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Shovel-truck cycle simulation methods in surface mining

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S H O V E L – T R U C K
C Y C L E S I M U L A T I O N M E T H O D S
I N
S U R F A C E M I N I N G

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0102871H

A research report submitted to the Faculty of Engineering and Built Environment, University of Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Masters of the Science in Engineering

UNIVERSITY OF THE WITWATERSRAND

Johannesburg, 2006

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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December 2006

ABSTRACT

This study investigates the main factors of production, their interaction and influence on cycle time efficiency for shovel-truck systems on surface mines. The main factors are truck payload, cycle time and operator proficiency. It is now routine that shovel-truck cycles are analysed using simulation methods. The Elbrond, FPC, Talpac, Arena and Machine Repair simulation models are discussed to explain how their model characteristics contribute to the differences in their reported cycle efficiency as indicated by productivity results. The Machine Repair Model based on Markov chains is adapted for shovel-truck systems and examined for calculating shovel-truck cycle times.

The various probability distributions that can be use to model particular cycle time variables and some methods in selecting the "best" fit are examined. Truck cycle time variable sensitivity is examined by using the Excel® add-on program @Risk (Palisade Corp.) in determining their respective weighting or contribution within the total cycle time variability.

The analysis of cycle efficiency leads ultimately to sizing of a shovel-truck system. When determining a fleet size for a particular surface operation the planning engineers will tend to use one and to a lesser extent perhaps two separate simulation models. This study calculates the productivity (tonnes per hour) for a "virtual mine" with a variable number of trucks, variable cycle distances and variable truck loading times. The study also includes a separate analysis of cycle time variables and their probability distributions for the Orapa diamond mine in Botswana, to show possible distributions for various cycle variables.

The study concludes with a calculation of the truck fleet size using the Elbrond, FPC, Talpac and Arena and Machine Repair models for the Optimum Colliery coal mine and then compares the results and their correlation.

The main findings are that the calculation of waiting time is different for the various models, each model yields a unique fleet sizing solution and any solution in effect represents a range of results.

DEDICATION

Ek dra die werk op aan Yahweh, die enigste een wat ‘n ware sin vir tyd het en nie daaraan gebode is nie.

ACKNOWLEDGEMENT

I would like to thank Mr. Conri Moolman, Johan Beukes (Coaltech 2020 Program Manager) and my supervisor Mr. Cuthbert Musingwini (Lecturer, University of the Witwatersrand), who provided me with the means and support to conduct this study.

I also want to thank Vukani Shabalala (Mining Engineer, Optimum Colliery) for assisting me with the time study and gathering some of the data used in this report.

Finally, I want to thank Malathee Padayachy for her endless patience and support.

TABLE OF CONTENTS

1 INTRODUCTION 1
2 FACTORS OF PRODUCTION 5
2.1 Payload 6
2.2 Cycle Time 7
2.3 Variance in the Virtual Mine's Production Results 11
2.3.1 Mine Specific Design 11
2.3.2 Truck Characteristics 11
2.3.3 Real truck loading time 12
2.3.4 Operator proficiency 12
2.3.5 Ergonomics 13
2.3.6 Number of trucks and tipping points 13
2.4 Operator Proficiency 14

3 CYCLE TIME CALCULATION MODELS 16
3.1 Queue Model Notation 16
3.2 Elbrond Queue Model 17
3.3 FPC® (Caterpillar Software) 25
3.3.1 Process for FPC 26
3.4 Talpac® (Runge Software) 32
3.4.1 Description of a Monte Carlo Simulation 32
3.4.2 Stochastic Variable Parameters 33
3.4.3 Stochastic Variables in Talpac 34
3.5 Arena® (Rockwell Software) 35
3.5.1 Differences between Arena and Talpac 35
3.6 Adapted Machine Repair Model 38

4 DISTRIBUTIONS 43
4.1 Probability Density Function (PDF) 43
4.2 Histogram 46
4.3 Cumulative Distribution Function (CDF) 46
4.4 Major Distributions Characteristics 46
4.5 Chi²-square Goodness of Fit 47
4.6 Standard Error of the Estimate (S_{xy}) 51

5 DISTRIBUTIONS OF CYCLE VARIABLES (Orapa Case Study) 53
5.1 Process followed 53
5.2 Research Findings on distributions for cycle variables 54

6 MODEL COMPARISON FOR VIRTUAL MINE MODEL 56
6.1 Virtual Mine Layout 57
6.2 Cycle Variables of the Virtual Mine 59
6.3 Simulation in Arena® 60
6.4 Model Distribution Fitting 61
6.5 Main Observations in regards to the Loads per Shift 63

7 RISK CALCULATIONS FOR THE VIRTUAL MINE 65
7.1 Cycle Time Variation 65
7.1.1 Real Operator Proficiency 65
7.1.2 Payload Implications 65
7.1.3 Paper Mines 66
7.1.4 Dump Site Neglect 67
7.2 Sensitivity Analysis 67
7.2.1 Distribution Fitting 67
7.2.2 Sensitivity Analysis Results 72
7.3 Cashflow Risk 74

8 PRODUCTIVITY CALCULATIONS 77
8.1 Operating Active Hours 77
8.2 Interdependence of System Units 79

9 OPTIMUM COLLIERY CASE STUDY 82
9.1 Background 82
9.2 Geology 86
9.3 Material Characteristics 88
9.4 Simulation Process 88
9.5 Machine Standards 89
9.5.1 Machine Availability and Utilization 89
9.5.2 Cycle Components 90
9.6 Haulage Definition 91
9.6.1 Travel Distance 91
9.6.2 Speed Restriction 93
9.7 Operator Proficiency 94
9.8 Calendar Hours Breakdown 94
9.9 Productivity Calculation (TPH) 95
9.9.1 Site Scheduled Hours Distribution 95
9.10 Cycle Time Breakdown 96
9.11 Simulated Truck Requirement 98
9.12 Discussion of Simulation Results for Optimum Colliery 99

10 CONCLUSION 100

Appendix A: Loads per shift for the Virtual Mine 102
Appendix B: Results of Sensitivity using @Risk® 107
Appendix C: Cashflow Results for the Virtual Mine 109
Appendix D: Material Densities 113
Appendix E: Bucket Fill Factors 114
Appendix F: Travel Times in Optimum Colliery Case Study 115
Appendix G: Cycle Time Results for the Optimum Colliery Case Study 116

REFERENCES 121

LIST OF FIGURES

Figure 2.1 The Value Rainbow 5
Figure 2.2 Maximum Loads per 8 hr Shift, Arena 10
Figure 2.3 Travel Empty to Travel Full Relationship 14

Figure 3.1 Elbrond (1990) Queue Equation System 18
Figure 3.2 Elbrond ρP values 21
Figure 3.3 Elbrond ρA Values 21
Figure 3.4 ρA minus ρP variation with no. of trucks (Elbrond Model) 22
Figure 3.5 Accumulation of trucks and initial waiting time 23
Figure 3.6 FPC and EIA Simulation Process 26
Figure 3.7 FPC Matching vs. Bunching Correction Factor (BF) 28

Figure 4.1 PDF and CDF of Normal and Log Normal Probability Models 44
Figure 4.2 PDF and CDF of Exponential and Erlang Probability Models 45
Figure 4.3 Shovel service time observations 48
Figure 4.4 Chi² PDF 49
Figure 4.5 Observed frequencies and expected probabilities per category 50

Figure 6.1 Virtual Mine Layout 57
Figure 6.2 Typical hauling distances for mobile equipment 57
Figure 6.3 Simulation process in Arena® 60
Figure 6.4 Loads per Shift for Virtual Mine using Elbrond Model 62
Figure 6.5 Models Correlation with Arena (Virtual mine: loads/ shift) 63

Figure 7.1 Loads per Shift Results of Scenario 1 using FPC for the Virtual Mine 69
Figure 7.2 Difference in Percentile Values for the Virtual Mine 70
Figure 7.3 Cumulative Distribution Function, Elbrond (Virtual Mine) 71
Figure 7.4 Sensitivity Analysis Results: Elbrond (Virtual Mine) 73
Figure 7.5 Operator Proficiency on Distance (FPC) 74
Figure 7.6 Cashflow Difference Results of Elbrond vs. Arena for the Virtual Mine 76

Figure 8.1 Types of machine in Load-and-Haul Systems 80

Figure 9.1 Aerial photograph of the North (Rail) Section 83
Figure 9.2 Aerial photograph of the Central Section 84
Figure 9.3 Aerial photograph of the South Section 85
Figure 9.4 Section through North (Rail) Area 87
Figure 9.5 Section through Central Area 87
Figure 9.6 Section through South Section 87
Figure 9.7 Production Schedule (Feb. 06 – Jan.'07) 92
Figure 9.8 Cycle time breakdown results for Optimum using the Elbrond Model 97

LIST OF FIGURES IN APENDICES

Figure A- 1 Loads per Shift for Virtual Mine using FPC 103
Figure A- 2 Loads per Shift for Virtual Mine using Winston 104
Figure A- 3 Loads per Shift for Virtual Mine using Talpac 105
Figure A- 4 Loads per Shift for Virtual Mine using Arena 106

Figure B- 1 Sensitivity Analysis Results for Virtual Mine using FPC 107
Figure B- 2 Sensitivity Analysis Results for Virtual Mine using Winston 108

Figure C- 1 Cashflow Difference Results of FPC vs. Arena for the Virtual Mine 110
Figure C- 2 Cashflow Difference Results of Winston vs. Arena for the Virtual Mine 111
Figure C- 3 Cashflow Difference Results of Talpac vs. Arena for the Virtual Mine 112

Figure G- 1 Cycle time breakdown results for Optimum using FPC Model 117
Figure G- 2 Cycle time breakdown results for Optimum using Talpac Model 118
Figure G- 3 Cycle time breakdown results for Optimum using Arena Model 119
Figure G- 4 Cycle time breakdown results for Optimum using Winston Model 120

LIST OF TABLES

Table 2.1 Different Queue Models 8

Table 3.1 Kendall Notation for Queue Systems 16
Table 3.2 FPC Bunching Factor Selection 27
Table 3.3 FPC Production Calculation example 30
Table 3.4 Analogy between Machine Repair Model and Adapted Model for load-and-haul shovel- truck systems 40

Table 4.1 Major Characteristics of Distributions used in this research 46
Table 4.2 Chi² values for the Orapa load time example 49
Table 4.3 Hypothesis test results for the given example 51
Table 4.4 Standard error of estimate for given example 52

Table 5.1 Weighted Least Square Errors for distribution models applied to Orapa data 55
Table 5.2 Range of applicable distribution types for cycle variables for Orapa data 55

Table 6.1 Rolling Resistance Classification 58
Table 6.2 Machine an Cycle Variables for Virtual Mine 59

Table 7.1 Distributions fitted to cycle time variables for the Virtual Mine 68

Table 8.1 General Truck Calendar Breakdown 77
Table 8.2 Machine Hours Breakdown 78
Table 8.3 A Simple Calculation of Actual Production Hours 81

Table 9.1 Load Cycle Components 90
Table 9.2 Annual Production per Section 91
Table 9.3 Haulage Profile Breakdown 93
Table 9.4 Speed Restriction 93
Table 9.5 Calendar Breakdown (FPC and EIA) 94
Table 9.6 Site Hours Distribution (Tonnes per Annum per Area) 95
Table 9.7 Tonnes per Hour Results 96
Table 9.8 Simulated Truck Requirement 98

LIST OF TABLES IN APPENDICES

Table D- 1 Material Densities 113
Table E- 1 Bucket Fill Factors 114
Table F- 1 Optimum case study travel time (in minutes) 115

1 INTRODUCTION

Shovel-truck operations are generally discrete processes because truck loads are delivered to a destination like a dump site or plant tipping bin at somewhat variable intervals. Irrespective of what shovel-truck, load-and-haul mining method will be followed they all have the same load-and-haul cycle variables namely: truck spotting at shovel or loader, loading time, travel full time, travel empty time, spotting at destination (plant tipping bin or dump site), dumping time, waiting at shovel (or wheeled loader) and waiting at destination.

