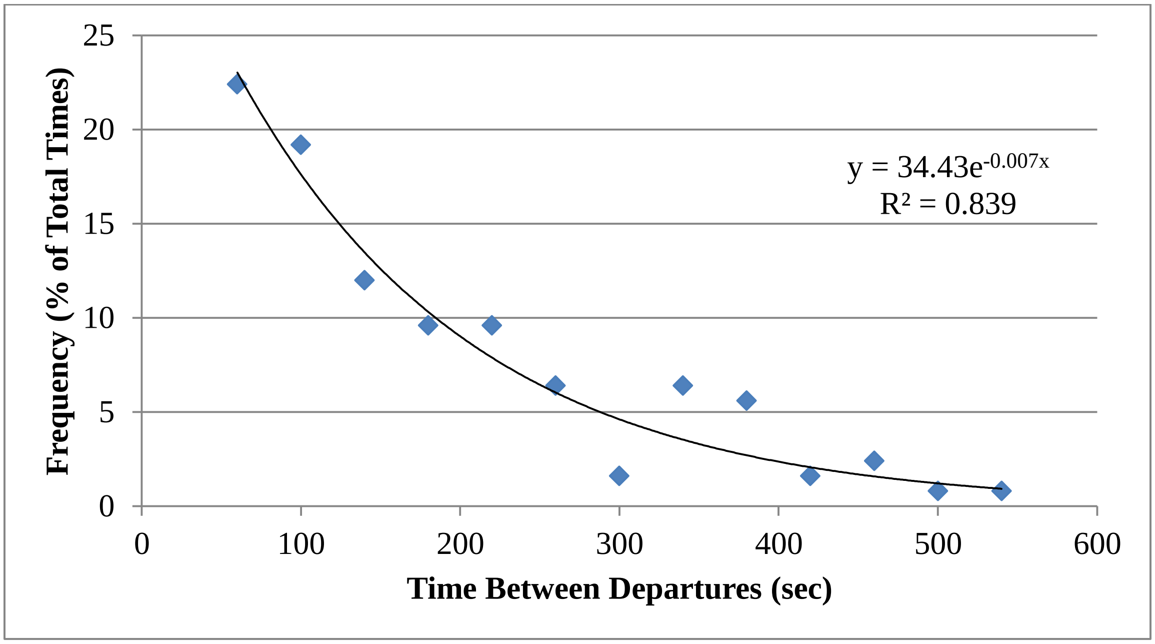

Figure 3.17: Service Distribution for a Single Loader

3.8.5 Validation of Model and Results

The mining operations in the north pit do not fit any distribution, and cannot be represented using mathematical equations. In the south pit, both the interarrival times of new trucks to the pit and the service rates of the loaders fit exponential distributions. Data from the mining operations in the south pit can be used as inputs for the queuing model created, since it fulfills the requirements of exponential arrival distributions and service rates. Not all mining operations will be able to be applied to the model, since they will not all have similarly distributed loading and interarrival rates, as evidenced by the north pit, which clearly does not meet these requirements.

The south pit of the mine described operates with either two or three loaders in the pit depending on the shift and the haul trucks dump ore at the crusher and waste material at the dump site as previously described. Figure 3.18 below is a queuing schematic of the haulage operations for the south pit.

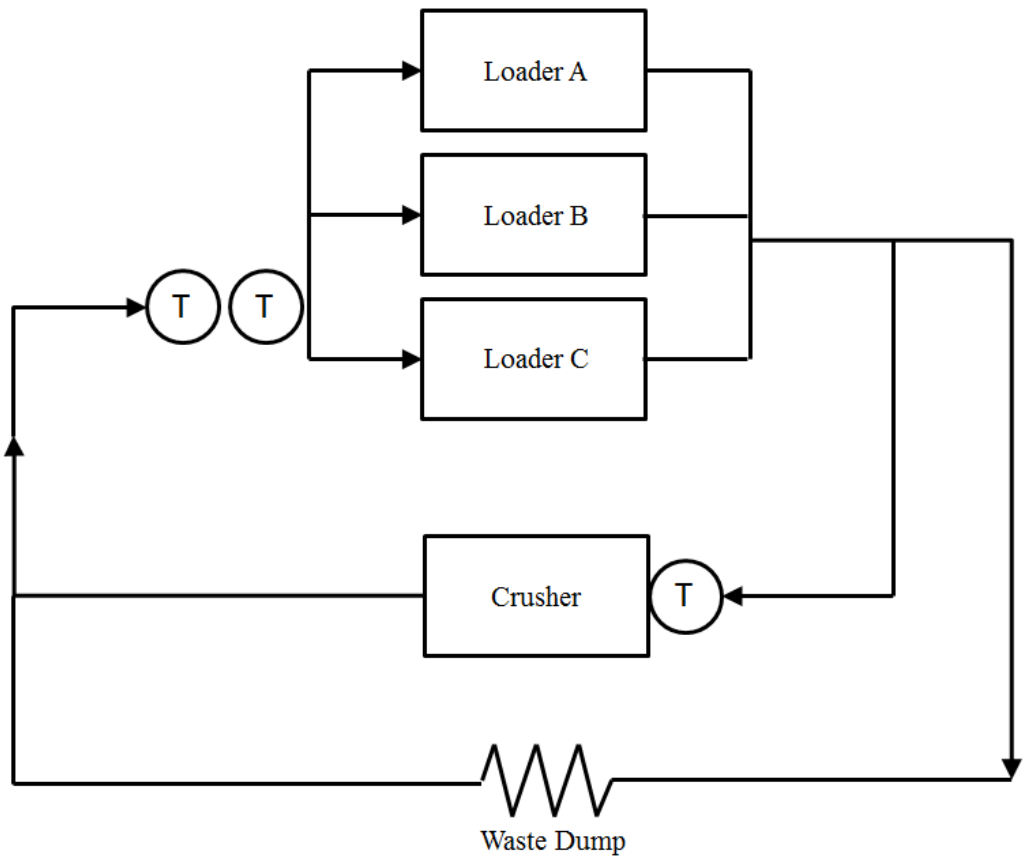

Figure 3.18: Queuing Schematic of Mine Haulage Route

The queuing model developed can be applied to the pit operations of this mine, represented by the top half of the above schematic. The arrival and service distributions for the south pit operations have been confirmed to fit exponential distributions, so an (M/M/3) queuing model is appropriate for this application. Loaded haul trucks exiting the queuing system of the pit will either travel to the crusher or the waste dump before returning to the pit to be loaded again. Which dumping location a truck will utilize is dependent upon whether the loader filled the truck with ore or waste material, and varies according to the geology of the ore body in the pit and the cutoff grade the mine is using. A metric that includes this information would be necessary to expand the current queuing model to apply to the entire haulage system, and is beyond the scope of this project.

Haul truck data from a twelve hour shift the night of July 23, 2012 was examined and used to verify the queuing model created. A table of all relevant data from this twelve hour operating period is available in Appendix A: Haul Truck Data. The service and arrival rates for this shift were confirmed to fit exponential distributions. This shift began operations with three loaders and 22 haul trucks, but one loader was taken out of service approximately five hours into the shift, leaving two loaders working in the pit. Table 3.6 below contains the loading data, analyzed on an hourly basis. The number of new arrivals was calculated for each hour, and a service rate of 13.48 trucks per hour was used for the entire shift, since it is difficult to get a good measure of the service rate by only looking at one hour's worth of data at a time.

Table 3.6: Hourly Loading Data

Begin Time	End Time	Number of Loaders	Arrivals per Hour	Service Rate (trucks/hr)	Average Number in System
1343067870	1343071470	3	31	13.48	3.12
1343071470	1343075070	3	31	13.48	3.29
1343075070	1343078670	3	25	13.48	2.55
1343078670	1343082270	3	27	13.48	2.64
1343082270	1343085870	3	29	13.48	3.24
1343085870	1343089470	2	22	13.48	4
1343089470	1343093070	2	22	13.48	3.15
1343093070	1343096670	2	23	13.48	3.41
1343096670	1343100270	2	26	13.48	2.93
1343100270	1343103870	2	23	13.48	4.17
1343103870	1343107470	2	23	13.48	3.52

In order to have an actual value to which the model output variables can be compared, the total number of trucks in the system, L, was calculated at three minute time intervals for this particular shift. This was done by isolating all of the data points for trucks inside of the pit and counting the number of different truck IDs during any given three minute interval. A three minute interval was selected to ensure that the sampling window would be large enough to include a data point from each truck in the pit, since the GPS units only created data points for trucks on approximately thirty second intervals during times when the trucks location and velocity were not changing. Three minutes is also shorter than the majority of the service times, so it was selected as the interval to be used when determining the actual number of trucks in the system.

The loading rate and average arrival rates for each hour segment were entered into the queuing model, using an (M/M/3) model for the first five hours of the shift and an (M/M/2) model for the remainder, since the number of loaders in operation changed during the shift. Table 3.7 below contains the outputs generated by the queuing model, based on the inputs from Table 3.6. The model calculated the average number of trucks in the pit system (L), the number of trucks waiting for service (L_q), the average amount of time trucks spent in the pit system (W), the average amount of time trucks spent waiting for service (W_q), and server utilization (ρ).

Table 3.7: Queuing Model Outputs for Hourly Data

Hour	L	L_q	W (hours)	W_q (hours)	ρ (%)
1	3.187	0.888	0.103	0.029	76.6
2	3.187	0.888	0.103	0.029	76.6
3	2.201	0.348	0.088	0.014	61.8
4	2.474	0.472	0.091	0.018	66.7
5	2.793	0.643	0.096	0.022	71.7
6	3.5	1.869	0.159	0.085	81.6
7	3.5	1.869	0.159	0.085	81.6
8	4.248	2.543	0.185	0.111	85.3
9	14.87	12.94	0.572	0.498	96.4
10	4.248	2.543	0.185	0.111	85.3
11	4.248	2.543	0.185	0.111	85.3

The shift was also analyzed as a whole, broken down into the segments with 3 and 2 loaders. The average arrival rates and service rates were calculated and used as inputs for the model. These results are shown below in Table 3.8.

Table 3.8: Queuing Model Outputs for Entire Shift

	L	L_q	W	W_q	ρ	θ
3 loaders	2.724	0.604	0.095	0.021	70.7	39
2 loaders	4.408	2.69	0.19	0.116	85.9	26.4

To see if the model's outputs match the actual results, the expected number of trucks in the system, L, was compared to the actual number of trucks in the system for these timeframes. The predicted results were plotted vs. the actual results, as shown in Figure 3.19.