The aim of this study is to investigate some of the various methods of calculating cycle time and more specifically waiting time. The various models associated with these methods which are covered in this document are:

- Iteration methods with discrete empirical values fitted to cycle components.
  Example(s): Elbrond (1990), Winston (2004)
- Regressive models with waiting time as a function of fleet matching and bunching correction factors. They can also be described as static simulation algorithms which are driven by prescribed processing flow that is not dependent on time or interaction of resources.
  Example: FPC® (Caterpillar Inc.)
- Stochastic Monte Carlo type simulations with probability distributions fitted to cycle components e.g. Loader bucket payload, loader cycle time, truck payload, truck travel time and truck maintenance availability.
  Example: Talpac® (Runge Software)
- Stochastic graphic simulation methods with trucks and shovels (loaders) being represented with physical entities within a virtual environment following probability distributions within a Monte Carlo simulation environment.
  Example: Arena® (Rockwell Software)

Through the years there have been a number of other commercial software packages developed to calculate shovel-truck fleet sizes. Not included in this study is the Shovel Truck Analyses Package (STRAPAC) reported by Panagiotou and Michalakopoulos (1994). STRAPAC was a family of IBM PC programs that could be

used for the planning and analysis of shovel-truck systems. STRAPAC included deterministic and stochastic simulators that could be used to calculate cycle time depending on shovel-truck system characteristics. This program had the functionality to provide visual information of the system simulated generated in association with the GPSS/H® program (Wolverine Software Corp.). Today the STRAPAC™ name is associated with plastic holding ties produced by Sublett Co.

In a GPSS/H ® simulation model, transactions or blocks representing entities such as trucks compete for the use of system resources, for instance a shovel. As transactions flow through the process representation, they automatically queue up when they cannot gain control of a necessary resource in the same manner as trucks queue up at a loader. The modeller does not have to specify the transaction's waiting time or its queuing behaviour for this to occur. Hence the passage of time in a GPSS/H® model can be represented implicitly as in the case of a part waiting for a machine to become free or like a truck being loaded, or explicitly, as in the case of a part being processed by a machine or a truck sent for repairs. The software is versatile and can be used for underground mine simulations like work done by Dowborn and Taylor (2000). GPSS/H® was also used by Sturgul (1996) in a hypothetical surface iron ore mine simulation and reported satisfactory results.

Caterpillar developed a stochastic model called Vehicle Simulation (VEHSIM) in the late 1960's with basically the same program setup and functionality as their current Fleet Production and Costing (FPC) program. VEHSIM was primarily developed for sales and technical support for the 779 (85 ton) electric drive off-highway truck, but was discontinued with the truck's decline in use.

Vallée (2000) undertook a survey of the performance of mining projects world wide (eighteen major mine developments that took place between 1965 and 1981 were included). For each project, four questions were asked:

- Was the project on time?
- Did it expect any over run costs?
- Was the mine ultimately able to achieve design production level, if not why?
- Has the cashflow generated by the project met the forecast?

Highlights taken from this article are as follows:

- Even the best set of plans cannot always anticipate the variability encountered in real life mining. Cashflow generation is of paramount importance in achieving all set goals within any project.
- Reaching a designed level of production is important as it generates the cashflow needed to counter the high initial capital invested. Apart from the high investment in plant equipment, mining equipment will constitute a considerable portion of the total cost.
- In only 11% of all cases were the wrong type of equipment selected, which leaves it open to interpretation as to what importance the mineralogy or equipment capacity to produce featured in the total 67%.
- Reaching production levels does however weigh heavier towards equipment capacity and thus stresses the importance of adequate planning and optimal mine equipment utilisation and processing infrastructure.
- Equipment utilisation involves the analysis of cycle time. It thus follows that for a scoping or planning exercise it is important to include as much variability as possible, which involves fitting distributions on as many cycle components as possible. It is also important to understand the underlying assumptions which govern the results of any particular fleet sizing program or model used as their results differ.

Project planning and execution has, since this article was published; significantly improved the production and economical potential of projects. The importance of this article's findings is however, timeless.

One of the variables impacting on the cycle time efficiency of a haul truck is the waiting time observed at destinations. Waiting time is thus inherent within any load-and-haul system and can have a minor or major role in influencing system efficiency. The calculation of waiting time is complicated as it is a function of all other load-and-haul cycle variables for a specific load-and-haul system and should such system be a sub-system of a larger system, it becomes even more complicated. Waiting time is thus a dependent variable amongst the cycle time components. Should waiting time be the only cycle time variable that is underestimated, then the implication is an

“under-equipped” operation not able to realize planned production targets. This loss in potential production due to waiting time might not be noticed at first as there are a multitude of other factors such as human, geological, technical and environmental factors which can lead to, either directly or indirectly, production losses. It is therefore vital to answer the question as to what role waiting time will play in a system in determining operational and economical efficiency.

This study starts by investigating the main factors of production these being payload, cycle time and operator proficiency and how they interact and influence the cycle time efficiency of a shovel-truck, load-and-haul system on surface mines. The Elbrond, FPC, Talpac, Arena and Machine Repair models are then discussed to explain how their model characteristics contribute to the differences in their reported productivity results. A reason as to why the various models each provide their own unique solution is due to the way they process the cycle time variables in calculating total truck cycle time which includes waiting time. The Machine Repair Model based on Markov chains is adapted for shovel-truck systems and examined for calculating shovel-truck cycle times.

This document examines the various probability distributions that can be used to model particular cycle time variable and some methods in selecting the “best” fit. The truck cycle time variable sensitivity is examined using the Excel® add-on program, @Risk (Palisade Corp.), in determining their respective weighting or contribution within the total cycle time variability.

In general, when determining a fleet size for a particular surface operation, the planning engineers will use one or to a lesser extent two separate models. This study calculates the productivity (tonnes per hour) for a “virtual mine” with a variable number of trucks, variable cycle distances and variable truck loading times. This study also includes a separate study of cycle time variables and their probability distributions for the Orapa diamond mine in Botswana.

The study concludes with a calculation of the truck fleet size using the Elbrond, FPC, Talpac and Arena and Machine Repair models for the Optimum Colliery coal mine and then compares their results and examines their correlation.

2 FACTORS OF PRODUCTION

There are a multitude of variables that influence the load, haul and dump process. The three main production factors - truck payload, cycle time and operator efficiency– and their relation to some of the other variables are illustrated in Figure 2.1

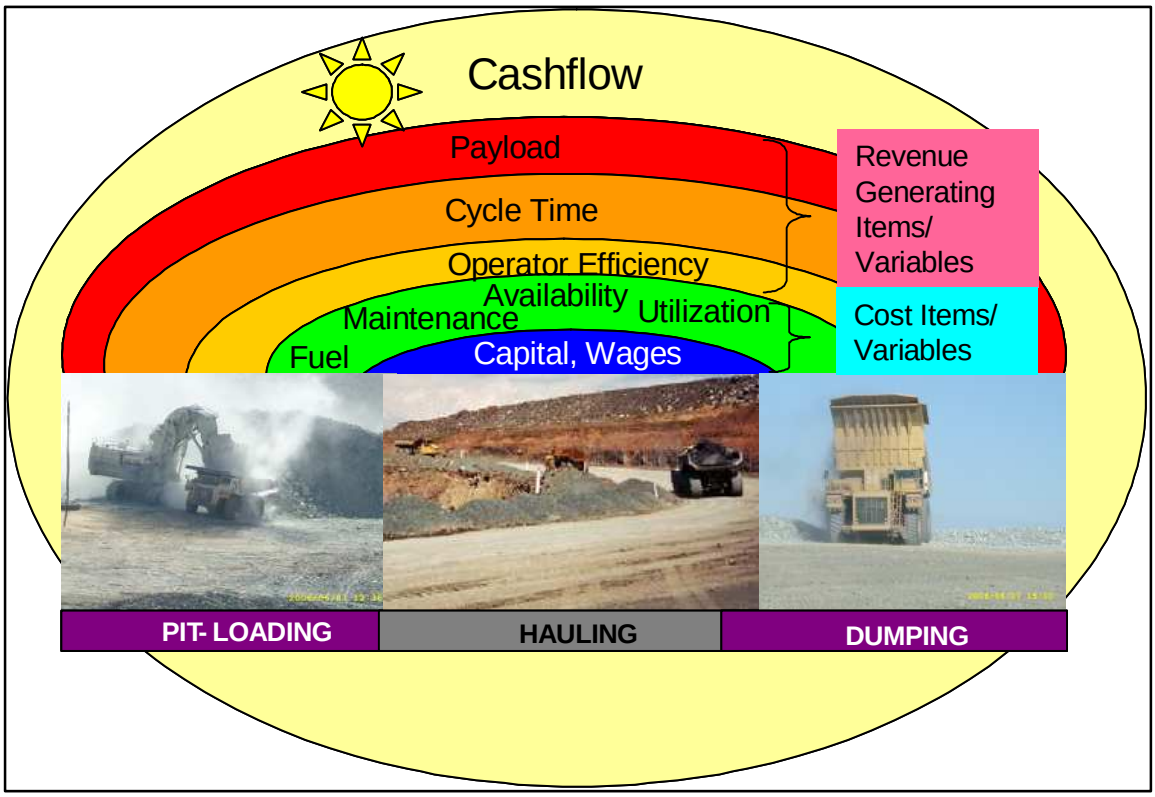


Figure 2.1 The Value Rainbow

For a load-and-haul system, production involves loading, hauling and dumping. The bands within Figure 2.1 can be described as a "value rainbow" with the revenue related variables placed higher due to their relative importance in realising cashflow goals. Mining operations generally focus only on the loading area but, Figure 2.1 shows that hauling and dumping are equally important in realizing cycle efficiency and most importantly cashflow. Inherent to these main variables is the concept of waiting time. Waiting time is in effect a natural occurrence throughout the load-and-haul process with the main load-and-haul cycle stages as follows:

- Waiting at shovel (or loader)
- Truck spotting at shovel or loader (loading unit)

- Loading time
- Travel full time (can include bunching or waiting for slow haulers on ramps).
- Waiting at destination
- Spotting at destination (plant tipping bin, stockpile or dump site)
- Dumping time
- Travel empty time (can include bunching or waiting for slow haulers on ramps).

The relevance and complex interaction of these variables with load-and-haul fleet production, in relation to the three factors of production, is discussed in the following sections.

2.1 Payload

The volume to be conveyed by the hauler is fixed for a specific piece of equipment. Calculating the number of haulers to satisfy the production requirement will mainly depend on the pit profile, haulage route, hauler speed (rimpull and retarding performance) and thus the cycle time.

The impact of these variables can be minimised by focusing on training and adopting sound maintenance standards and practices. There is technology available such as Caterpillar's VIMS (Vital Information Management System) and its CAT 20-10-10 payload policy which monitors machine performance under load and directly improves machine availability. The CAT 20-10-10 payload policy, Caterpillar (2002, p.1); states that: *"The mean or average of the payload distribution shall not exceed the target payload and no more than 10% of payloads may exceed 1.1 times the truck target payload and no single payload shall ever exceed 1.2 times the target payload."*

The relationship between payload and waiting time is linked to the cycle time variables of the haulage system. For a specific haulage network a specific truck size and loader is selected. The number of trucks within a selection will predominantly determine the amount of waiting time in the system. As mining progresses further or deeper from the starting point (ramp, crusher or conveyor) the haulage distances in such a system will increase with time warranting an increase in the number of trucks.

The attempt to maintain the initial level of production with the associated increase in the number of trucks will result in an increase in waiting time. Curbing the effective productivity loss of an individual truck within the fleet might force the initial system design to migrate towards a larger truck payload. Waiting time thus tends to increase truck payload demands.

2.2 Cycle Time

Cycle time is a function of service components, machine characteristics (e.g. loader bucket size, truck ability to travel on grade), machine efficiency (shovel cycle time, truck dumping time), material characteristics (e.g. material density, loading unit's bucket fill factor and swell) and system characteristics which involve issues like the number of servers and queue discipline. The aforementioned variables and their variability can be determined with some ease but waiting time is a system dependent variable and is more complex to determine.

There are several methods for calculating cycle time and choosing the method to use is primarily driven by the time available to set up a system representing the reality and level of accuracy that is needed in the results.

In general, a Monte Carlo simulation process will yield higher levels of accuracy compared to a queuing model using iterative calculations in that more variables can be incorporated and fitted with their probability distributions within a simulation. Higher levels of detail can thus be simulated for example individual machine availability and machine repair cycles.

In selecting iterative queue models there are a number of layouts that can be used and these are summarized in Table 2.1, (Chase, Richard B., Nicholas J. Aquilano and F. Robert Jacobs, 1995).

Table 2.1 Different Queue Models

Model	Layout	Service Phase	Source Population	Arrival Pattern (Rate)	Queue* Discipline	Service Patterm	Permissible Queue Length	Typical Example
1	Single Channel	Single	Infinite	Poisson	FCFS	Exponential	Unlimited	Drive-in Teller
2	Multi Channel	Single	Infinite	Poisson	FCFS	Constant	Unlimited	Roller Coaster
3	Single Channel	Single	Infinite	Poisson	FCFS	Exponential	Unlimited	Parts Counter
4	Single Channel	Single	Finite	Poisson	FCFS	Exponential	Unlimited	Machine Breakdown and Repair Shop

**FCFS: First Come, First Served*

As can be seen from Table 2.1, arrival patterns (trucks) and service patterns (loader) follow some form of distribution. In mining, service is seldom constant and can be expected to follow a distribution pattern. Reasons for this can be: material fragmentation changes with a change in geology and blast technology and/or efficiency, machine life-cycle changes and deviation from Original Equipment Manufacturers (OEM) standards, operator technique (multi shift operations) and environmental factors (night time visibility, climate). In general, a load-and-haul system can be described as model 4, the Machine Repair Model. That is, trucks represent a finite source population and can have a service pattern (loading time) that follows an exponential distribution with their arrival rate (trucks arriving per time unit) following a Poisson distribution. In reality the probability distributions representing the service times and inter-arrival rates can follow any probability distribution such as normal distributions, triangular distributions or lognormal distributions.

Figure 2.2 depicts the maximum truck loads for a specific truck fleet size and shovel service time that can be expected over a haul route with an increase in distance. Figure 2.2 is based on a virtual mine with 10 m high benches that extend down to a depth of 135 m. Its ramps have a 6% grade resistance and all haul roads have a 4% rolling resistance. It further assumes that inter-arrival rates follow a Poisson distribution with inter-arrival time and service time at both the loading unit and dump destinations following an exponential distribution. The half cycle travel distance ranges between 600 m and 2200 m.

Figure 2.2 has several features:

- The loads per shift values are for shift a duration of 8 hours with 30 minutes deducted for shift change. The total active shift minutes are thus 450.
- The shovel follows a single side loading technique. While the shovel is loading a particular truck other trucks are not allowed to approach the shovel.
- As the service time increases, the loads delivered decrease.
- The loads delivered decrease with an increase in travel distance.
- The loads delivered increase with an increase in trucks in the circuit.
- The low-end shovel/ loader service time (3 minutes excl. hauler exchange) reaches a 140 loads/ shift "ceiling" with an increase in truck numbers.
- The mid-range loading unit service time (4 minutes excl. hauler exchange) reaches a 110 loads/ shift ceiling with an increase in truck numbers.
- The high-end loading unit service time (6 minutes excl. hauler exchange) reaches a 95 loads/ shift ceiling with an increase in truck numbers.
- The lower-end service times series (3 minutes) experience a higher rate drop in loads per shift with increase in truck numbers and illustrate the effect distance (travel time) and queue have on the system performance.
- Within a particular service time series (loader total service time) and with an increase in distance it is also seen that as the number of trucks increase the rate change becomes lower. This can be explained by the greater number of trucks that support a particular load per shift level with an increase in distance.
- The incremental change in loads per shift and increase in truck numbers also highlights the effect that with an increase in truck numbers the benefit of each additional truck decreases. In effect the introduction of more trucks into the system will increase the loads per shift but the individual truck efficiency is lowered due to the higher total waiting time which is a function of the number of trucks in the system.
- Looking at the loads per shift curves (within a service time series and with increase in service time), it appears that there is some underlying power function that governs the system's results. This will be investigated in later sections.

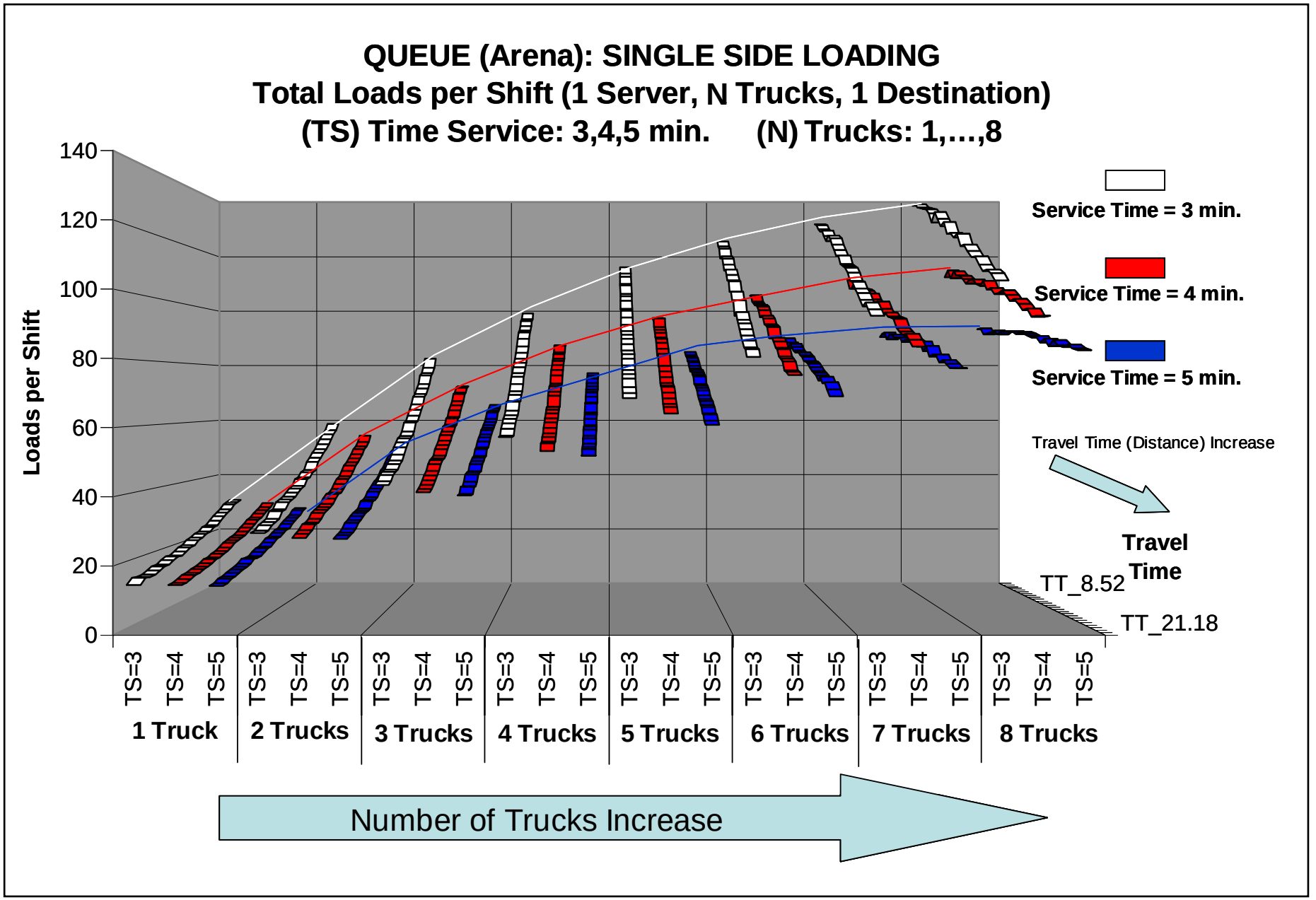


Figure 2.2 Maximum Loads per 8 hr Shift, Arena

A loading unit might predominantly be allocated to a specific material type or production zone based on its setup of ground engaging tools (GET), bucket type (rock bucket or bucket for soft material) and bench characteristics (matched to its maximum reach or ability to load trucks). Trucks however can in most cases be loaded anywhere in a mine production environment provided that the loader can load them.

2.3 Variance in the Virtual Mine's Production Results

The loads per shift results of Figure 2.2 are not fixed and can change. This will be explained in the following sub-sections on mine specific design, truck characteristics, actual loading time, operator proficiency, ergonomics and number of trucks.

2.3.1 Mine Specific Design

The travel time full versus empty travel time (ratio) is a function of a mine's design or production method. Open pit mines are more sensitive to ramp design compared to bench stripping operations where more emphasis is placed on bench road conditions. Bench striping operations with a generally lower number of ramp switches and bends (depending on the pit depth) can have a lower difference between the individual full and empty travel times compared to quarries and pits where the average full and empty travel times are wider apart compared to the fore mentioned (more ramp travelling on grade).

2.3.2 Truck Characteristics

Machine gradeability and retardability influences its travel time full (TF) versus empty travel time (TE), ratio, and varies between the different manufacturers and types of technology (electric drive vs. mechanical drive). For a truck with a lower travel time full versus empty travel time (ratio) or a truck with less engine power a lower total cycle speed can be expected which will decrease its loads per shift.

Truck bowl design can also affect truck productivity. There are two types of bowls, standard truck bowls and Mine Specific Design's (MSD). Both influence the weight of the truck, its sensitivity to underfoot condition and its total cycle travel time.

There is currently a debate between the real benefit of electric drive trucks with their high under-the-line speed (at low fuel consumption) and the real Panto-graph utilization as a percentage of the total course distance (higher of-the-line fuel consumption due to added weight of Panto structure on the truck).

2.3.3 Real truck loading time

Loading method can be a single sided or a double sided loading technique. In the case of double sided loading, the shovel utilizes the second side to dig while a truck is spotting to provide a reduced loading cycle or an approaching truck utilizes the open space to reduce its waiting time. Double sided loading is in effect a combined single and double sided method, this is due to such a shovel periodically loading on the high wall side as the muck pile is being loaded out. When loading on the high wall side the second side is blocked by the shovel which increases the total service time and reduces the second loading side benefit. Figure 2.2 was constructed for discrete service times of 3, 4 and 5 minutes, with real truck loading times that can differ and either cause higher or lower truck productivity.

2.3.4 Operator proficiency

Adequate and continuous training of operators can lower service time and increase productivity. Machine features that enhance machine control and manoeuvrability such as operator controls and hydraulic control features, such as Caterpillar's Auto Dig feature with the machine automatically performing certain dig and load operations more proficiently, can reduce service time. In general, a lower truck service time can increase truck productivity.

2.3.5 Ergonomics

The move towards continuous operations driven by high commodity demand and the need to lower operating cost and increase worker productivity has operators working 12 hour shifts. Machine comfort and operator isolation from elements such as temperature, dust and sound therefore becomes paramount in ensuring continuous optimal productivity through consistent service time. This also applies to the trucks and truck operators and their impact on travel time, queuing at destinations, the shovel's productivity and the loads per shift delivered.

2.3.6 Number of trucks and tipping points

The individual shovel and truck circuits, dependent on the number of tipping points at the plant destination and the collective number of trucks sharing such facilities, will individually suffer a reduction in their performance which is proportional to the percentage of the total truck number. Waiting time features as the main driver in such instances. In an open-end circuit such as a dump destination (no server), the possibility exists that the support equipment is not available or that dumping space is constricted which will cause the loads per shift to decrease.