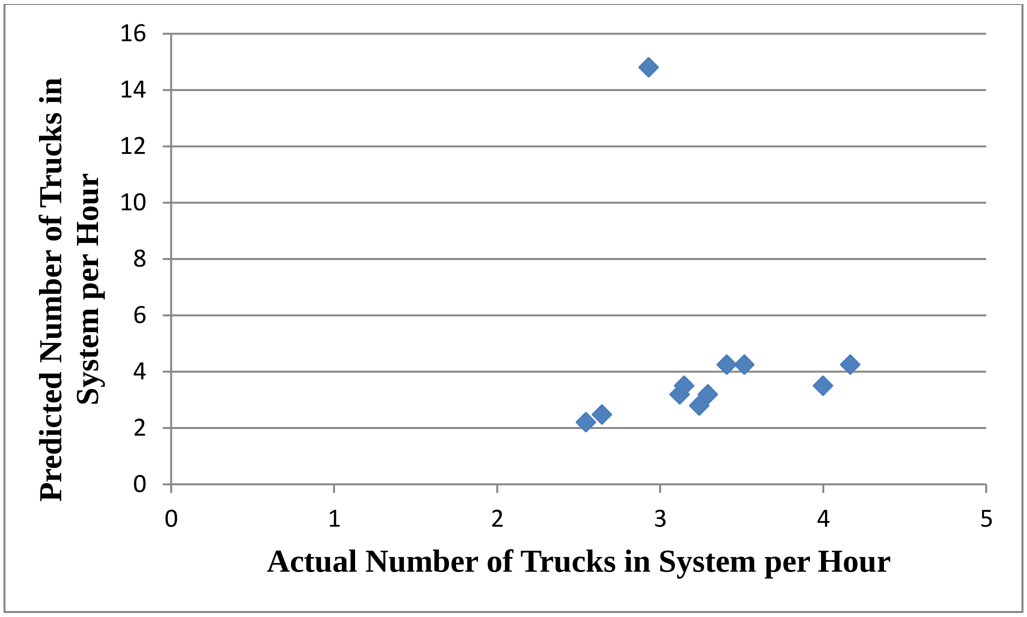

Figure 3.19: Predicted vs. Actual Number of Trucks in System

The results show a fairly linear relationship with one noticeable outlier. As is shown in Table 3.6, the ninth hour of operation had a larger than expected number of new truck arrivals. It is not clear how this was handled in the pit, but the actual system was not nearly as congested as the model anticipated it would be. When this outlier is removed, the overall results are reasonably linear, as shown below in Figure 3.20.

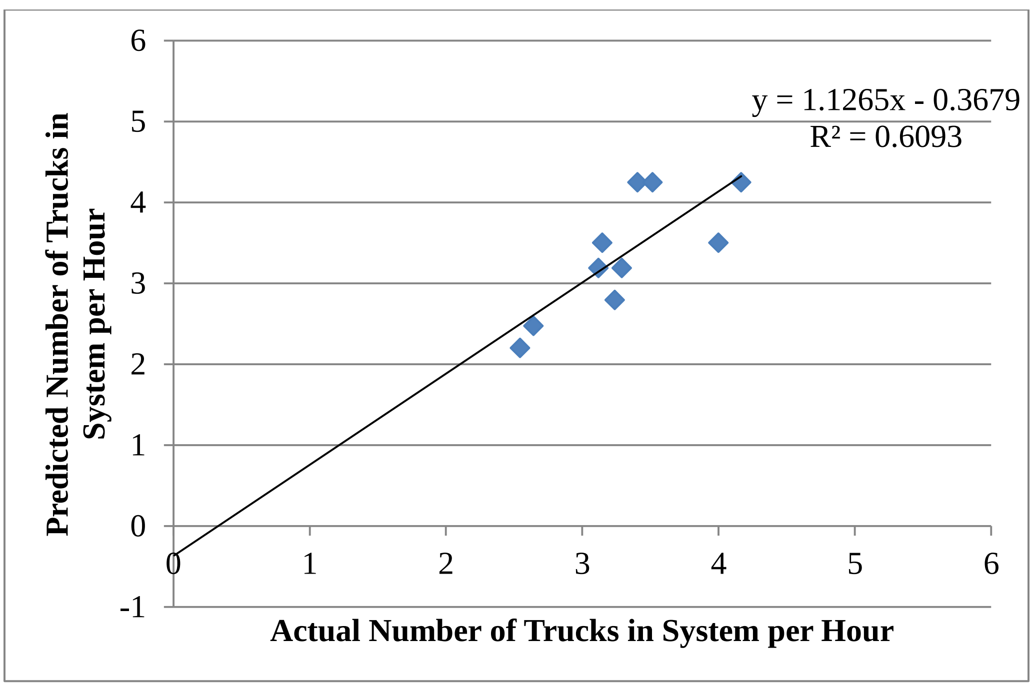

Figure 3.20: Predicted vs. Actual Number of Trucks in System with Outlier Removed

The line of best fit created in the previous graph was modified to force the line through the origin, since there can never be a negative number of trucks in the system. The resulting modified graph is shown below in Figure 3.21.

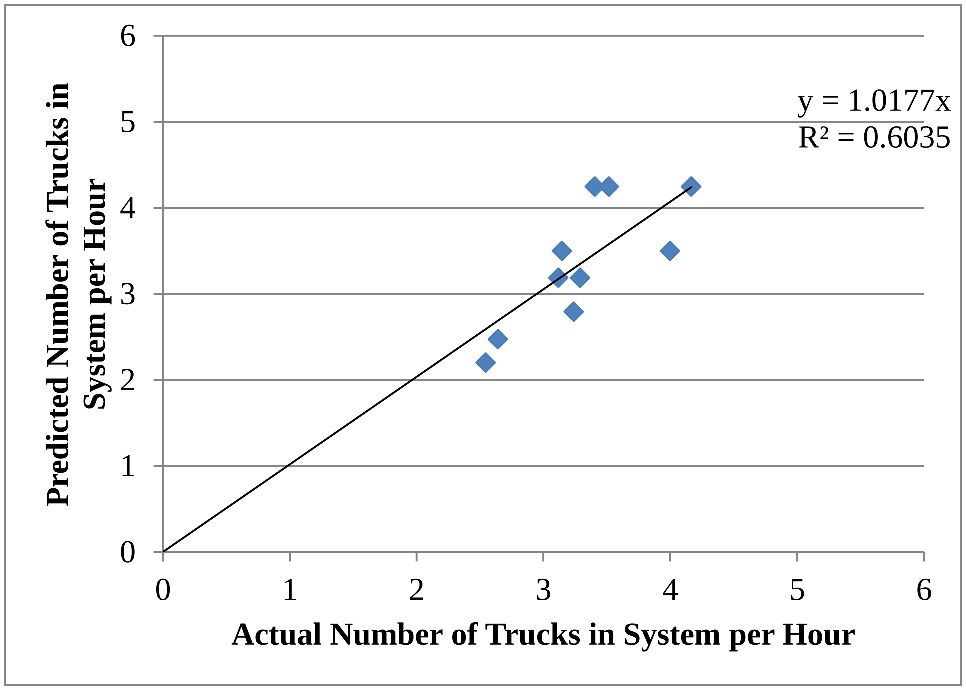

Figure 3.21: Predicted vs. Actual Number of Trucks in System, Modified

The relationship between the predicted number of trucks in the system and the actual number of trucks in the system is very close to 1 to 1, indicating that the outputs of the (M/M/3) queuing model can accurately describe the state of the haulage system being modeled.

3.9 Analysis

This queuing model is useful for analyzing the efficiency of mining haulage and loading operations for the configurations in which they are currently operating. The amount of time trucks spend waiting to be loaded, W_q, and the server utilization, ρ, are both indicators of how efficiently the system is operating. The larger the values of W_q, the longer trucks are spending idling waiting at the loaders, burning fuel without contributing to the haulage process. The server utilization indicates what proportion of operational time loaders are actually in use. Both of these values can be combined with costing data for the equipment in use to find out how much money is being spent on idling equipment.

For example, a pit system operating with two loaders, an arrival rate of 16 trucks per hour, and a service rate of 12 trucks per hour per loader is found to have a loader utilization of 66.7%, a system output of 23.5 trucks per hour, and an average of 0.0435 hours spent waiting in the queue per truck for each loading cycle. Since each truck passing through the system would potentially have to spend time waiting at the loader, the system output multiplied by the average time spent waiting in the queue is the average amount of time trucks are idling in the pit per hour. Over an eight hour shift, this comes to a combined total of 8.18 hours of truck idling time. Based on the loader utilization, each loader was not in use for 33.3% of the shift. This comes to a total of 5.34 hours of idle time between the two loaders for the eight hour period. This mine could be operating a pair of EX2600 hydraulic shovels with a fleet of CAT 793D haul trucks, which cost $421 per hour and $356 per hour respectively to operate (InfoMine). This comes to a total of $5,158.54 spent on idling equipment during one eight-hour shift. If the haulage operations were adjusted, either by changing the number of loaders operating or adjusting the fleet size, the new arrival rate that results can be used to run the model again, and see whether the changes made would be valuable to the system in terms of the cost to operate unnecessary equipment.

If there are usually multiple trucks waiting for the loaders, as indicated by L_q, it would likely be beneficial to decrease the fleet size to reduce the amount of time trucks are spending waiting to be loaded. Changes to the queuing model can be made by adjusting the arrival rate of new trucks to the system to see how the system would react to trucks arriving more or less frequently. While this is similar to comparing the effects of adding or removing trucks to the system, the amount of change in arrival rate caused by changing the fleet size will vary depending on the specific characteristics and layout of each mine.

As the model currently exists, the effects of changes to fleet size can only be examined if the changes are actually made in the pit, the new inputs are determined, and the model is run again. This is due to the fact that the arrival rate, which is a necessary queuing input, is dependent upon more than just the number of trucks in the system. To determine an optimal fleet size for a given mine layout and loading configuration without running a full simulation, it may be more useful to use models involving stochastic simulation, such as Monte Carlo simulation to incorporate haul routes, travel times, and fleet sizes. This would allow various fleet sizes and configurations to be compared without having to make real world changes to acquire additional inputs for the model, as would be necessary for the queuing model. The queuing model can analyze the efficiency of haulage systems as they currently exist, but it cannot be used alone to optimize haulage operations, since the arrival rate being used in the model depends on more than simply the number of trucks in operation.

Chapter 4: Summary and Conclusion

4.1 Summary

The haulage process undertaken by haul trucks in open pit mines can be represented as cyclic or network queues, or broken down into individual components which can each be treated as single or multichannel queues. In queuing notation, trucks are treated as customers in a system where loaders are the servers. Trucks arrive to be loaded and form a queue if the loaders are busy.

An (M/M/c) queuing model was developed to model truck and shovel interactions within the pit. This model makes the assumption of exponentially distributed truck interarrival times and service times, and can be applied to operations with seven or fewer loaders. To apply this model the user must know the average arrival rate of new trucks to the system, λ, the number of loaders, and the average service rate per loader, μ. Based on these inputs, the model calculates several outputs describing system behavior. Table 4.1 below lists the outputs created by the model along with their associated units and descriptions.

Table 4.1: Model Outputs

Variable	Units	Description
ρ	%	Loader Utilization
W	hours	Time spent in system
W_q	hours	Time spent in queue
L	Number of trucks	Number of trucks in system
L_q	Number of trucks	Number of trucks in queue
θ	Trucks per hour	System output

These outputs can be used to measure the efficiency of haulage operations based on their current configurations. If changes are made to the system, new values for the average interarrival times and service rates would need to be calculated so that the model could be run again to compare the efficiency of the new system to the values before changes were made.

4.2 Conclusion

Queuing theory can be used to model truck and shovel behavior in open pit mines. The (M/M/c) model developed is consistent with the data from one open pit operation. Exponential interarrival times and exponential service times are consistent with the data from this mine, so the assumptions of the model are valid for some operations.

The (M/M/c) model is capable of analyzing haulage systems as they currently exist and can be used to evaluate the efficiency of operations based on their current fleet sizes. This can also be combined with costing data for the equipment in use to find out how much money is being spent to operate idling equipment that is not directly contributing to production.