The above examples serve to illustrate the dynamic environment within which load-and-haul systems function causing performance to vary. There are other issues like workers striking, unexpected changes in geology or market demand that can change the current system and thus the system performance.

Figure 2.3 is constructed for 8 mine trucks (CAT 769D to Cat 793C) with varying payloads and illustrates the impact that grade % (road inclination) and rolling resistance % (condition) has on the travel time empty to travel time full ratio. In general, the lower the total resistance, the lower the difference in load speed and the faster the over-all system will be.

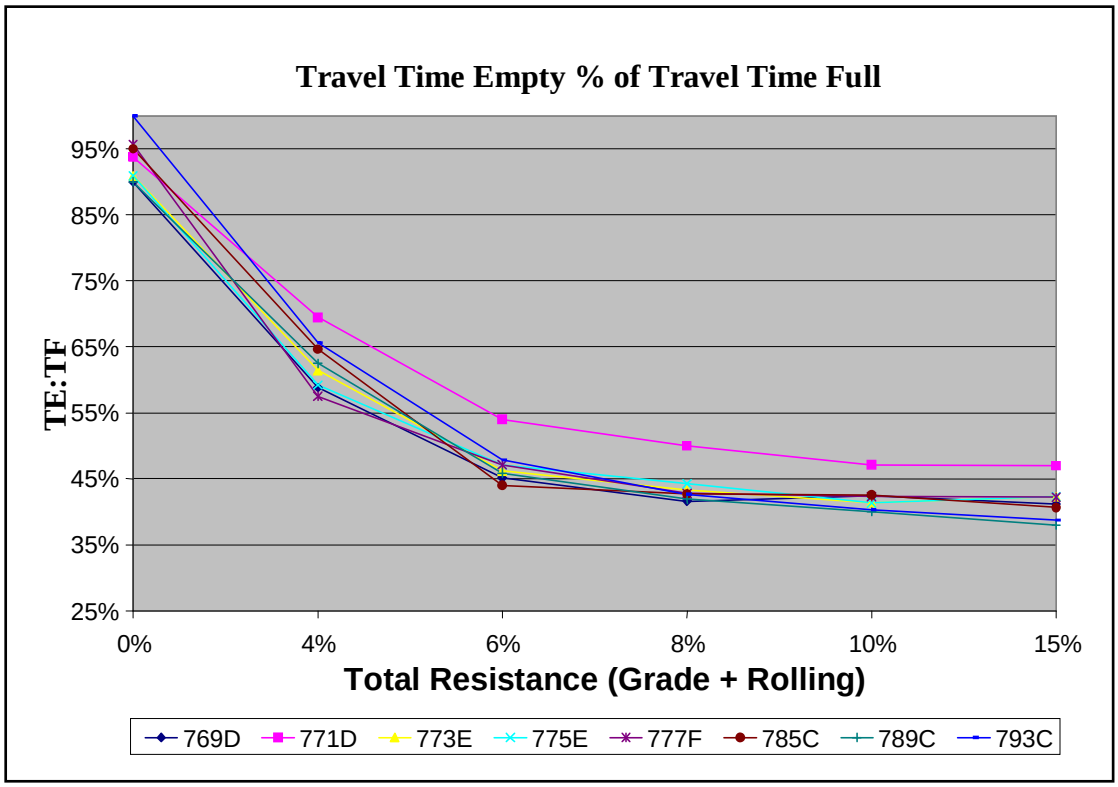


Figure 2.3 Travel Empty to Travel Full Relationship

Figure 2.3 shows that where there is no grade percentage, such as on a flat road segment, the travel times of an empty truck are about 95% compared to that of a fully loaded truck and the difference increases as a fully loaded truck is subjected to grade.

2.4 Operator Proficiency

Proficiency refers to being competently or well qualified physically and intellectually in a required skill and is a better way to describe human efficiency. Production tonnes are directly reduced by the combined proficiencies of the truck and shovel operators and to a lesser extent the plant operator. Plant operators, on the mine side interface, use rock hammers for the size reduction of material flowing through tipping grids. Apart from the shovel, truck and plant operators there are secondary equipment operators using wheel loaders or dozers for dump management.

It is thus vital to ensure that this resource is adequately trained to ensure optimal safety, optimal production and subsequently the optimal cash flow is obtained and maintained.

A few ways in which operator proficiency influences cycle times and thus waiting time is described:

- Lunch Breaks

  When a shift starts the trucks will generally bunch, with bunching gradually clearing with time. A reason for this is that operators on a specific shift will enter the system at the same time normally from a communal parking area. Should there be a number of loaders in a fleet serving these trucks preference will be given to certain loaders based primarily on availability and production priority. The shovels are said to be "non- collaborative" with each other or certain shovels are over-trucked in order to reach a set priority. With time progressing into the shift they might become more collaborative which will alleviate the bunching of trucks. Should lunch breaks not be managed it can lead to a "virtual" shift re-start which will cause bunching or waiting time to increase and shift productivity to decrease.
- Training and skill of shovel and truck operators

  Operators are the only single variable present throughout the whole system. They thus affect most of the load-and-haul variables in a direct and indirect way. Loading methodology is an art on its own to ensure maximum machine performance and protection. Adequate training also ensures enhanced operational performance and thus cashflow generation, machine protection and thus machine availability and reduced maintenance and repair cost. An operator not fully proficient might incorrectly align the shovel to the face and truck loading position which will cause inefficient digging and discharge of the load into the truck bowl. The total load cycle will be longer and can cause truck loading cycles to be longer. Longer truck loading cycles will eventually lead to a higher probability for trucks to bunch or queue at either the shovel and or the dumping destinations.
- Bad habits such as the over-loading of trucks results in higher service times and disrupts truck cycles leading to increased waiting time. Its negative effects cascade throughout the system with machine structures prematurely failing causing unavailability which reverts back to heightened pressure on the remaining equipment.

3 CYCLE TIME CALCULATION MODELS

In this section the various methods that exist for calculating cycle time will be discussed. It should be noted that waiting time or queuing time is integral to the calculation of cycle time.

The models that will be examined are:

1. Elbrond (1990), an iterative queue model.
2. Winston (2004), an iterative queue model based on the Machine Repair Model.
   These two are iterative methods, hence can be simulated in Excel.
3. Talpac® (Runge Software), a stochastic Monte Carlo type simulation.
4. FPC® (Caterpillar's: Fleet Production and Costing), a regressive model.
   Both these models are commonly used within the mining industry.
5. Arena® (Rockwell Software), a graphic Monte Carlo simulation.
   Arena can be programmed with any probability model and will be used as the benchmark for this study.

3.1 Queue Model Notation

Kendall (1951) devised a notation by which any queue system can be described by using 6 characters shown in Table 3.1 (Winston, 2004).

Table 3.1 Kendall Notation for Queue Systems

<table>
<tr><th colspan="7">Kendall Notation (1,2,3,4,5,6)</th></tr>
<tr><th>Notation Number</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Component</td><td>Inter Arrival Time</td><td>Service Time</td><td>No. of Parallel Servers</td><td>Queue Discipline</td><td>Customers in Service and Waiting</td><td>Population Size</td></tr>
<tr><td rowspan="4">Variation or Description</td><td>Independent, Identically Distributed (idd)</td><td>Independent, Identically Distributed (idd)</td><td rowspan="4">Number of e.g.. Tipping bins or number loading sides at a loading unit</td><td>FCFS: First Come, First Serve</td><td rowspan="4">At individual Server</td><td rowspan="4">Population from which customers (e.g.. Trucks) are drawn and can be infinite</td></tr>
<tr><td>Interarrival Times are idd and deterministic</td><td>Interarrival Times are idd and deterministic</td><td>LCLS: Last Come, Last Served</td></tr>
<tr><td>Interarrival Times are idd and Erlangs with shape parameter k</td><td>Interarrival Times are idd and Erlangs with shape parameter k</td><td>SIRO: Service in Random Order</td></tr>
<tr><td>Interarrival times are idd and governed by some general distributions</td><td>Interarrival times are idd and governed by some general distributions</td><td>GD: General Queue Discipline</td></tr>
</table>

As an example: M/M/R/GD/K/K describes the Machine Repair model with the inter-arrival times and service times both having an exponential distribution, with *R* repair bays, *K*-trucks serviced by some general queue discipline and with the 2nd *K* stating that the trucks come from a population with size *K*.

Definitions:

independent, identical distributed (iid)

Preceding inter-arrival rate or service time provides no indication as to subsequent inter-arrival rates or service times. The remaining time leading to the following inter-arrival rate and / or service time is not dependent on the current time or past values but is governed by some general distribution.

Deterministic

Inter-arrival times and service rates have zero variance.

3.2 Elbrond Queue Model

Elbrond (1990) devised a system of queuing equations that combined work done by three other persons on queue systems, based on three system conditions:

- Average service time that has random length and is equal to the standard deviation of the service time, with a return time (average) that is random and equal to its standard deviation. This was based on work done by Posner and Berholtz (1967).
- Service time that is constant (deterministic) with the return time being random. This was based on work done by Ashcroft (1957).
- Service and Return time are both constant (trivial case).

The simplest load-and-haul system has two servers, the shovel and the tipping bin or crusher (or dump site) and this will now be discussed.

The following notation is used to describe the system:

TS: Service Time

STS: Standard deviation of service time

RT: Return time

SRT: Standard deviation of return time

N: Number of clients

k = TS / RT

ρP : Utilization factor of Palm (1947)

STE: Standard deviation of travel empty time

ρA : Utilization Factor of Ashcroft (1957)

WP: Palm's (1947) waiting time

WA: Ashcroft's (1957) waiting time

WB: Waiting time in constant case

WS: Adjusted waiting time

TF: Travel Time Full

TE: Travel Time Empty

STF: Standard deviation of travel time full

The interpolation procedure:

The queue system can be graphically illustrated as shown in Figure 3.1.

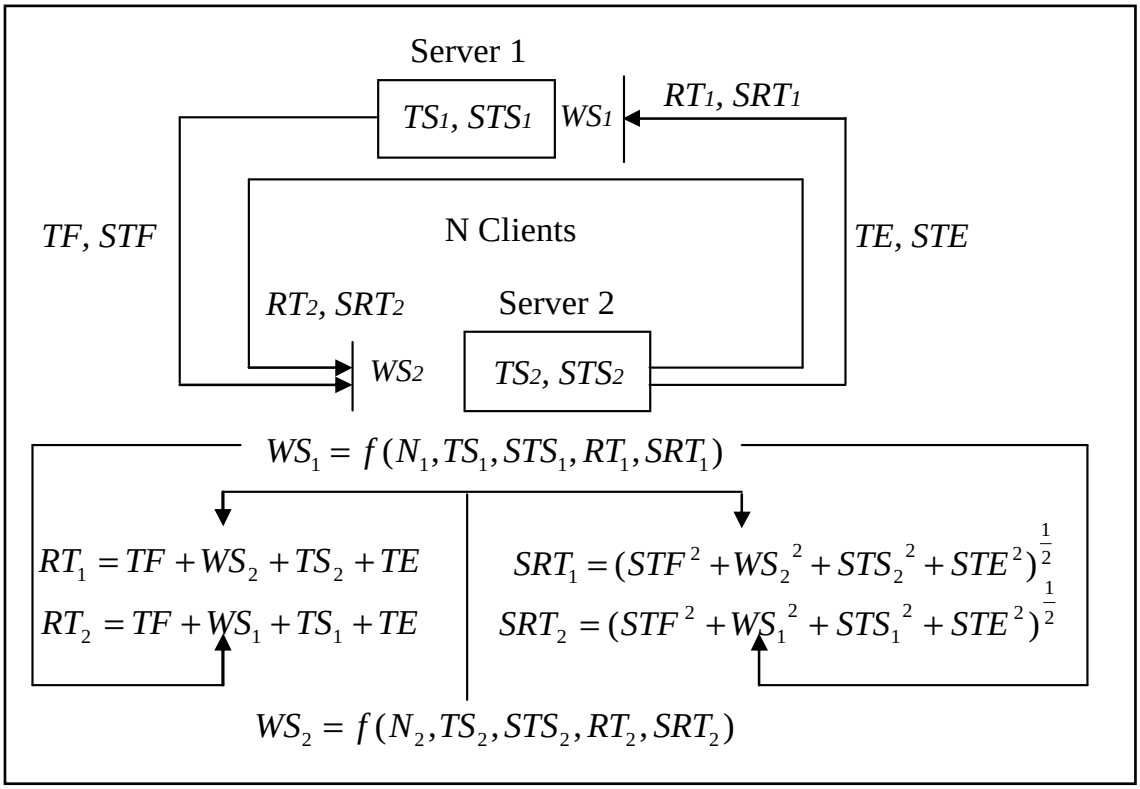


Figure 3.1 Elbrond (1990) Queue Equation System

Figure 3.1 is for a system with one server (shovel) loading trucks which dump at a single destination server (plant or dump).

Elbrond (1990, p 744) describes the calculation process as follows:

"…the waiting time (WS_1) at the first server is calculated using the service time (TS_1) and the return time (RT_1), which is known and which is the sum of the travel time (TF) to the second server, its service time (TS_2) and the travel time (TE) back to the first server. The standard deviation (STS_1) of the service time is known and the standard deviation (SRT_1) of the return time is estimated as the statistical sum of the component's standard deviations…. The calculation is then reversed to the second server, whereby the waiting time (WS_2) at the server is calculated using the service time (TS_2) and the return time (RT_2), which is now known, namely the sum of the travel time to the first server (TE), just calculated waiting time at the first server (WS_1), its service time (TS_1), and the travel time back (TF). The standard deviation of the service time (STS_2) is known and the standard deviation of the return time (SRT_2) is estimated…hereby the standard deviation of the estimated waiting time is assumed to be equal to the waiting time itself. The procedure then reverses to calculate a new waiting time using the second server in the return time".

For this procedure, Waiting Time (WS) = $f(WP, TS, STS, WA, SRT, WB, RT)$ with the formulae as follows:

$$WS = WP * \frac{STS}{TS} + 2 * WA * (\frac{1 - STS}{TS}) * \frac{SRT}{RT} + WB * (\frac{1 - STS}{TS}) * (1 - \frac{2 * SRT}{RT}) \quad (3.1)$$

$$\rho P = 1 - [1 + \sum_{n=1}^{N} \prod_{i=1}^{n} \{(N - i + 1) * k\}]^{-1} \quad (3.2)$$

$$\rho A = 1 - [1 + \{N * k * (1 + \sum_{n=1}^{n-1} \prod_{i=1}^{n} \frac{(N - i) * (e^{k*i} - 1)}{i}\}^{-1}]^{-1} \quad (3.3)$$

$$WP = N * \frac{TS}{\rho P} - (TS + RT) \quad (3.4)$$

$$WA = N * \frac{TS}{\rho A} - (TS + RT) \quad (3.5)$$

$$WB = N * TS - (TS + RT) \quad (3.6)$$

Elbrond's method, 1960-1970, was based on empirical observations calculating the relationship of WP, WA, WB in terms of two ratios STS/TS and SRT/RT ratios. In his observations both these ratios were about 0.3 indicating that the various systems had a varying degree of randomness, with zero randomness representing a deterministic case.

The concept where the number of trucks (N) in the system multiplied by the service time (TS) is reduced by the sum of the service time and the return time (excluding waiting time at the server, which needs to be calculated) will also feature later when the calculation method used by FPC is examined. It effectively calculates the difference in time a truck spends at the loading unit and the time it spends away or alternatively, the shovel matching. Should the time spent away from the shovel be high, the shovel will be under-utilized and is said to be under-trucked. It then follows that with the net sum being high (short haul distance) the adjustment will be high for the various types of randomness, which has a specific inter-relationship calculated by Elbrond (1974).

Apart from ρP and ρA being functions of the TS/RT ratio (k) and the number of trucks (N), examining the nature of ρP in Figure 3.2 and ρA in Figure 3.3 provides insight to the degree of randomness and underlying power functions that can be present in a system.

In Figure 3.2 and Figure 3.3 it can be seen that the WP and WA are driven by power functions with both ρP and ρA that increase with an increase in truck numbers present in a circuit and decrease as the return time decreases (i.e. when TS/RT reaches one).

Alternatively, for a fixed number of trucks, as the time trucks spend away from the shovel increases (less queuing e.g. longer haul distances) the ρP and ρA values will both decrease thus decreasing the WP and WA values. As the waiting time at the server WS is the sum of WP, WA and WB, all decreasing; it follows that the waiting at the shovel will decrease as in the case of trucks having an increase in haul distance.

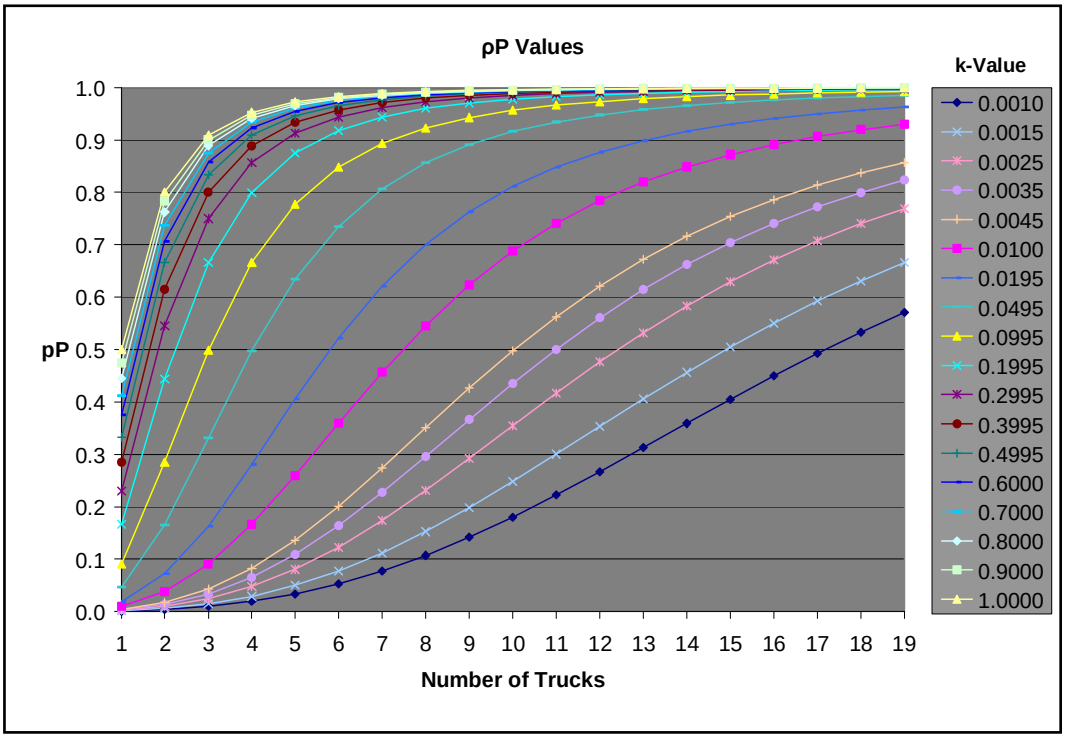


Figure 3.2 Elbrond ρP values

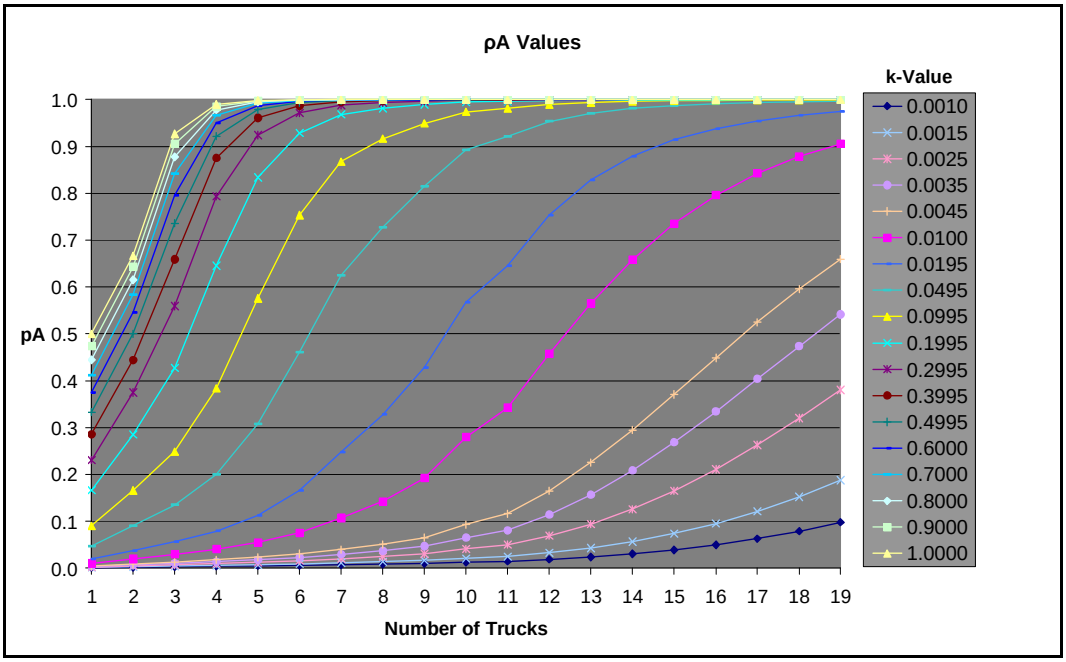


Figure 3.3 Elbrond ρA Values

Figure 3.4 shows that within Elbrond's model, irrespective of the shovel matching; an increase in truck numbers will cause the system to become less random ($\rho A > \rho P$). It also shows that in all cases of shovel matching there is a turning point where the system

becomes more random with an increase in the number of trucks. This might be explained in cases where a higher number of trucks will cause the inter-arrival rate to increase which causes queuing to increase and places the shovel under pressure. A practical example of this is when the load rate of a shovel increase, the frequency of a shovel to relocate to other points in the muck pile will increase, this combined with other activities like the movement of the electric cable mast poles will cause the service rate to vary and thus add more randomness to the system.