As the model currently exists, the effects of changes to fleet size can only be examined if the changes are actually made in the pit, and the model is run again using new inputs, calculated after the changes had been made. This is due to the fact that the arrival rate, which is a necessary queuing input, is dependent upon more factors than just the number of trucks in the system.

While queuing theory can be used to model haulage operations at some mine sites, it may not be the best or the easiest method to use for fleet analysis. Queuing theory can only be applied to mining operations where the arrival times of trucks to the pit and service times of the loaders can be fit to distributions. For operations that meet these requirements, inputs for the model must be obtained from active mining operations, and changes to the system can only be run through the model after these changes have been implemented in the field and used to obtain new inputs for the model.

To determine an optimal fleet size for a given mine layout and loading configuration without running a full simulation, it may be more useful to use models involving stochastic simulation, such as Monte Carlo simulation, to incorporate haul routes, travel times, and fleet sizes. This would allow various fleet sizes and configurations to be compared without having to make real world changes to acquire additional inputs for the model, as would be necessary for the queuing model. This type of stochastic model could also be used in situations when queuing theory is not applicable, for example in mines where the loading operations do not fit the distributions necessary for queuing theory to be applied. The queuing model can analyze the efficiency of haulage systems as they currently exist, but it cannot be used alone to optimize haulage operations, since the arrival rate being used in the model depends on more than simply the number of trucks in operation.

4.3 Future Work

The (M/M/c) model developed can be expanded upon and customized to individual mine layouts to include the rest of the haulage route, and not just the activities located in the pit. Because of the large variety of different haul routes used at different mine locations, this queuing network would be different for every individual mine, so the model would need to be tailored to each specific operation.

In addition to expanding the queuing system to involve hauling and dumping activities, the model could be altered to incorporate the number of trucks in operation to affect the interarrival rate. This rate would vary as mining progressed and the haul route becomes longer, and would also be site-specific.

Works Cited

Alkass, S., El-Moslmani, K., & AlHussein, M. (2003). A Computer Model for Selecting Equipment for Earthmoving Operations Using Queuing Theory. Montreal, Canada: Concordia University.

Barbaro, R., & Rosenshine, M. (1987). Evaluating the Productivity of a Shovel-Truck Materials Haulage System using a Cyclic Queueing Model. In *AIME Transactions Volume 282* (pp. 1824-1827). Society of Mining Engineers of AIME.

Barnes, R. J., King, M. S., & Johnson, T. B. (1979). Probability Techniques for Analyzing Open Pit Production Systems. In *16th Application of Computers and Operations Research in the Mineral Industry - 1979* (pp. 462-476). SME.

Billette, N. R. (1986). Haulage System Capacity: Analytical and Simulation Models Revisited. In *19th International Symposium 1986 - Application of Computers and Operations Research* (pp. 355-364). SME.

Burton, A. K. (1975). Off-Highway Trucks: How to Calculate Truck Fleet Requirements. In *Mining Engineering 1975 Vol. XXVII* (pp. 36-43). AIME.

Carmichael, D. G. (1987). *Engineering Queues in Construction and Mining.* Chichester, West Sussex, England: Ellis Horwood Limited.

Çetin, N. (2004, September). Open Pit Truck/Shovel Haulage System Simulation. Middle East Technical University.

Cooper, R. B. (1972). *Introduction to Queueing Theory.* New York: The Macmillan Company.

Czaplicki, J. M. (2009). *Shovel-Truck Systems: Modelling, Analysis and Calculation.* London: CRC Press.

Deshmukh, S. S. (1970). Sizing of Fleets In Open Pits. In *Mining Engineering 1970 Vol. XXII* (pp. 41-45). AIME.

Elbrond, J. (1977, October). Calculation of an Open Pit Operation's Capacity. St. Louis, Missouri: SME.

El-Moslmani, K. (2002, May). Fleet Selection for Earthmoving Operations using Queueing Method. Montreal, Canada: Concordia University.

Ercelebi, S. G., & Bascetin, A. (2009). Optimization of Shovel-Truck System for Surface Mining. *The Journal of The Southern African Institute of Mining and Metallurgy* , 433-439.

Giffin, W. C. (1978). *Queueing: Basic Theory and Applications.* Columbus, Ohio: Grid, Inc.

Gross, D., & Harris, C. M. (1998). *Fundamentals of Queueing Theory*. New York: John Wiley & Sons, Inc.

Hartman, H. L., & Mutmansky, J. M. (2002). *Introductory Mining Engineering.* Hoboken, NJ: John Wiley & Sons, Inc.

InfoMine. (n.d.). *Mining Cost Service*. Retrieved 2012, from CostMine: www.costs.infomine.com

Koenigsberg, E. (1958). Cyclic Queues. *Operational Research Quarterly*, 22-35.

Krause, A., & Musingwini, C. (2007, August). Modelling Open Pit Shovel-Truck Systems Using the Machine Repair Model. *The Journal of The Southern African Institute of Mining and Metallurgy*, pp. 469-476.

Maher, M. J., & Cabrera, J. G. (1973). The Transient Behavior of a Cyclic Queue. *Operational Research Quarterly*, 603-613.

Muduli, P. K., & Yegulalp, T. M. (1996, March). Modeling Truck-Shovel Systems as Multiple-Chain Closed Queuing Networks. Phoenix, Arizona: SME.

Najor, J., & Hagan, P. (2004). Mine Production Scheduling within Capacity Constraints. Sydney, Australia: The University of New South Wales.

Runge. (2011). *Tapac Fact Sheet*. Retrieved May 25, 2011, from http://www.runge.com/en/technology_solutions/talpac

Ta, C. H., Ingolfsson, A., & Doucette, J. (2010). Haul Truck Allocation via Queueing Theory. *European Journal of Operational Research*.

Appendix A: Haul Truck Data

Table A-1: All New Truck Arrivals

Easting	Northing	Elevation	Time Stamp	Truck ID
123640.0000'	257554.0000'	1059.000'	1343067870	10
123547.0000'	257421.0000'	1061.000'	1343067982	3
123602.0000'	257680.0000'	1064.000'	1343068028	27
123637.0000'	257561.0000'	1065.000'	1343068082	4
123673.0000'	257574.0000'	1062.000'	1343068118	18
123686.0000'	257596.0000'	1060.000'	1343068130	21
123549.0000'	257431.0000'	1066.000'	1343068247	2
123630.0000'	257570.0000'	1066.000'	1343068497	11
123613.0000'	257682.0000'	1059.000'	1343068617	5
123659.0000'	257569.0000'	1061.000'	1343068636	23
123670.0000'	257572.0000'	1054.000'	1343068782	1
123676.0000'	257581.0000'	1052.000'	1343068975	13
123626.0000'	257674.0000'	1060.000'	1343069181	19
123534.0000'	257407.0000'	1068.000'	1343069276	7
123617.0000'	257566.0000'	1070.000'	1343069477	25
123656.0000'	257561.0000'	1080.000'	1343069557	24
123591.0000'	257685.0000'	1064.000'	1343069762	4
123633.0000'	257559.0000'	1058.000'	1343069978	27
123667.0000'	257569.0000'	1057.000'	1343069993	3
123526.0000'	257415.0000'	1050.000'	1343070008	18
123669.0000'	257581.0000'	1071.000'	1343070107	23
123594.0000'	257678.0000'	1061.000'	1343070117	11
123546.0000'	257436.0000'	1056.000'	1343070138	2
123617.0000'	257675.0000'	1065.000'	1343070478	5
123640.0000'	257557.0000'	1061.000'	1343070522	1
123545.0000'	257428.0000'	1058.000'	1343070571	10
123648.0000'	257558.0000'	1058.000'	1343070956	13
123608.0000'	257672.0000'	1048.000'	1343070987	7
123521.0000'	257412.0000'	1063.000'	1343071307	25
123619.0000'	257672.0000'	1059.000'	1343071312	19
123638.0000'	257559.0000'	1056.000'	1343071435	30
123545.0000'	257439.0000'	1068.000'	1343071508	27
123727.0000'	257548.0000'	1077.000'	1343071667	23
123647.0000'	257556.0000'	1058.000'	1343071763	3
123663.0000'	257568.0000'	1076.000'	1343071828	11
123657.0000'	257596.0000'	1053.000'	1343071992	1
123642.0000'	257671.0000'	1062.000'	1343072073	4

123636.0000'	257555.0000'	1049.000'	1343072278	31
123546.0000'	257443.0000'	1061.000'	1343072328	2
123595.0000'	257668.0000'	1042.000'	1343072518	5
123631.0000'	257556.0000'	1050.000'	1343072521	10
123553.0000'	257445.0000'	1055.000'	1343072607	7
123587.0000'	257687.0000'	1055.000'	1343072876	30
123512.0000'	257427.0000'	1060.000'	1343072902	20
123636.0000'	257552.0000'	1054.000'	1343073296	13
123577.0000'	257682.0000'	1056.000'	1343073324	3
123546.0000'	257443.0000'	1060.000'	1343073378	25
123637.0000'	257676.0000'	1067.000'	1343073429	27
123634.0000'	257553.0000'	1045.000'	1343073498	23
123546.0000'	257438.0000'	1062.000'	1343073693	4
123629.0000'	257552.0000'	1059.000'	1343073718	11
123580.0000'	257661.0000'	1059.000'	1343074172	10
123555.0000'	257457.0000'	1056.000'	1343074183	1
123617.0000'	257566.0000'	1048.000'	1343074228	31
123642.0000'	257678.0000'	1056.000'	1343074319	5
123670.0000'	257683.0000'	1045.000'	1343074348	7
123636.0000'	257552.0000'	1041.000'	1343074399	2
123555.0000'	257482.0000'	1055.000'	1343074646	30
123623.0000'	257553.0000'	1072.000'	1343074807	24
123662.0000'	257562.0000'	1061.000'	1343074883	20
123625.0000'	257678.0000'	1058.000'	1343074947	13
123542.0000'	257481.0000'	1052.000'	1343074974	3
123621.0000'	257553.0000'	1071.000'	1343075298	23
123589.0000'	257660.0000'	1058.000'	1343075319	27
123647.0000'	257559.0000'	1082.000'	1343075418	25
123532.0000'	257440.0000'	1060.000'	1343075854	4
123628.0000'	257554.0000'	1058.000'	1343076032	10
123593.0000'	257667.0000'	1055.000'	1343076149	31
123548.0000'	257443.0000'	1053.000'	1343076163	1
123587.0000'	257660.0000'	1066.000'	1343076448	7
123629.0000'	257552.0000'	1055.000'	1343076449	5
123638.0000'	257672.0000'	1054.000'	1343076538	19
123663.0000'	257567.0000'	1059.000'	1343076547	24
123549.0000'	257444.0000'	1071.000'	1343076743	20
123548.0000'	257450.0000'	1058.000'	1343076798	23
123638.0000'	257553.0000'	1057.000'	1343076867	13
123625.0000'	257553.0000'	1063.000'	1343077060	27
123585.0000'	257670.0000'	1062.000'	1343077076	11
123626.0000'	257557.0000'	1060.000'	1343077564	4
123536.0000'	257437.0000'	1063.000'	1343077910	2

123590.0000'	257660.0000'	1066.000'	1343077919	31
123632.0000'	257549.0000'	1060.000'	1343077923	10
123525.0000'	257436.0000'	1061.000'	1343078138	30
123593.0000'	257656.0000'	1066.000'	1343078249	7
123631.0000'	257551.0000'	1059.000'	1343078250	5
123660.0000'	257558.0000'	1067.000'	1343078288	24
123545.0000'	257436.0000'	1055.000'	1343078669	19
123635.0000'	257672.0000'	1057.000'	1343078818	13
123552.0000'	257445.0000'	1080.000'	1343078844	20
123630.0000'	257552.0000'	1061.000'	1343078869	23
123659.0000'	257558.0000'	1062.000'	1343078967	11
123547.0000'	257445.0000'	1071.000'	1343079065	4
123629.0000'	257554.0000'	1059.000'	1343079392	25
123597.0000'	257661.0000'	1066.000'	1343079400	27
123610.0000'	257568.0000'	1066.000'	1343079620	2
123526.0000'	257436.0000'	1061.000'	1343079777	1
123595.0000'	257659.0000'	1051.000'	1343079900	31
123623.0000'	257677.0000'	1059.000'	1343080119	30
123556.0000'	257454.0000'	1077.000'	1343080169	7
123628.0000'	257548.0000'	1061.000'	1343080170	5
123686.0000'	257577.0000'	1077.000'	1343080178	24
123605.0000'	257666.0000'	1070.000'	1343080647	11
123637.0000'	257673.0000'	1065.000'	1343080979	19
123662.0000'	257674.0000'	1047.000'	1343080991	27
123622.0000'	257562.0000'	1066.000'	1343081015	4
123541.0000'	257432.0000'	1061.000'	1343081072	25
123617.0000'	257567.0000'	1079.000'	1343081331	2
123523.0000'	257437.0000'	1078.000'	1343081454	18
123616.0000'	257559.0000'	1061.000'	1343081534	9
123617.0000'	257555.0000'	1071.000'	1343081907	1
123590.0000'	257658.0000'	1062.000'	1343081940	31
123651.0000'	257563.0000'	1068.000'	1343081949	30
123543.0000'	257430.0000'	1087.000'	1343082008	24
123645.0000'	257543.0000'	1079.000'	1343082120	7
123593.0000'	257670.0000'	1080.000'	1343082598	11
123619.0000'	257556.0000'	1072.000'	1343082631	5
123737.0000'	257641.0000'	1046.000'	1343083011	2
123524.0000'	257433.0000'	1071.000'	1343083019	13
123556.0000'	257444.0000'	1069.000'	1343083053	25
123583.0000'	257677.0000'	1062.000'	1343083080	19
123627.0000'	257681.0000'	1062.000'	1343083182	10
123657.0000'	257548.0000'	1076.000'	1343083184	9
123668.0000'	257584.0000'	1071.000'	1343083224	18

123664.0000'	257575.0000'	1067.000'	1343083318	1
123664.0000'	257573.0000'	1073.000'	1343083450	30
123611.0000'	257653.0000'	1075.000'	1343083839	24
123546.0000'	257428.0000'	1068.000'	1343083861	31
123626.0000'	257576.0000'	1070.000'	1343083920	7
123659.0000'	257558.0000'	1066.000'	1343084207	27
123522.0000'	257435.0000'	1057.000'	1343084551	5
123547.0000'	257667.0000'	1064.000'	1343084722	2
123616.0000'	257661.0000'	1064.000'	1343084996	20
123614.0000'	257560.0000'	1057.000'	1343084999	13
123576.0000'	257654.0000'	1071.000'	1343085030	19
123620.0000'	257671.0000'	1071.000'	1343085058	11
123546.0000'	257428.0000'	1067.000'	1343085145	18
123642.0000'	257549.0000'	1060.000'	1343085148	1
123547.0000'	257435.0000'	1076.000'	1343085153	25
123674.0000'	257581.0000'	1053.000'	1343085162	10
123682.0000'	257594.0000'	1065.000'	1343085228	23
123663.0000'	257575.0000'	1056.000'	1343085371	30
123553.0000'	257450.0000'	1076.000'	1343085571	7
123607.0000'	257668.0000'	1073.000'	1343085700	24
123654.0000'	257559.0000'	1055.000'	1343085977	27
123617.0000'	257552.0000'	1056.000'	1343085992	31
123621.0000'	257560.0000'	1066.000'	1343086658	4
123550.0000'	257432.0000'	1059.000'	1343086828	1
123542.0000'	257466.0000'	1064.000'	1343086933	10
123611.0000'	257555.0000'	1063.000'	1343086951	19
123610.0000'	257442.0000'	1067.000'	1343086965	9
123648.0000'	257547.0000'	1065.000'	1343086968	23
123663.0000'	257564.0000'	1064.000'	1343087036	20
123674.0000'	257595.0000'	1061.000'	1343087052	30
123689.0000'	257605.0000'	1065.000'	1343087129	11
123611.0000'	257436.0000'	1063.000'	1343087224	25
123686.0000'	257604.0000'	1066.000'	1343087395	18
123613.0000'	257442.0000'	1067.000'	1343087401	7
123517.0000'	257441.0000'	1054.000'	1343088062	31
123623.0000'	257441.0000'	1060.000'	1343088158	4
123686.0000'	257622.0000'	1067.000'	1343088168	27
123547.0000'	257428.0000'	1086.000'	1343088490	24
123646.0000'	257558.0000'	1057.000'	1343088749	1
123557.0000'	257485.0000'	1065.000'	1343088792	30
123664.0000'	257574.0000'	1058.000'	1343088996	5
123544.0000'	257480.0000'	1062.000'	1343089155	9
123541.0000'	257461.0000'	1065.000'	1343089677	20

123615.0000'	257546.0000'	1050.000'	1343089723	10
123610.0000'	257443.0000'	1066.000'	1343089831	13
123656.0000'	257538.0000'	1070.000'	1343089984	25
123669.0000'	257580.0000'	1051.000'	1343090006	18
123672.0000'	257582.0000'	1052.000'	1343090259	4
123551.0000'	257435.0000'	1052.000'	1343090448	27
123551.0000'	257423.0000'	1086.000'	1343090651	24
123652.0000'	257547.0000'	1053.000'	1343090704	23
123634.0000'	257540.0000'	1065.000'	1343091140	30
123641.0000'	257546.0000'	1057.000'	1343091212	7
123667.0000'	257582.0000'	1057.000'	1343091577	5
123654.0000'	257551.0000'	1073.000'	1343091584	10
123544.0000'	257438.0000'	1058.000'	1343091721	13
123539.0000'	257445.0000'	1062.000'	1343091755	25
123646.0000'	257548.0000'	1075.000'	1343091987	20
123659.0000'	257564.0000'	1057.000'	1343092107	18
123675.0000'	257583.0000'	1084.000'	1343092142	11
123600.0000'	257443.0000'	1065.000'	1343092543	3
123665.0000'	257565.0000'	1061.000'	1343092549	27
123627.0000'	257454.0000'	1065.000'	1343092560	1
123510.0000'	257428.0000'	1045.000'	1343092563	31
123641.0000'	257546.0000'	1079.000'	1343093120	30
123546.0000'	257451.0000'	1060.000'	1343093163	7
123556.0000'	257433.0000'	1059.000'	1343093504	10
123602.0000'	257558.0000'	1065.000'	1343093507	9
123633.0000'	257559.0000'	1056.000'	1343093732	13
123603.0000'	257566.0000'	1058.000'	1343093737	5
123596.0000'	257569.0000'	1052.000'	1343094095	25
123538.0000'	257422.0000'	1059.000'	1343094207	18
123618.0000'	257565.0000'	1061.000'	1343094544	31
123604.0000'	257560.0000'	1051.000'	1343094575	23
123643.0000'	257544.0000'	1065.000'	1343094619	27
123662.0000'	257566.0000'	1060.000'	1343094646	2
123543.0000'	257416.0000'	1046.000'	1343094813	11
123542.0000'	257446.0000'	1060.000'	1343094854	3
123539.0000'	257484.0000'	1050.000'	1343094951	30
123680.0000'	257590.0000'	1069.000'	1343095067	9
123613.0000'	257570.0000'	1062.000'	1343095141	1
123675.0000'	257581.0000'	1080.000'	1343095242	24
123620.0000'	257562.0000'	1063.000'	1343095805	25
123505.0000'	257417.0000'	1069.000'	1343096115	10
123537.0000'	257437.0000'	1060.000'	1343096247	18
123615.0000'	257554.0000'	1067.000'	1343096314	31

123626.0000'	257547.0000'	1037.000'	1343096588	5
123651.0000'	257554.0000'	1072.000'	1343096705	23
123543.0000'	257411.0000'	1056.000'	1343096717	2
123555.0000'	257427.0000'	1056.000'	1343096947	16
123621.0000'	257535.0000'	1064.000'	1343096960	27
123650.0000'	257552.0000'	1044.000'	1343097061	1
123646.0000'	257548.0000'	1056.000'	1343097273	7
123642.0000'	257546.0000'	1094.000'	1343097393	11
123655.0000'	257562.0000'	1067.000'	1343097435	3
123504.0000'	257416.0000'	1060.000'	1343097493	24
123681.0000'	257592.0000'	1055.000'	1343097543	13
123541.0000'	257417.0000'	1064.000'	1343097606	25
123684.0000'	257591.0000'	1082.000'	1343097621	30
123607.0000'	257443.0000'	1057.000'	1343098356	19
123633.0000'	257540.0000'	1066.000'	1343098506	23
123554.0000'	257409.0000'	1045.000'	1343098558	18
123618.0000'	257546.0000'	1064.000'	1343098757	2
123669.0000'	257588.0000'	1061.000'	1343098832	1
123637.0000'	257543.0000'	1048.000'	1343099078	16
123640.0000'	257549.0000'	1063.000'	1343099103	7
123513.0000'	257414.0000'	1043.000'	1343099139	5
123537.0000'	257413.0000'	1071.000'	1343099238	9
123659.0000'	257532.0000'	1040.000'	1343099415	3
123643.0000'	257548.0000'	1059.000'	1343099692	30
123646.0000'	257549.0000'	1064.000'	1343099797	25
123495.0000'	257399.0000'	1068.000'	1343099893	24
123536.0000'	257421.0000'	1053.000'	1343099959	27
123672.0000'	257577.0000'	1052.000'	1343100336	23
123623.0000'	257569.0000'	1065.000'	1343100346	10
123682.0000'	257601.0000'	1053.000'	1343100389	18
123523.0000'	257482.0000'	1065.000'	1343100408	2
123511.0000'	257415.0000'	1051.000'	1343100427	19
123668.0000'	257578.0000'	1052.000'	1343100452	1
123688.0000'	257559.0000'	1063.000'	1343100729	16
123541.0000'	257444.0000'	1056.000'	1343100755	31
123664.0000'	257575.0000'	1055.000'	1343100783	7
123651.0000'	257549.0000'	1064.000'	1343101216	3
123683.0000'	257577.0000'	1060.000'	1343101249	9
123700.0000'	257598.0000'	1056.000'	1343101312	30
123633.0000'	257537.0000'	1075.000'	1343101574	24
123542.0000'	257427.0000'	1075.000'	1343101657	25
123557.0000'	257433.0000'	1060.000'	1343102240	27
123611.0000'	257568.0000'	1056.000'	1343102348	19