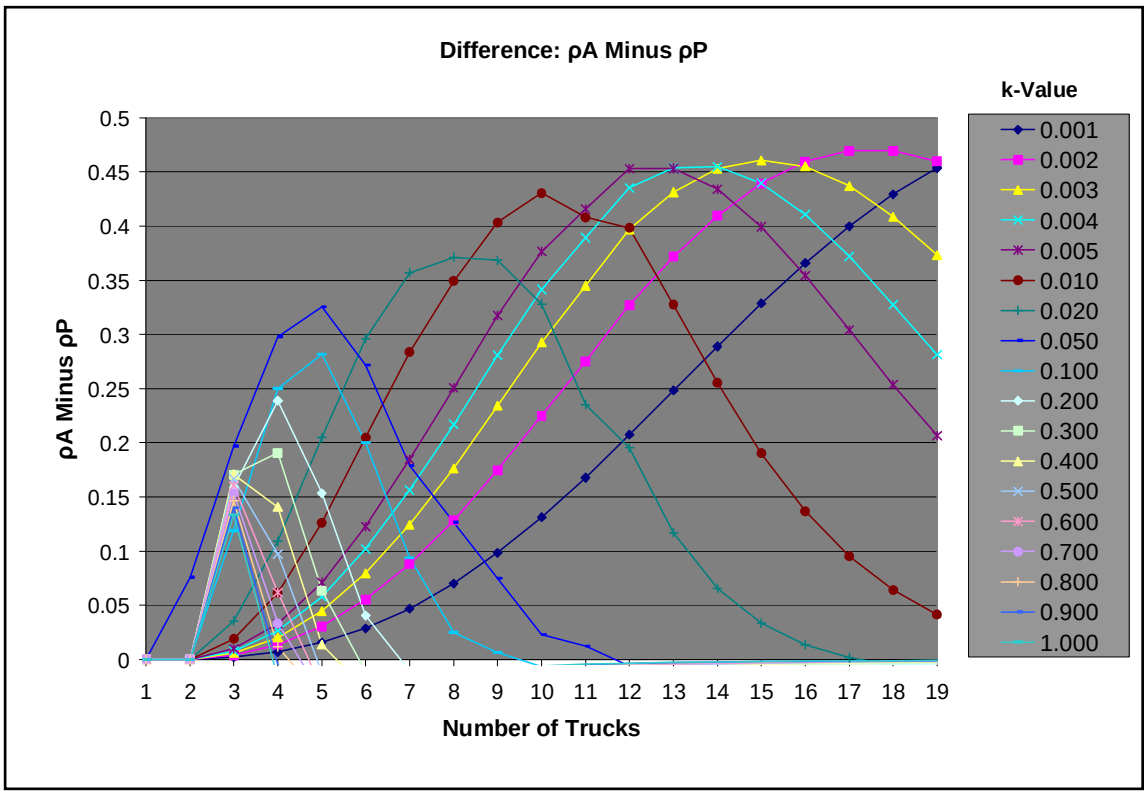
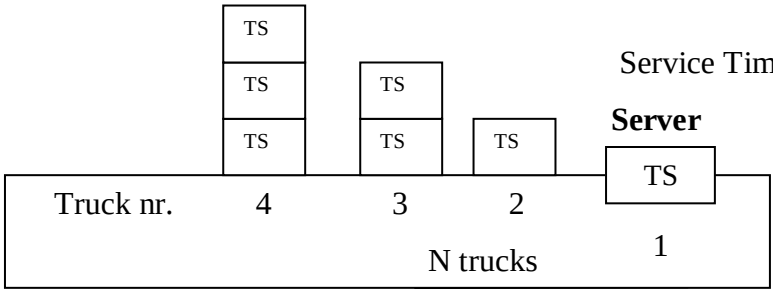


Figure 3.4 ρA minus ρP variation with no. of trucks (Elbrond Model)

The main observations made from this model are as follows:

- There is a degree of randomness within any queue system and this is explained by variance in the cycle components.
- The TS/RT ratio is important as it bears directly on the size of the queue that can be expected.
- Calculating the net cycle time involves calculating the waiting time which is an iterative process involving both end-servers being the loading unit and dumping destination.

The average waiting time trucks will experience at a server in a single side loading scenario is shown in Figure 3.5.



$$Avg.Waiting = TS * \sum_{n=2}^{N} \frac{(n-1)}{N} \qquad (3.7)$$

Figure 3.5 Accumulation of trucks and initial waiting time

Figure 3.5 shows that the waiting time follows a power series.

Reasons why trucks might be in this situation are as follows:

- Shift start up, with trucks leaving a communal parking area where pre-shift inspections and safety talks are usually conducted.
- Relocation of a shovel, with trucks temporarily sent for service or relocated to other shovels while the shovel move is conducted.
- In the field lunch breaks with the single most important operator, the shovel operator, not in operation.
- After a shovel has received an in-field service or after a breakdown.
- Cable moves in the case of electric driven shovels and where the shovel is used to move the heavy electric cable.
- Shovel relocation due to blasting operations and move to a safe distance.
- Queue at repair bays.

From the above it can be seen that queuing in load-and-haul systems is unavoidable and is actually a very natural part for this type of system.

There are various ways to alleviate the compounded impact that such disruptions have on truck productivity as listed below:

- Making use of relief operators for the shovel operators (lunch breaks, stop for toilette) or multi-skilling shift supervisors to assist in such instances.
- Leaving some of the empty trucks at the shovel at the end of a shift to split the trucks in distance and time by a take over shift. The truck and shovel operators coming on duty are normally transported to the shovel with a light utility vehicle to speed up the process of pre-shift checks preformed on the equipment.
- Leaving full trucks waiting to tip at plant or crusher destinations just prior to shift end. This has the same effect as the previously mentioned point in that pressure is removed from the shovel with the next shift's start up.
- Using technical personnel such as diesel mechanics who are not directly part of the mining production personnel to examine the equipment during shift start up (especially at the shovel/ loader), thus removing that time consuming action from the operators.
- Where the number of technical personnel is low the skilling of operators to effectively monitor the equipment during their shift can prevent sudden unexplained failures with the following shift's start.
- Installing auto machine diagnostic systems on the equipment to speed up the machine inspection process enabling the shovel-end of the system to start up faster. Caterpillar has such systems available e.g. VIMS®
- Proficient planning of services and balanced machine allocation made possible by adequately trained and equipped production personnel. Production scheduling software such as Modular System's Dispatch® program which monitors truck and shovel production can be used to assist schedule personnel to monitor and control truck allocations. This scheduling software is however a reactive system based on a set plan and real time fleet availability. Such software manages a fleet in real time but cannot make forecasts needed for planning and does not provide a production plan.
- Having secondary production equipment or "construction" equipment that are highly mobile like diesel driven front end loaders that closely match the primary

fleet sizes to assist the primary equipment with shift start up or in the event of breakdowns.

Elbrond (1990) also presented other systems to calculate the cycle time for systems with two circuits that can be expanded to accommodate more loading units to a specific destination and also a machine repair circuit to calculate the waiting time at machine repair bays.

Maintenance extracts trucks from the system and will in effect reduce the number of trucks in a specific circuit and thus reduce the waiting time and reduce the circuit time or net truck cycle time. The combined circuit productivity will however suffer the loss of such a truck for the portion of time it is sent for maintenance. In most commercial software provision for such maintenance related production loss is made by the reduction of production hours. The reduction of available production hours will cause any such calculation to increase the required tonnes per hour requirement which will result in either a truck payload increase and / or an increase in the truck population size.

3.3 FPC® (Caterpillar Software)

Fleet Production and Costing (FPC) is a PC software tool designed to estimate the productivity, cost, and time required for a wide variety of earthmoving or other material handling fleets, to move material from one location to another over one or more courses. FPC is widely used as the first method for establishing a potential customer's fleet requirements.

FPC is further used as an input to Equipment Investment Analysis (EIA), a Caterpillar software for calculating the financial implication of a selected fleet in FPC. The main drivers of EIA are haulage variables. These variables are travel full, travel empty, load time, dump time, spot or exchange time and waiting time which are calculated by FPC.

3.3.1 Process for FPC

Figure 3.6 shows the process followed for a typical FPC simulation.

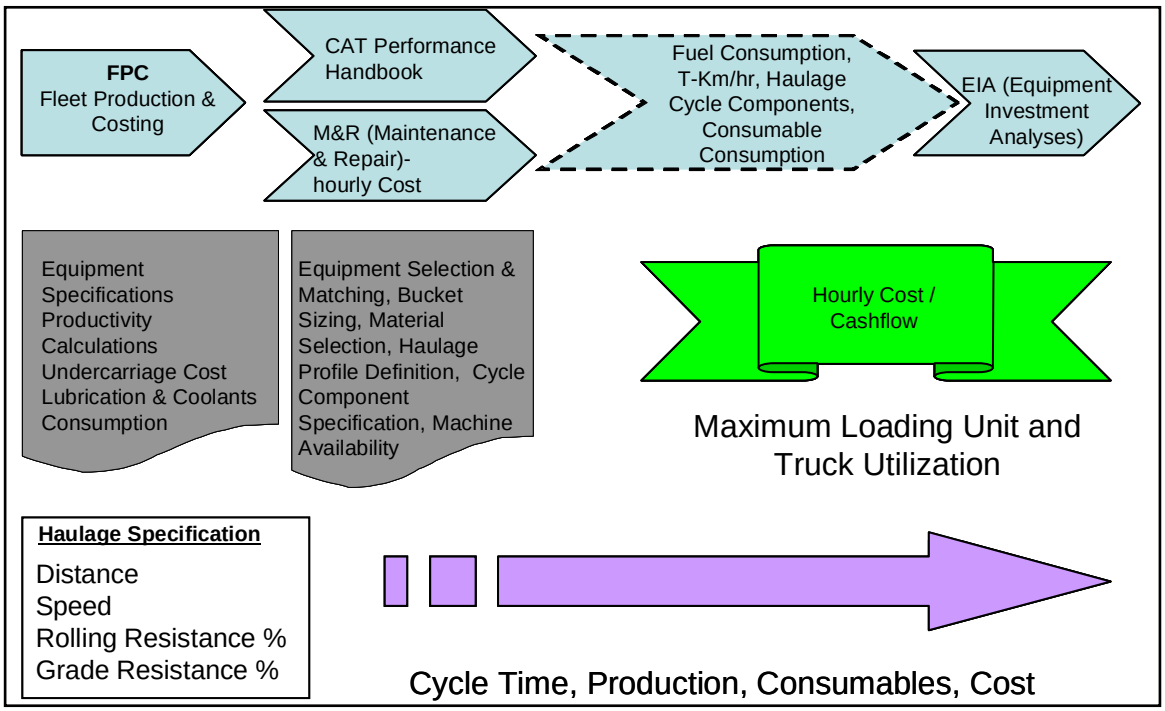


Figure 3.6 FPC and EIA Simulation Process

In Figure 3.6 a simulation starts by specifying the machine characteristics from manufacturer performance handbooks or built in features within the program. Additional information such as the production hour distribution, haul road characteristics, material specifications and costing components are programmed to quantify and qualify the system.

The machine maintenance and repair cost values can be specified in the program but is usually calculated by specialist programs externally. The aim is to calculate cashflow and for this the values obtained from FPC are programmed into the E.I.A. program considering various financial parameters like discount rates, insurance rates and tax rates.

FPC has two important selections that can be made:

1. Degree of Bunching
2. Haul Road Discipline

The degree of bunching refers to the percentage of production loss due to bunching or queuing and the haul road discipline refers to the ability of trucks to pass each other on a particular haul course.

The FPC program uses empirical estimations to calculate waiting time or bunching based on numerous field observations and case studies. The waiting time is based on a selection as indicated in Table 3.2, FPC Users Manual (2003, p. 102).

Table 3.2 FPC Bunching Factor Selection

Bunching Choice	Production Loss %	Production Efficiency
None	0%	100%
Minimum	10%	90%
Average	15%	85%
Maximum	20%	80%

Production is thus de-rated based on field observations or experience, which is not clearly qualified and quantified and thus left to the user to specify.

Fleet Matching is calculated as follows:

$$\text{Fleet Match} = \frac{\text{Load with Exchange}}{\text{Potential Cycle Time}} \quad (3.8)$$

$$= \frac{(\text{Passes Required}-1) \times \text{Shovel Cycle} + \text{First Bucket Dump} + \text{Hauler Exchange}}{\text{Haul} + \text{Dump \&Manoeuvre} + \text{Return}} \quad (3.9)$$

The relationship between Fleet Match and Bunching is shown in Figure 3.7 (FPC Users Manual, 2003, p. 102).