123642.0000'	257548.0000'	1055.000'	1343102497	23
123699.0000'	257719.0000'	1052.000'	1343102519	18
123665.0000'	257573.0000'	1056.000'	1343103543	1
123604.0000'	257560.0000'	1064.000'	1343103559	2
123549.0000'	257449.0000'	1054.000'	1343103634	7
123557.0000'	257465.0000'	1076.000'	1343103825	24
123635.0000'	257549.0000'	1052.000'	1343103846	31
123635.0000'	257542.0000'	1057.000'	1343104030	5
123657.0000'	257566.0000'	1049.000'	1343104036	13
123650.0000'	257537.0000'	1073.000'	1343104553	30
123625.0000'	257475.0000'	1066.000'	1343104577	10
123529.0000'	257415.0000'	1056.000'	1343104868	19
123675.0000'	257577.0000'	1052.000'	1343104927	23
123717.0000'	257678.0000'	1080.000'	1343105114	12
123669.0000'	257532.0000'	1142.000'	1343105168	23
123526.0000'	257410.0000'	1060.000'	1343105269	2
123662.0000'	257561.0000'	1085.000'	1343105301	27
123645.0000'	257543.0000'	1058.000'	1343105734	1
123549.0000'	257425.0000'	1052.000'	1343105760	18
123547.0000'	257450.0000'	1057.000'	1343105765	7
123657.0000'	257557.0000'	1061.000'	1343105890	16
123549.0000'	257452.0000'	1058.000'	1343106101	5
123543.0000'	257496.0000'	1056.000'	1343106165	24
123640.0000'	257538.0000'	1042.000'	1343106223	4
123650.0000'	257546.0000'	1061.000'	1343106407	13
123640.0000'	257540.0000'	1053.000'	1343106504	30
123556.0000'	257429.0000'	1055.000'	1343106909	19
123655.0000'	257578.0000'	1042.000'	1343107220	2
123551.0000'	257447.0000'	1046.000'	1343107458	10
123653.0000'	257574.0000'	1050.000'	1343107461	27
123561.0000'	257423.0000'	1043.000'	1343107478	23
123680.0000'	257597.0000'	1061.000'	1343107564	1
123557.0000'	257442.0000'	1035.000'	1343107626	11
123683.0000'	257597.0000'	1060.000'	1343107650	18
123548.0000'	257423.0000'	1061.000'	1343107991	16
123685.0000'	257610.0000'	1063.000'	1343108075	7
123645.0000'	257582.0000'	1049.000'	1343108174	4
123552.0000'	257434.0000'	1054.000'	1343108207	13
123684.0000'	257596.0000'	1061.000'	1343108388	3
123558.0000'	257437.0000'	1049.000'	1343108501	5
123634.0000'	257574.0000'	1058.000'	1343108615	7
123687.0000'	257600.0000'	1070.000'	1343108686	24
123668.0000'	257618.0000'	1062.000'	1343108934	30

123529.0000'	257408.0000'	1062.000'	1343109189	19
123568.0000'	257437.0000'	1036.000'	1343109260	2

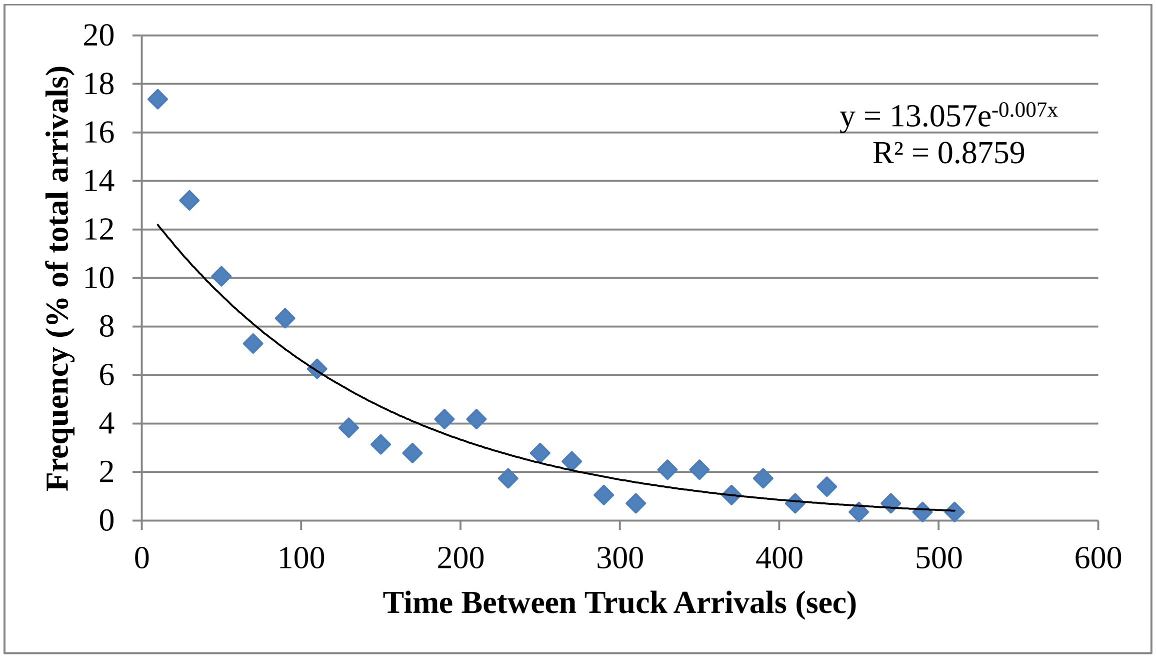

Figure A-1: Arrival Distribution

Table A-2: Truck Departures from Loader 1

Easting	Northing	Elevation	Time	Truck	Loader
123533.0000'	257410.0000'	1053.000'	1343068372	3	1
123521.0000'	257408.0000'	1090.000'	1343068637	2	1
123535.0000'	257407.0000'	1068.000'	1343069456	7	1
123529.0000'	257404.0000'	1048.000'	1343070498	2	1
123517.0000'	257406.0000'	1083.000'	1343070811	10	1
123522.0000'	257413.0000'	1064.000'	1343071577	25	1
123531.0000'	257415.0000'	1066.000'	1343071869	27	1
123538.0000'	257422.0000'	1064.000'	1343072382	1	1
123520.0000'	257410.0000'	1069.000'	1343072688	2	1
123544.0000'	257420.0000'	1056.000'	1343072938	7	1
123529.0000'	257419.0000'	1063.000'	1343073292	20	1
123519.0000'	257415.0000'	1058.000'	1343073798	25	1
123527.0000'	257443.0000'	1061.000'	1343074294	4	1
123548.0000'	257445.0000'	1055.000'	1343074663	1	1
123535.0000'	257443.0000'	1052.000'	1343075006	30	1
123544.0000'	257439.0000'	1048.000'	1343075304	3	1
123526.0000'	257438.0000'	1057.000'	1343076064	4	1
123547.0000'	257443.0000'	1053.000'	1343076344	1	1
123541.0000'	257436.0000'	1055.000'	1343077073	20	1
123534.0000'	257436.0000'	1062.000'	1343077339	23	1
123530.0000'	257436.0000'	1052.000'	1343078090	2	1
123536.0000'	257439.0000'	1063.000'	1343078408	30	1
123541.0000'	257436.0000'	1043.000'	1343079204	20	1
123533.0000'	257504.0000'	1054.000'	1343079269	19	1
123537.0000'	257437.0000'	1062.000'	1343079455	4	1
123547.0000'	257437.0000'	1065.000'	1343080347	1	1
123538.0000'	257432.0000'	1065.000'	1343081342	25	1
123541.0000'	257433.0000'	1054.000'	1343081634	18	1
123533.0000'	257431.0000'	1018.000'	1343082189	24	1
123545.0000'	257437.0000'	1069.000'	1343083289	13	1
123543.0000'	257420.0000'	1084.000'	1343083563	25	1
123545.0000'	257428.0000'	1068.000'	1343084101	31	1
123544.0000'	257427.0000'	1074.000'	1343085325	18	1
123506.0000'	257437.0000'	1074.000'	1343085633	25	1
123547.0000'	257432.0000'	1071.000'	1343086021	7	1
123514.0000'	257420.0000'	1018.000'	1343086600	24	1
123551.0000'	257432.0000'	1058.000'	1343086978	1	1
123536.0000'	257428.0000'	1055.000'	1343087263	10	1
123539.0000'	257426.0000'	1057.000'	1343087505	9	1
123520.0000'	257416.0000'	1044.000'	1343087824	25	1
123542.0000'	257464.0000'	1060.000'	1343088181	7	1

123547.0000'	257429.0000'	1056.000'	1343088422	31	1
123529.0000'	257428.0000'	1074.000'	1343089090	24	1
123534.0000'	257428.0000'	1055.000'	1343089332	30	1
123529.0000'	257417.0000'	1050.000'	1343089576	9	1
123544.0000'	257413.0000'	1062.000'	1343090221	13	1
123528.0000'	257411.0000'	1058.000'	1343090517	20	1
123532.0000'	257419.0000'	1071.000'	1343090868	27	1
123536.0000'	257401.0000'	1058.000'	1343091161	24	1
123538.0000'	257407.0000'	1053.000'	1343091602	7	1
123523.0000'	257413.0000'	1063.000'	1343092171	13	1
123521.0000'	257421.0000'	1059.000'	1343092505	25	1
123522.0000'	257421.0000'	1056.000'	1343092833	31	1
123521.0000'	257422.0000'	1060.000'	1343093204	3	1
123522.0000'	257410.0000'	1052.000'	1343093580	1	1
123520.0000'	257410.0000'	1063.000'	1343093883	7	1
123514.0000'	257411.0000'	1056.000'	1343094567	18	1
123510.0000'	257414.0000'	1042.000'	1343095383	11	1
123520.0000'	257409.0000'	1055.000'	1343095634	3	1
123512.0000'	257405.0000'	1050.000'	1343095911	30	1
123627.0000'	257468.0000'	1049.000'	1343096535	10	1
123516.0000'	257405.0000'	1045.000'	1343096878	18	1
123513.0000'	257409.0000'	1060.000'	1343097167	2	1
123521.0000'	257403.0000'	1057.000'	1343097428	16	1
123513.0000'	257407.0000'	1068.000'	1343098296	25	1
123523.0000'	257402.0000'	1057.000'	1343098657	19	1
123530.0000'	257402.0000'	1060.000'	1343098888	18	1
123525.0000'	257401.0000'	1052.000'	1343099409	5	1
123501.0000'	257403.0000'	1060.000'	1343099688	9	1
123501.0000'	257404.0000'	1059.000'	1343100103	24	1
123540.0000'	257515.0000'	1058.000'	1343100589	27	1
123513.0000'	257404.0000'	1055.000'	1343100607	19	1
123510.0000'	257403.0000'	1049.000'	1343100888	2	1
123521.0000'	257408.0000'	1053.000'	1343101236	31	1
123530.0000'	257408.0000'	1053.000'	1343101509	16	1
123640.0000'	257445.0000'	1062.000'	1343102993	30	1
123568.0000'	257491.0000'	1047.000'	1343103008	25	1
123542.0000'	257408.0000'	1051.000'	1343103590	27	1
123539.0000'	257408.0000'	1053.000'	1343103929	18	1
123538.0000'	257409.0000'	1055.000'	1343104234	7	1
123534.0000'	257399.0000'	1039.000'	1343104515	24	1
123534.0000'	257409.0000'	1052.000'	1343105168	19	1
123528.0000'	257396.0000'	1039.000'	1343105509	2	1
123534.0000'	257405.0000'	1052.000'	1343105774	12	1

123533.0000'	257408.0000'	1053.000'	1343106120	18	1
123537.0000'	257403.0000'	1050.000'	1343106395	7	1
123533.0000'	257408.0000'	1061.000'	1343106791	5	1
123517.0000'	257423.0000'	1065.000'	1343107155	24	1
123529.0000'	257405.0000'	1060.000'	1343107479	19	1
123525.0000'	257415.0000'	1067.000'	1343107778	23	1
123502.0000'	257410.0000'	1019.000'	1343108028	10	1
123531.0000'	257408.0000'	1051.000'	1343108316	11	1
123515.0000'	257399.0000'	1060.000'	1343108651	16	1
123537.0000'	257402.0000'	1064.000'	1343109047	13	1
123519.0000'	257400.0000'	1065.000'	1343109402	5	1
123534.0000'	257404.0000'	1050.000'	1343109740	2	1
123592.0000'	257422.0000'	1066.000'	1343109910	19	1

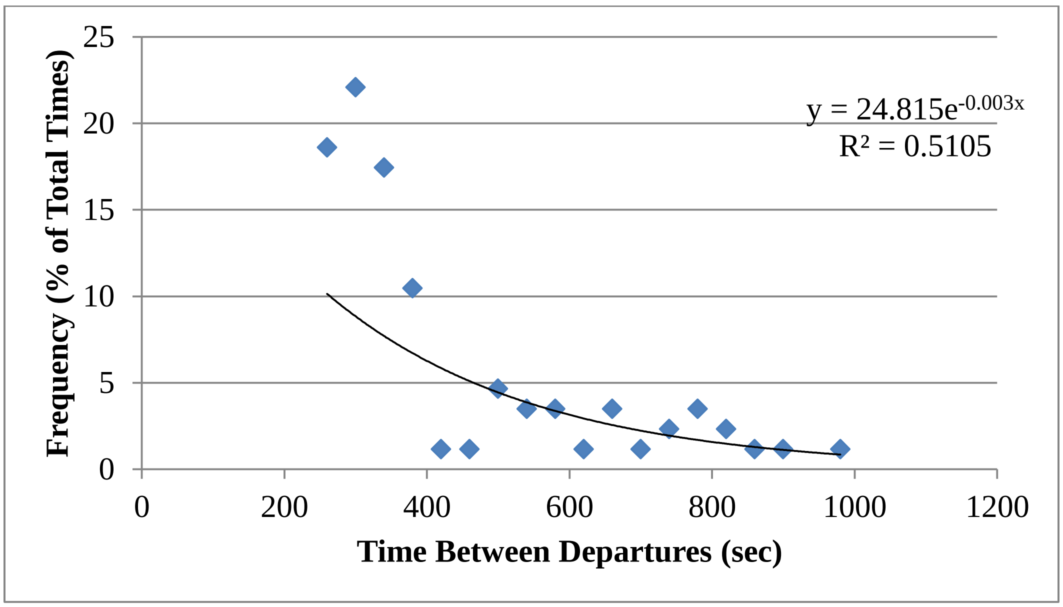

Figure A-2: Loader 1 Service Distribution

Table A-3: Truck Departures from Loader 2

Easting	Northing	Elevation	Time	Truck	Loader
123637.0000'	257563.0000'	1067.000'	1343067990	10	2
123626.0000'	257562.0000'	1077.000'	1343068172	4	2
123631.0000'	257561.0000'	1065.000'	1343068358	18	2
123617.0000'	257562.0000'	1067.000'	1343068520	21	2
123632.0000'	257562.0000'	1065.000'	1343068647	11	2
123624.0000'	257567.0000'	1068.000'	1343068816	23	2
123640.0000'	257557.0000'	1059.000'	1343068962	1	2
123637.0000'	257558.0000'	1059.000'	1343069185	13	2
123619.0000'	257570.0000'	1068.000'	1343069567	25	2
123628.0000'	257561.0000'	1067.000'	1343069737	24	2
123626.0000'	257563.0000'	1077.000'	1343070098	27	2
123630.0000'	257557.0000'	1067.000'	1343070263	3	2
123712.0000'	257548.0000'	1064.000'	1343070368	18	2
123628.0000'	257561.0000'	1082.000'	1343070437	23	2
123640.0000'	257556.0000'	1061.000'	1343070642	1	2
123648.0000'	257558.0000'	1057.000'	1343071136	13	2
123636.0000'	257561.0000'	1059.000'	1343071585	30	2
123645.0000'	257558.0000'	1045.000'	1343071883	3	2
123639.0000'	257561.0000'	1060.000'	1343072068	11	2
123637.0000'	257553.0000'	1045.000'	1343072428	31	2
123633.0000'	257559.0000'	1054.000'	1343072611	10	2
123637.0000'	257551.0000'	1052.000'	1343073386	13	2
123637.0000'	257554.0000'	1044.000'	1343073618	23	2
123625.0000'	257556.0000'	1055.000'	1343073808	11	2
123618.0000'	257567.0000'	1049.000'	1343074378	31	2
123635.0000'	257560.0000'	1034.000'	1343074489	2	2
123611.0000'	257559.0000'	1066.000'	1343074927	24	2
123622.0000'	257557.0000'	1066.000'	1343075123	20	2
123622.0000'	257558.0000'	1065.000'	1343075388	23	2
123625.0000'	257561.0000'	1063.000'	1343075568	25	2
123626.0000'	257557.0000'	1058.000'	1343076152	10	2
123630.0000'	257553.0000'	1062.000'	1343076539	5	2
123616.0000'	257563.0000'	1083.000'	1343076697	24	2
123638.0000'	257553.0000'	1057.000'	1343076957	13	2
123621.0000'	257555.0000'	1063.000'	1343077654	4	2
123625.0000'	257561.0000'	1066.000'	1343078043	10	2
123614.0000'	257563.0000'	1084.000'	1343078498	24	2
123616.0000'	257552.0000'	1060.000'	1343078959	23	2
123628.0000'	257554.0000'	1065.000'	1343079147	11	2
123624.0000'	257559.0000'	1055.000'	1343079482	25	2
123613.0000'	257563.0000'	1069.000'	1343079800	2	2

123633.0000'	257548.0000'	1063.000'	1343080260	5	2
123615.0000'	257578.0000'	1099.000'	1343080508	24	2
123621.0000'	257563.0000'	1069.000'	1343081075	4	2
123619.0000'	257570.0000'	1073.000'	1343081391	2	2
123618.0000'	257560.0000'	1071.000'	1343081624	9	2
123617.0000'	257555.0000'	1072.000'	1343081997	1	2
123621.0000'	257554.0000'	1054.000'	1343082129	30	2
123620.0000'	257557.0000'	1075.000'	1343082300	7	2
123620.0000'	257560.0000'	1072.000'	1343082721	5	2
123621.0000'	257573.0000'	1051.000'	1343083221	2	2
123627.0000'	257570.0000'	1083.000'	1343083364	9	2
123621.0000'	257560.0000'	1092.000'	1343083524	18	2
123612.0000'	257560.0000'	1075.000'	1343083678	1	2
123624.0000'	257571.0000'	1068.000'	1343083840	30	2
123617.0000'	257555.0000'	1078.000'	1343084100	7	2
123699.0000'	257546.0000'	1059.000'	1343085031	5	2
123614.0000'	257559.0000'	1055.000'	1343085089	13	2
123619.0000'	257553.0000'	1055.000'	1343085298	1	2
123624.0000'	257566.0000'	1055.000'	1343085432	10	2
123623.0000'	257551.0000'	995.000'	1343085588	23	2
123623.0000'	257556.0000'	1046.000'	1343085761	30	2
123616.0000'	257552.0000'	1053.000'	1343086082	31	2
123625.0000'	257586.0000'	1083.000'	1343086277	27	2
123620.0000'	257560.0000'	1071.000'	1343086748	4	2
123605.0000'	257555.0000'	1061.000'	1343087101	19	2
123612.0000'	257566.0000'	1069.000'	1343087298	23	2
123612.0000'	257562.0000'	1066.000'	1343087472	30	2
123600.0000'	257566.0000'	1054.000'	1343087636	20	2
123633.0000'	257592.0000'	1072.000'	1343088506	18	2
123621.0000'	257563.0000'	1070.000'	1343088659	11	2
123612.0000'	257561.0000'	1077.000'	1343088888	27	2
123621.0000'	257555.0000'	1060.000'	1343089199	1	2
123619.0000'	257557.0000'	1066.000'	1343089446	5	2
123688.0000'	257631.0000'	1046.000'	1343089934	10	2
123611.0000'	257564.0000'	1043.000'	1343090314	25	2
123621.0000'	257554.0000'	1070.000'	1343090516	18	2
123613.0000'	257556.0000'	1057.000'	1343090739	4	2
123615.0000'	257564.0000'	1071.000'	1343090914	23	2
123614.0000'	257554.0000'	1057.000'	1343091320	30	2
123616.0000'	257551.0000'	1064.000'	1343091794	10	2
123614.0000'	257563.0000'	1070.000'	1343092117	5	2
123613.0000'	257562.0000'	1062.000'	1343092587	18	2
123617.0000'	257554.0000'	1054.000'	1343092969	27	2

123600.0000'	257566.0000'	1046.000'	1343093222	11	2
123623.0000'	257557.0000'	1066.000'	1343093390	30	2
123598.0000'	257557.0000'	1054.000'	1343093597	9	2
123601.0000'	257573.0000'	1059.000'	1343093857	5	2
123621.0000'	257554.0000'	1057.000'	1343094002	13	2
123592.0000'	257567.0000'	1044.000'	1343094215	25	2
123708.0000'	257561.0000'	1064.000'	1343094435	10	2
123603.0000'	257561.0000'	1049.000'	1343094695	23	2
123623.0000'	257549.0000'	1060.000'	1343094874	31	2
123597.0000'	257564.0000'	1044.000'	1343095069	27	2
123608.0000'	257560.0000'	1058.000'	1343095216	2	2
123604.0000'	257566.0000'	1063.000'	1343095411	1	2
123609.0000'	257554.0000'	1060.000'	1343095667	9	2
123600.0000'	257572.0000'	995.000'	1343095872	24	2
123613.0000'	257556.0000'	1051.000'	1343096046	25	2
123604.0000'	257561.0000'	1065.000'	1343096464	31	2
123625.0000'	257546.0000'	1028.000'	1343096708	5	2
123616.0000'	257556.0000'	967.000'	1343096885	23	2
123594.0000'	257558.0000'	1043.000'	1343097140	27	2
123623.0000'	257545.0000'	1039.000'	1343097331	1	2
123625.0000'	257546.0000'	1050.000'	1343097513	7	2
123612.0000'	257553.0000'	1051.000'	1343097663	11	2
123627.0000'	257545.0000'	1046.000'	1343097825	3	2
123624.0000'	257549.0000'	1049.000'	1343098023	13	2
123617.0000'	257550.0000'	1059.000'	1343098221	30	2
123611.0000'	257550.0000'	1060.000'	1343098423	24	2
123609.0000'	257548.0000'	1052.000'	1343098686	23	2
123615.0000'	257545.0000'	1054.000'	1343098847	2	2
123621.0000'	257546.0000'	1056.000'	1343099042	1	2
123658.0000'	257595.0000'	1056.000'	1343099288	16	2
123618.0000'	257544.0000'	1065.000'	1343099403	7	2
123625.0000'	257542.0000'	1062.000'	1343099595	3	2
123616.0000'	257546.0000'	1054.000'	1343099872	30	2
123605.0000'	257550.0000'	1059.000'	1343100067	25	2
123614.0000'	257559.0000'	1063.000'	1343100556	10	2
123608.0000'	257563.0000'	1077.000'	1343100726	23	2
123610.0000'	257553.0000'	1056.000'	1343100959	18	2
123614.0000'	257549.0000'	1051.000'	1343101263	1	2
123606.0000'	257576.0000'	1053.000'	1343101504	7	2
123604.0000'	257555.0000'	1057.000'	1343101666	3	2
123610.0000'	257579.0000'	1057.000'	1343101934	24	2
123613.0000'	257561.0000'	1059.000'	1343102149	9	2
123685.0000'	257606.0000'	1053.000'	1343103128	19	2