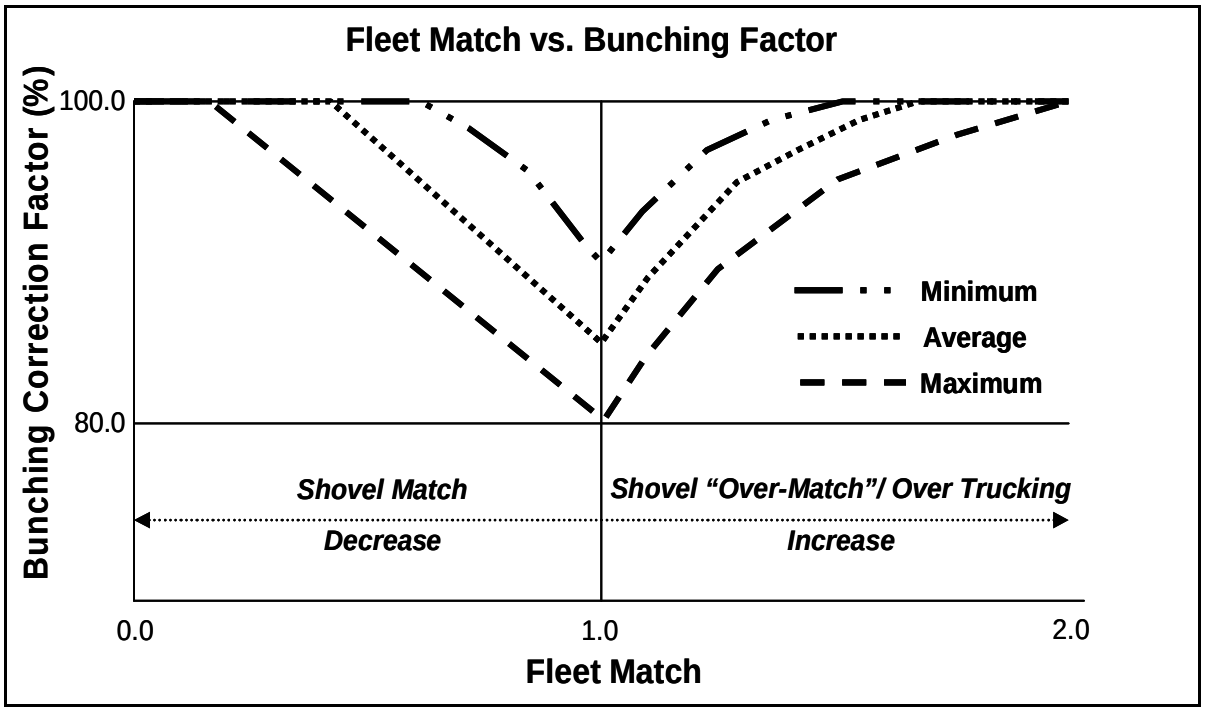


Figure 3.7 FPC Matching vs. Bunching Correction Factor (BF)

From Figure 3.7 it follows that for a truck:

- Left of the 1.00 Fleet Match value –

  Shovel matching decreases which might be due to less trucks in the system or trucks travelling longer distances. A lower bunching correction factor implies a decrease in the total cycle time due to a reduction in waiting time bringing it closer to the potential cycle time. Production increases left from this value.

- Right of the 1.00 Fleet Match value –

  The time trucks spend at the shovel increases which increases the bunching correction factor. The result is a production increase due to the higher number of trucks in the system and can be explained by the trucks forcing the shovel productivity to increase. The individual truck productivity does however decrease. This phenomenon was also observed in Figure 2.2.

The following extract describes how FPC evaluates bunching and shows the impact of waiting, as stated in the FPC Users Manual (2003, p. 102-103):

"The loss in production due to bunching cannot be calculated in the precise manner that "mismatch" can…extensive job studies have established a range of "bunching" production losses tied to the "Fleet Match" or the ratio of the number of Haulers in the fleet compared to the ideal number to just keep the Loader busy all of the time… if there are too many Haulers in the fleet and the Haulers have to wait to be loaded anyway, "bunching" does not contribute much more to their "wait time to be loaded"..."For fleets with the ideal number of Haulers for the Loaders, measured losses varied from 10 to 23 percent or a production efficiency of 77 to 90 percent."

The statements are valid in that the accuracy of the program's results is reduced due to the fact that mathematical formulas are used to represent a stochastic system. In reality no program can incorporate all the variables present in a system nor anticipate the dynamic changes that might occur.

The underlying assumptions that define this model are inter-arrival times and service times that follow an exponential distribution (arrival rate being a Poisson distribution), an optimal number of servers at the final destination to ensure minimal queuing and trucks that adhere to a FCFS queue discipline which are drawn from a finite population. This is in effect a type of a machine repair model.

In FPC the potential production is calculated as indicated in Table 3.3 with a Caterpillar 793C Off-Highway truck and single Caterpillar 944D wheel loader on a simple course where mining takes place at a 10 metre depth (Rolling Resistance% = 4, Grade% =8). The main calculation is essentially quite simple (with credit given to its designers) as expressed in equation (3.10).

$$\text{Total Cycle Time} = \frac{\text{Potential Cycle Time (minute(s))} \times \text{Fleet Match}}{\text{Bunching Correction Factor}} \qquad (3.10)$$

Table 3.3 FPC Production Calculation example

	FPC Production Calculation						
	Matching Calculation (793 C, 994D; Pit Depth 10 m.)						**Calculation**
	At Shovel	**1 Truck**	**2 Trucks**	**3 Trucks**	**4 Trucks**	**5 Trucks**	
(1)	System Passes	4.13	4.13	4.13	4.13	4.13	
(2)	Shovel Cycle (min.)	0.65	0.65	0.65	0.65	0.65	
(3)	Hauler Exchange Time (min.)	0.7	0.7	0.7	0.7	0.7	
(4)		**3.38**	**3.38**	**3.38**	**3.38**	**3.38**	(1)*(2)+(3)
	Away from Shovel (minutes)						
(5)	Haul	2.15	2.15	2.15	2.15	2.15	
(6)	Dump & Maneuver	1.2	1.2	1.2	1.2	1.2	
(7)	Return	1.17	1.17	1.17	1.17	1.17	
(8)		**4.52**	**4.52**	**4.52**	**4.52**	**4.52**	(5)+(6)+(7)
(9)	Potential Cycle Time	**7.90**	**7.90**	**7.90**	**7.90**	**7.90**	(4)+(8)
(10)	Truck Match	**0.43**	**0.43**	**0.43**	**0.43**	**0.43**	(4)/(9)
(11)	Fleet Size	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	
(12)	Fleet Match	**0.43**	**0.86**	**1.28**	**1.71**	**2.14**	(10)*(11)
(13)	Bunching Correction Factor	100.0%	76.1%	94.5%	99.7%	99.7%	Figure 3.7 based on (12)
(14)	Potential Cycle Time (min.)	7.92	7.92	7.92	7.92	7.92	
(15)	Waiting Time (min.)	0.00	0.99	2.84	5.68	9.08	(16)-(14)
(16)	Total Cycle Time (min.)	**7.92**	**8.91**	**10.76**	**13.60**	**17.00**	(12)*(14)/(13)
	Cycles per Hour Calculation						
(17)	Cycles/ hr	7.58	6.73	5.57	4.41	3.53	60/(16)
(18)	Fleet Availability	81.00%	81.00%	88.67%	89.82%	89.98%	
(19)	Operator Efficiency	81.00%	81.00%	81.00%	81.00%	81.00%	
(20)	Utilization	100%	100%	100%	100%	100%	
(21)	Cycles/ hr Deration	**5.0**	**4.4**	**4.0**	**3.2**	**2.6**	(17)*(18)*(19)*(20)
	Tons per Hour Calculation						
(22)	Truck Payload (tonnes)	222.9	222.9	222.9	222.9	222.9	
(23)	Tons per Hour Calculated	1107.9	1969.0	2677.0	2862.0	2867.0	(11)*(21)*(22)
(24)	T.P.H. FPC	1108.0	1969.0	2677.0	2862.0	2867.0	
(25)	Comparison	**100%**	**100%**	**100%**	**100%**	**100%**	
(26)	Scheduled Hours	7250	7250	7250	7250	7250	
	Production Calculation (tonnes)						
(27)	Tons/ Yr	8 032 379	14 275 250	19 408 250	20 749 500	20 785 750	(23)*(26)
(28)	FPC Calculated	8 032 379	14 275 250	19 408 250	20 749 500	20 785 750	
(29)	Comparison	**100%**	**100%**	**100%**	**100%**	**100%**	

The potential cycle time excludes queue time which is unknown and needs to be calculated and the fleet match value relates to the TS / RT ratio discussed in Section 3.2. The bunching correction factor incorporates fleet size (fleet match) and the potential to total cycle time ratio. It therefore includes all the components necessary to calculate waiting time and thus cycle time. This compared to Elbrond's method is a faster and more stable method of calculation. Stability refers to the use of computer spreadsheets to conduct iterative calculations with the templates (operating programs like Microsoft Excel) having a tendency to fail occasionally due to large numbers of variables that are interlinked. The main driver of the potential cycle time is the travel times (full and empty). FPC is programmed to calculate most Caterpillar travel times and can programmed to incorporate user defined machines. The mathematics behind these

calculations incorporates concepts like gradeability which involves using rimpull curves and retarding graphs.

Rimpull curves make use of the gross machine weight (machine weight plus payload), rolling resistance % (RR%) and grade % (GR%) of a segment to calculate the acceleration, speed and travel time per road segment. This is then derated based on operator proficiency over distance (gear shift frequency and loss of acceleration of the machine). Retarding graphs are the reverse of rimpull curves and focus on the machine's ability to gear down and brake over distance. The main assumptions made (by the user) in these calculations are the selection of RR% and GR% which is obtained through field observations and cycle time studies.

Fleet matching involves the calculation of loading unit cycle time, this is the number of passes multiplied by the time per pass and if applicable it will include the travel time that the loader takes to reach the truck (load and carry operations). This involves the concept of truck and shovel matching.

A loader or shovel with a small bucket capacity to truck bowl capacity ratio will require a large number of passes to fill the truck and will result in low truck matching and therefore a high TS/RT ratio which will cause an increase in waiting time.

The main observations made from this model are as follows:

- Calculating cycle time involves calculating waiting time.
- The number of trucks, servers and the queue discipline (haul course) in the system is very important in calculating cycle time.
- The TS/RT ratio which refers to shovel matching as discussed in Section 3.2 is also included in this model and in effect stresses the importance of having the correct truck and shovel match.
- The importance of accurately calculating travel time is highlighted. It incorporates machine specific characteristics like gradeability and retardability (which is haul

segment specific, a function of the RR% and GR% for that segment and the operator's proficiency in correctly gearing the machine).

- The 3 most important factors of production: payload, cycle time and operator proficiency as seen earlier on in Figure 2.1 is reaffirmed.

3.4 Talpac® (Runge Software)

Talpac is similar to FPC in that it uses the same machine type, haul road and production calendar specifications for a simulation. The main difference between these packages is in the calculation of waiting time.

Talpac uses a Monte Carlo type simulation based on distributions that are fitted to the loader bucket payload, loader cycle time, truck payload, truck travel time and truck maintenance availability (payload, cycle time and operator proficiency). Unlike FPC that has at its core a machine repair model type queue model, Talpac is not restricted in that it is driven by the user defined distributions. Talpac can in accordance with the Kendall (1951) notation be described as a GI/G/R/GD/K/K queue model, with inter-arrival rate and service times both having some general distributions, with *R* parallel servers at the destination (optimal number to ensure minimal queue), *K*-trucks served by some general queue discipline and with the 2nd *K* stating that the trucks come from a population with size *K*.

3.4.1 Description of a Monte Carlo Simulation

Monte Carlo simulation refers to a method where the distribution of possible outcomes is generated by letting a computer recalculate a worksheet repetitively, each time using different randomly selected sets of values for the probability distributions in the cell values and formulas. The computer program is effectively trying all valid combinations of the values of input variables to simulate all possible outcomes. This is equivalent to running hundreds or thousands of "what-if" analyses on a worksheet. Monte Carlo

sampling refers to the traditional technique for using random or pseudo-random numbers to sample from a probability distribution.

The term Monte Carlo was introduced during World War II as a code name for the simulation of problems associated with the development of the atomic bomb. Today, Monte Carlo techniques are applied to a wide variety of complex problems involving random behaviour. A wide variety of algorithms are available for generating random samples from different types of probability distributions.