123604.0000'	257584.0000'	1095.000'	1343103277	23	2
123611.0000'	257568.0000'	1063.000'	1343103679	2	2
123604.0000'	257546.0000'	1050.000'	1343103873	1	2
123605.0000'	257545.0000'	1044.000'	1343104116	31	2
123604.0000'	257541.0000'	1041.000'	1343104330	5	2
123616.0000'	257526.0000'	1036.000'	1343104696	13	2
123613.0000'	257545.0000'	1054.000'	1343104913	30	2
123687.0000'	257576.0000'	1073.000'	1343105047	23	2
123602.0000'	257565.0000'	1080.000'	1343105298	10	2
123600.0000'	257570.0000'	1029.000'	1343105498	23	2
123602.0000'	257562.0000'	1065.000'	1343105721	27	2
123605.0000'	257546.0000'	1060.000'	1343106064	1	2
123607.0000'	257547.0000'	1061.000'	1343106250	16	2
123609.0000'	257554.0000'	1055.000'	1343106433	4	2
123603.0000'	257551.0000'	1065.000'	1343106677	13	2
123602.0000'	257557.0000'	1078.000'	1343106924	30	2
123640.0000'	257567.0000'	1010.000'	1343107490	2	2
123633.0000'	257569.0000'	1027.000'	1343107761	27	2
123642.0000'	257581.0000'	1049.000'	1343107954	1	2
123635.0000'	257568.0000'	1028.000'	1343108191	18	2
123653.0000'	257579.0000'	1071.000'	1343108495	7	2
123622.0000'	257559.0000'	1040.000'	1343108714	4	2
123634.0000'	257580.0000'	1048.000'	1343109005	7	2
123631.0000'	257562.0000'	1038.000'	1343109288	3	2
123625.0000'	257559.0000'	1021.000'	1343109616	24	2
123638.0000'	257571.0000'	1068.000'	1343109624	30	2

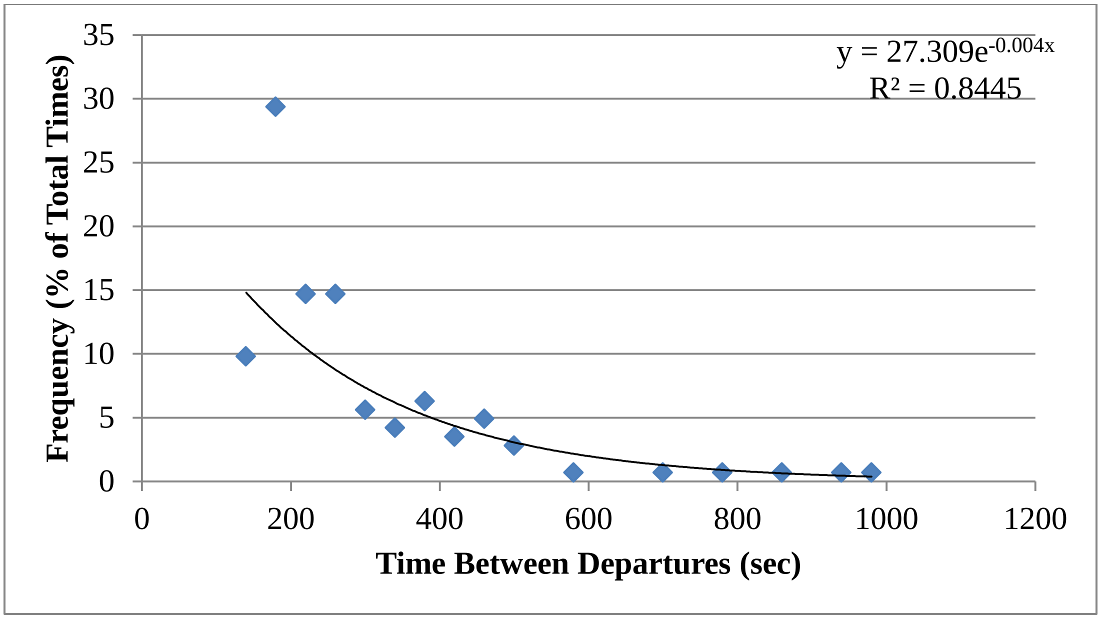

Figure A-3: Loader 2 Service Distribution

Table A-4: Truck Departures from Loader 3

Easting	Northing	Elevation	Time	Truck	Loader
123618.0000'	257745.0000'	988.000'	1343068508	27	3
123604.0000'	257700.0000'	1055.000'	1343068827	5	3
123611.0000'	257673.0000'	1063.000'	1343069481	19	3
123602.0000'	257696.0000'	1072.000'	1343070002	4	3
123607.0000'	257691.0000'	1076.000'	1343070297	11	3
123607.0000'	257668.0000'	1057.000'	1343070718	5	3
123613.0000'	257670.0000'	1047.000'	1343071167	7	3
123634.0000'	257668.0000'	1042.000'	1343071462	19	3
123562.0000'	257688.0000'	1042.000'	1343072087	23	3
123592.0000'	257684.0000'	1016.000'	1343072343	4	3
123602.0000'	257660.0000'	1046.000'	1343072698	5	3
123587.0000'	257693.0000'	1047.000'	1343073086	30	3
123572.0000'	257689.0000'	1052.000'	1343073474	3	3
123537.0000'	257699.0000'	1100.000'	1343073759	27	3
123559.0000'	257707.0000'	1047.000'	1343074352	10	3
123575.0000'	257681.0000'	1050.000'	1343074589	5	3
123604.0000'	257669.0000'	1058.000'	1343074888	7	3
123598.0000'	257677.0000'	1058.000'	1343075187	13	3
123577.0000'	257664.0000'	1046.000'	1343075499	27	3
123593.0000'	257666.0000'	1054.000'	1343076299	31	3
123590.0000'	257660.0000'	1066.000'	1343076628	7	3
123585.0000'	257666.0000'	1063.000'	1343076958	19	3

123721.0000'	257683.0000'	1087.000'	1343077270	27	3
123571.0000'	257676.0000'	1044.000'	1343077316	11	3
123592.0000'	257653.0000'	1083.000'	1343078129	31	3
123716.0000'	257662.0000'	1060.000'	1343078430	5	3
123594.0000'	257646.0000'	1094.000'	1343078519	7	3
123597.0000'	257656.0000'	1084.000'	1343079208	13	3
123585.0000'	257682.0000'	1078.000'	1343079580	27	3
123594.0000'	257661.0000'	1053.000'	1343080080	31	3
123583.0000'	257674.0000'	1091.000'	1343080389	30	3
123589.0000'	257652.0000'	1078.000'	1343080740	7	3
123574.0000'	257667.0000'	1010.000'	1343080977	11	3
123592.0000'	257661.0000'	1056.000'	1343081309	19	3
123534.0000'	257731.0000'	883.000'	1343081681	27	3
123589.0000'	257661.0000'	1066.000'	1343082241	31	3
123721.0000'	257682.0000'	1045.000'	1343082988	11	3
123595.0000'	257668.0000'	1062.000'	1343083320	19	3
123591.0000'	257679.0000'	995.000'	1343083602	10	3
123584.0000'	257668.0000'	1029.000'	1343084139	24	3
123724.0000'	257678.0000'	1076.000'	1343084627	27	3
123570.0000'	257661.0000'	1066.000'	1343084902	2	3
123569.0000'	257652.0000'	1059.000'	1343085210	19	3
123571.0000'	257659.0000'	1075.000'	1343085476	20	3
123575.0000'	257691.0000'	1078.000'	1343085719	11	3
123717.0000'	257662.0000'	1063.000'	1343092468	20	3

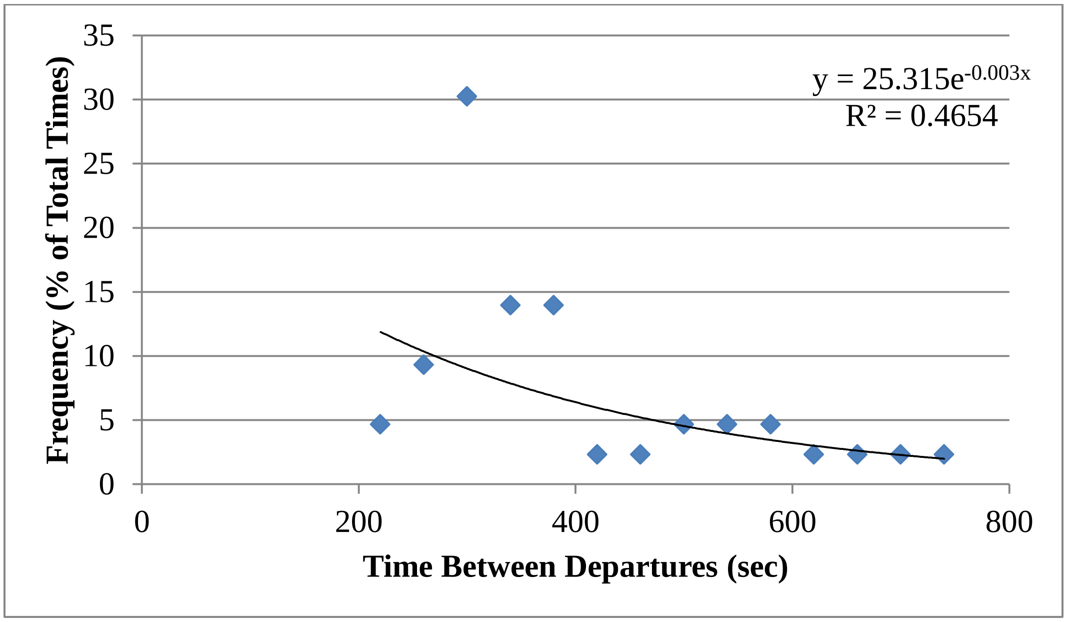

Figure A-4: Loader 3 Service Distribution

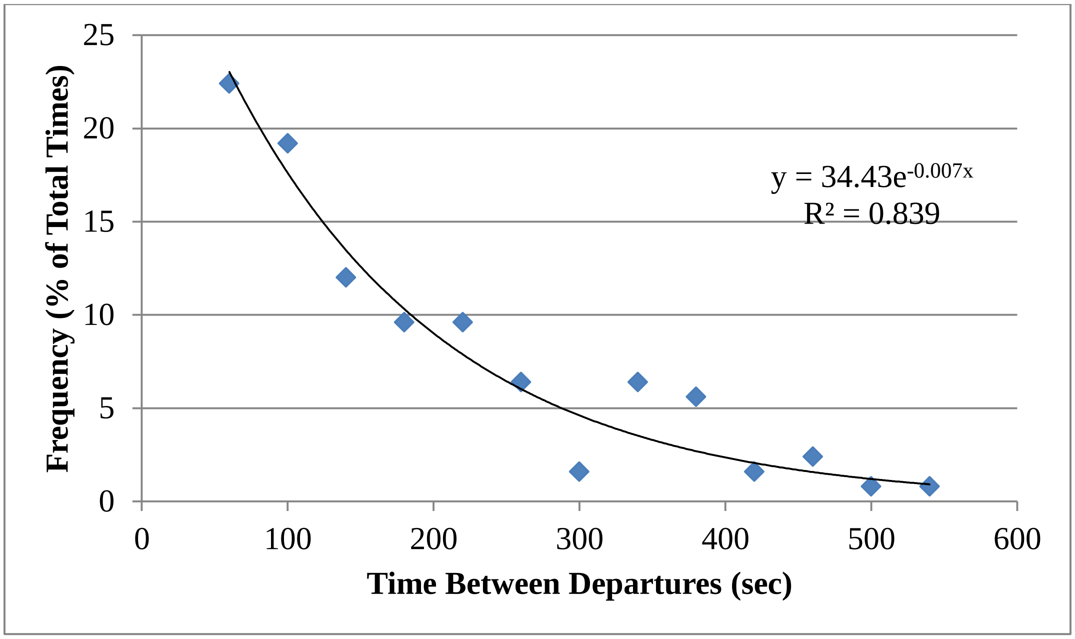

Figure A-5: Overall Service Distribution with 3 Loaders in Operation

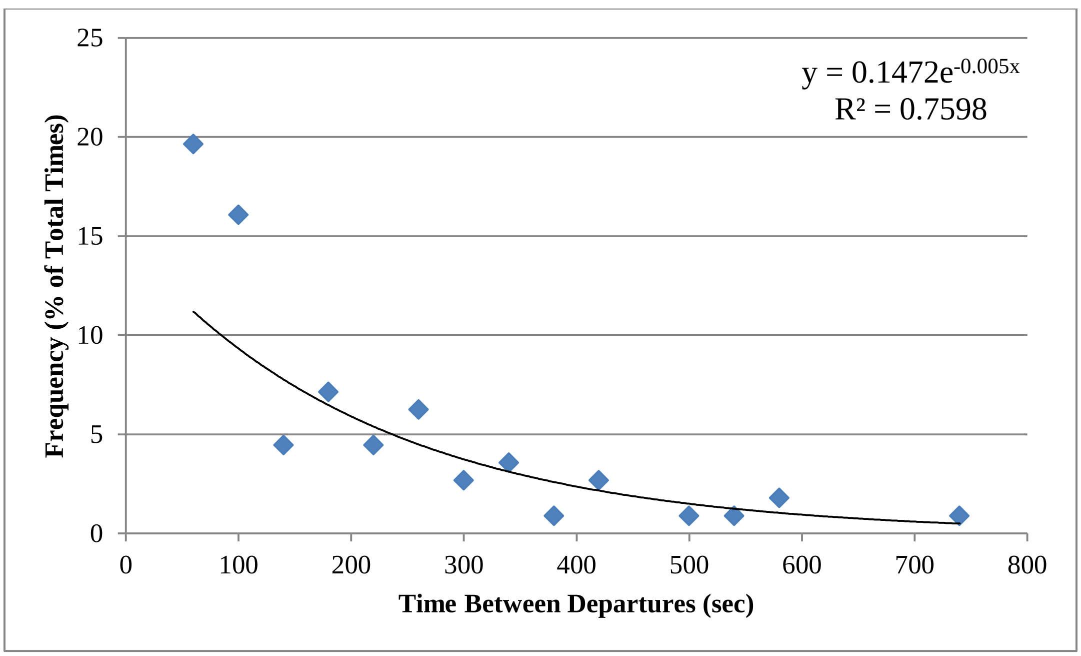

Figure A-6: Overall Service Distribution with 2 Loaders in Operation

Table A-5: Number of Trucks in System

Time Stamp	Number of Trucks in System
1343067870	2
1343068012	5
1343068208	5
1343068337	5
1343068460	4
1343068587	4
1343068726	3
1343068872	2
1343069035	1
1343069181	3
1343069306	2
1343069451	4
1343069617	1
1343069762	1
1343069912	4
1343070038	4
1343070167	5
1343070297	4
1343070437	4
1343070568	3
1343070691	2
1343070956	2
1343071077	2
1343071307	2
1343071432	4
1343071555	4
1343071718	4
1343071839	4
1343071967	4
1343072103	2
1343072232	3
1343072358	3
1343072508	4
1343072637	3
1343072817	2
1343072938	2
1343073296	3
1343073429	3
1343073558	3
1343073693	4
1343073843	1
1343074143	3
1343074273	7
1343074408	4
1343074529	4
1343074663	3
1343074798	3
1343074927	4
1343075064	2
1343075187	3
1343075319	3
1343075448	2
1343075854	1
1343076032	3
1343076163	2
1343076299	2
1343076448	3
1343076598	3
1343076748	3
1343076888	4
1343077013	4
1343077136	3
1343077270	3
1343077339	0
1343077564	1
1343077654	0
1343077910	2
1343078043	3
1343078168	4
1343078309	4
1343078430	3
1343078699	2
1343078848	5
1343078969	5
1343079095	4
1343079239	2
1343079365	3
1343079490	1
1343079620	1
1343079770	2
1343079897	2
1343080020	2
1343080167	5
1343080289	3
1343080418	1
1343080590	2
1343080737	2
1343080887	3
1343081015	2
1343081045	4
1343081171	3
1343081309	4
1343081454	3
1343081591	3
1343081634	0
1343081907	3
1343082038	4
1343082180	3
1343082270	0
1343082300	0
1343082598	2
1343082721	2
1343082868	1
1343083011	3
1343083139	6
1343083263	6
1343083392	5
1343083524	5
1343083648	2
1343083780	2
1343083920	2
1343084049	2
1343084207	1
1343084357	1
1343084507	2
1343084641	2
1343084782	2
1343084996	5
1343085118	8
1343085243	5
1343085371	4
1343085498	5
1343085629	5
1343085751	3
1343085880	2

1343086007	3
1343086157	2
1343086300	1
1343086450	1
1343086600	2
1343086748	2
1343086888	5
1343087011	7
1343087142	7
1343087263	7
1343087385	7
1343087515	5
1343087636	5
1343087759	4
1343087905	3
1343088029	4
1343088158	7
1343088308	3
1343088438	4
1343088569	4
1343088699	5
1343088820	4
1343088959	4
1343089086	5
1343089212	3
1343089336	2
1343089486	1
1343089677	1
1343089814	3
1343089984	4
1343090126	4
1343090247	4
1343090396	5
1343090517	3
1343090679	4
1343090801	3
1343090981	1
1343091131	3
1343091260	2
1343091320	0
1343091452	1
1343091577	3
1343091704	4
1343091841	3
1343091965	4
1343092087	6
1343092227	4
1343092348	4
1343092472	1
1343092603	5
1343092729	5
1343092860	4
1343092982	3
1343093114	5
1343093250	3
1343093373	3
1343093504	4
1343093643	4
1343093767	4
1343093895	2
1343094045	2
1343094185	3
1343094387	3
1343094619	3
1343094766	4
1343094889	5
1343095011	6
1343095141	7
1343095263	6
1343095394	5
1343095514	4
1343095637	3
1343095761	2
1343095911	2
1343095955	0
1343096115	1
1343096247	2
1343096398	2
1343096535	3
1343096668	4
1343096807	3
1343096947	4
1343097077	4
1343097211	3
1343097301	3
1343097423	5
1343097553	5
1343097675	5
1343097801	5
1343097933	3
1343098063	2
1343098191	2
1343098333	1
1343098477	2
1343098558	3
1343098686	3
1343098817	3
1343098952	1
1343099078	3
1343099168	4
1343099289	3
1343099415	2
1343099538	2
1343099688	2
1343099782	2
1343099893	3
1343100019	3
1343100199	1
1343100289	3
1343100389	7
1343100509	7
1343100632	5
1343100768	6
1343100899	5
1343101022	2
1343101143	4
1343101264	5
1343101389	5
1343101516	4
1343101639	5
1343101762	3
1343101904	3
1343102002	2
1343102122	3
1343102270	4
1343102377	4
1343102498	4
1343102609	4

1343102870	5
1343102990	5
1343103110	4
1343103230	3
1343103359	2
1343103500	4
1343103603	4
1343103724	4
1343103843	5
1343103975	5
1343104084	4
1343104204	4
1343104330	3
1343104455	3
1343104576	3
1343104696	3
1343104817	3
1343104927	3
1343105047	4
1343105178	3
1343105294	5
1343105414	4
1343105571	2
1343105684	5
1343105794	4
1343105915	4
1343106040	5
1343106165	5
1343106305	4
1343106433	4
1343106564	4
1343106701	3
1343106834	3
1343106969	2
1343107089	1
1343107220	2
1343107329	2
1343107449	5
1343107564	6
1343107688	6
1343107818	4
1343107938	5

1343102870	5
1343102990	5
1343103110	4
1343103230	3
1343103359	2
1343103500	4
1343103603	4
1343103724	4
1343103843	5
1343103975	5
1343104084	4
1343104204	4
1343104330	3
1343104455	3
1343104576	3
1343104696	3
1343104817	3
1343104927	3
1343105047	4
1343105178	3
1343105294	5
1343105414	4
1343105571	2
1343105684	5
1343105794	4
1343105915	4
1343106040	5
1343106165	5
1343106305	4
1343106433	4
1343106564	4
1343106701	3
1343106834	3
1343106969	2
1343107089	1
1343107220	2
1343107329	2
1343107449	5
1343107564	6
1343107688	6
1343107818	4
1343107938	5
1343108071	5

1343102738	4
1343108191	7
1343108315	6
1343108435	6
1343108561	5
1343108675	6
1343108801	5
1343108926	6
1343109047	5
1343109174	6
1343109294	5
1343109429	4
1343109550	4
1343109740	2

Table A-6: Predicted and Actual Number of Trucks in System

		Average Number of Trucks in System (L)	
Begin Time	**End Time**	**From Data**	**From Model**
1343067870	1343071470	3.120	3.187
1343071470	1343075070	3.292	3.187
1343075070	1343078670	2.545	2.201
1343078670	1343082270	2.643	2.474
1343082270	1343085870	3.240	2.793
1343085870	1343089470	4.000	3.5
1343089470	1343093070	3.148	3.5
1343093070	1343096670	3.407	4.248
1343096670	1343100270	2.929	14.8
1343100270	1343103870	4.167	4.248
1343103870	1343107470	3.517	4.248