Monte Carlo sampling techniques are entirely random - that is, any given sample may fall anywhere within the range of the input distribution. Samples are more likely to be drawn in areas of the distribution which have higher probabilities of occurrence. For a particular cumulative distribution, each Monte Carlo sample uses a new random number between 0 and 1. With enough iteration Monte Carlo sampling "recreates" the input distributions through sampling.

TALPAC uses stochastic variables to simulate haulage systems. A stochastic variable is not represented as a fixed number, but rather as a varying number.

3.4.2 Stochastic Variable Parameters

Stochastic variables are described by probability distributions, which are defined by parameters that include distribution type, spread value and truncation value.

3.4.2.1 Distribution Type

The distribution type may be one of the standard distributions such as normal, right skewed, left skewed or uniform or it may be customized or user defined distributions. The mean of the distribution is defined as the value of the variable for which there is a 50% probability of occurrence. If a deterministic (or fixed value) analysis was being done, then the variable would have this value.

3.4.2.2 Spread Value

The spread value is defined as the value of the variable for which there is an 84.1% probability of occurrence such as one standard deviation above the mean. The spread of a distribution defines how narrow or wide the distribution is. The spread is expressed as the percentage above the mean value of the variable, rather than the actual value of the variable. The larger the percentage, the greater the spread value and the greater the variation in the variable.

3.4.2.3 Truncation Values

These are the minimum and maximum values obtainable by the stochastic variable. The truncation values are used to restrict the range of the distribution. The values are expressed as a percentage probability of the distribution with defaults of 1% and 99%, respectively. The only exception to this is the truck availability, which has maximum truncation value defined as an absolute value rather than a distribution percentage since it is unrealistic to have an availability of more than 100%.

3.4.3 Stochastic Variables in Talpac

The following variables are treated as stochastic variables in Talpac:

- Truck Travel Time
- Truck Dumping Time
- Truck Availability
- Loader Cycle Time
- Loader Bucket Load

All other cycle variables are fixed. Any of the above variables may be fixed by using a uniform distribution.

The main observations made from this model are as follows:

- The three main variables depicted in Figure 2.1 namely payload (which defines the number of passes and thus loading unit cycle time), cycle time or cycle time components (truck travel time, truck dumping time and loader cycle time) and operator proficiency (build into all Talpac's stochastic variables) are treated as stochastic variables.
- Monte Carlo simulations can be used to replace iterative queue models to simulate cycle time.
- There are various distribution types that can be used to describe a variable's variability. This variability impacts on the three main variables which in turn impacts on the calculation of production and inevitably on the calculation of operational cost.
- This program can be programmed to follow a user defined distribution based on site specific experience or values obtained on site.

3.5 Arena® (Rockwell Software)

Arena (2006), like Talpac, is a program that follows a Monte Carlo type simulation process. The main differences between Arena and Talpac are discussed in the following sub-section.

3.5.1 Differences between Arena and Talpac

The following differences do not influence in any way the general accuracy of Talpac as a program and only serves to compare the programs so as to understand their respective nature.

3.5.1.1 Graphic Presentation of Simulation

Arena provides a graphical presentation of trucks and loaders as entities during a simulation run which enables the operator to monitor and control the logical operations programmed. Apart from the visual validation process, an added benefit to visually seeing a simulation progress is that other system specific characteristics or phenomena can be discovered which can be used in scenario analysis.

3.5.1.2 Truck Maintenance and Repair

Although Talpac treats a specific type of truck's availability as a stochastic variable, in reality trucks within a fleet each have a specific life history which will influence their repair and maintenance intervals and thus individual availabilities. Arena is able to record and track each individual truck's performance during a simulation and therefore its availability and impact on production.

In practice the life cycle analysis of a truck is a very important and also a very difficult variable to model and involves sophisticated software and highly trained individuals. Companies placing orders for new machines that are capital intensive will insist that a Life Cycle Costing (LCC) be preformed. The technology has not been developed to interlink machine production software with machine life cycle analytic tools to optimize such LCC calculations.

3.5.1.3 Dumping Site Specifics

FPC and Talpac are designed to simulate load-and-haul cycles and are not able to simulate the dynamic interaction of trucks-and-loaders with plant destinations. For example, the number of parallel servers (tipping bins) at a particular plant might be restrictive and cause trucks to queue and thus influence production. Talpac and FPC are both designed to calculate production for a destination with the optimum number of tipping bins. Should a user simulate a mine site with less than the optimum number of bins at a particular level of production then the result might be an over estimation of

production. It can be argued that fitting a distribution with a high variance in the dumping time might simulate a destination similar to a destination with a low number of tipping points (bins) and thus "capture" the inefficiency. This will raise a question regarding the characteristics of such a distribution.

In reality any particular loading unit might form part of more than one destination circuit (e.g. with material blending operations) and by fitting such distributions the real effect might be hard to isolate and verify. Arena is able to simulate the entire plant process to link with the mine operation and can thus provide more realistic production estimation compared to both FPC and Talpac. Plant variables that will influence the mine and thus the load-and-haul operations are for instance plant scheduled maintenances and unplanned breakdowns. The number of large projects which warrants such an intensive study of mine and plant dynamics is however small in comparison to the number of smaller projects and makes the overall risk relatively low.

3.5.1.4 User Friendliness and Setup Speed

Arena is a modular package meaning it has various types of building blocks that can represent for example a truck or shovel which makes it easier for a user to model a system. This enables the user to provide accurate results faster with graphical presentations to assist in presenting the results to a project team or customer. A disadvantage of Arena is however, the higher level of training and skill required from the simulator. Talpac has been programmed with most available trucks and loading units on the market making it more user friendly compared to Arena, with quick comparisons saving simulation time.

3.5.1.5 Statistical Functionality

Arena has the functionality to analyze observations from field cycle time studies. The simulation uses the field data to construct probability distributions that are fitted to stochastic variables. Although Talpac has the ability to accommodate user specified

distributions to be fitted to its stochastic variables it lacks the ability to analyse field observations which complicates the distribution fitting process. Talpac is able to accommodate a maximum of 5 stochastic variables compared to Arena which is able to accommodate all cycle components as stochastic variables.

In reality, and specifically in "green field" projects, there are no site specific values that can be used to simulate a future operation. It can be argued that using any cycle time calculation method will thus yield an acceptable result which can be re-simulated at a future date to provide higher accuracy.

3.6 Adapted Machine Repair Model

The simulated model is an adaptation of the Machine Repair Model and involves a truck that is sent for loading at a shovel or dumping (which is repair at a workshop in the original model) at every cycle with the number of shovels loading sides or tipping bins (repair bays) equal to *R*. The inter-arrival time at the shovel (travel full and empty, waiting time and dumping time) and the service time (loading time) are both assumed to have exponential distributions.

When arrivals to a system (trucks) are drawn from a small population the arrival rate may depend on the state of the system. The state of a system can be described as stable or unstable. Winston (2004) explains this concept by starting to define ρ as the traffic intensity for an M/M/1/GD/∞/∞ queue or model (recall such system will have exponential inter-arrival and service times).

Where, $\rho = \frac{\lambda}{\mu}$ (3.11)

λ = arrival rate, e.g. 5 trucks per hour arriving at a shovel.

μ = service rate or successful services per time unit e.g. a loading unit can service 10 trucks per hour.

Then for this example $\rho = \frac{5}{10} = 0.5 < 1$ which means that the loader can handle the number of trucks dispatched to it. This will be explained in more detail in this section. Winston (2004) also showed that an M/M/1/GD/∞/∞ queue process can be modelled as a birth-death process with the following parameters:

$$\lambda_j = \lambda \qquad (j = 0,1,2,\ldots)$$
$$\mu_0 = 0 \qquad (3.12)$$
$$\mu_j = \mu \qquad (j = 1,2,3,\ldots)$$

These equations are also called the flow balance equations of a birth-death process, with:

expected no. of departures from state *j* per unit time

= expected no. of entrances to state *j* per unit time

Winston then continued to define the steady state probabilities that *j* customers will be present as:

$$\pi = \frac{\lambda\pi_0}{\mu}, \pi_2 = \frac{\lambda^2\pi_0}{\mu^2}, \quad \ldots, \pi_j = \frac{\lambda^j\pi_0}{\mu^j} \qquad (3.13)$$

π_j is described as the probability that at an instant in the distant future, *j* customers (trucks) will be present or may be thought of (for the time in the distant future) as the fraction of time that the *j* customers are present at the shovel or dump.

Winston then defines:

$$\pi\,(1 + \rho + \rho^2 + \cdots) = 1 \qquad (3.14)$$

This infinite sum will diverge to infinity should $\rho \geq 1$, and should $\rho = 1$ no steady state will exist.

For the Machine Repair Model with a finite truck population it was stated that the arrival rate will depend on the state of the system. For example, should all the trucks

within a particular circuit be present at the loading unit and experiencing an unexpected breakdown; then the arrival rate will be zero. While at any other instant when there is less than the maximum number of trucks at the loading unit then the arrival rate will be positive.

It was stated in Section 3.1, that the Machine Repair Model can be described as M/M/R/GD/K/K, with inter-arrival and service times both having an exponential distribution, with *R* repair bays, *K*-trucks serviced by some general queue discipline and with the 2nd *K* stating that the trucks come from a population with size *K*.

The length of time that a truck remains in good condition follows an exponential distribution with rate λ, and the time it takes to repair a truck can thus assumed to be exponential with rate μ.

The Machine Repair Model can be used to simulate shovel-truck load-and-haul cycles as indicated by the analogy in Table 3.4. It is the opinion of the author that this model has never been formally stated to be a valid and accurate calculation method for load-and-haul systems.

Table 3.4 Analogy between Machine Repair Model and Adapted Model for load-and-haul shovel-truck systems

Notation	Machine Repair Model	Repair Model Adapted for Load and Haul System
	Description	
L	Expected number of broken trucks	Expected number of trucks at the loading unit or destination server (plant or dump)
L_q	Expected number of trucks waiting for service at the Workshop Repair Bays	Expected number of trucks waiting for service at the Loading unit or dumping destination
W	Average time a machine spends broken (down time)	Average time a truck spends at the loading unit or dump destination.
W_q	Average time a truck spends waiting for service	Average time a truck queue at the loading unit or the plant/ dump.

The following section discusses how the model can be adopted to simulate shovel-truck load-and-haul systems

If we define $\rho = \frac{\lambda}{\mu}$, the steady state probability distribution will be:

$$\pi_j = \left(K_j\right)\rho^j \pi_0 \qquad (j = 0,1,\ldots,R) \tag{3.15}$$

With,

$$\left(K_j\right) = \frac{K!}{j!(K-j)!} \tag{3.16}$$

and with (3.16) substituted in (3.15) which is expanded to include the Kth state,

$$\pi_j = \frac{\left(K_j\right)\rho^j\, j!\,\pi_0}{R!\,R^{j-R}} \qquad (j = R+1, R+2,\ldots, K) \tag{3.17}$$

$$L = \sum_{j=0}^{j=k} j\pi_j \tag{3.18}$$

$$L = \sum_{j-0}^{j=K} \lambda(K-j)\pi_j = \lambda(K-L) \tag{3.19}$$

To obtain W and W_q we will use Little's Queuing Formula (Winston, 2004, p. 1226):

$$L = \lambda W \tag{3.20}$$

$$L_q = \lambda W_q \tag{3.21}$$

The average number of truck arrivals per unit time is given by $\overline{\lambda}$, where

$$\overline{\lambda} = \sum_{j=0}^{j=K} \pi_j \lambda_j = \sum_{j=0}^{j=K} \lambda(K-j)\pi_j = \lambda(K-L) \tag{3.22}$$

If (3.21) is applied to trucks being repaired (serviced by loading unit or dumping) and those trucks awaiting repairs (to be serviced), we obtain:

$$W = \frac{L}{\bar{\lambda}} \tag{3.23}$$

And applying (3.22) to trucks waiting to be repaired (to be serviced), we obtain:

$$W_q = \frac{L_q}{\bar{\lambda}} \tag{3.24}$$

Later it will be shown that this model yields the same results when simulated in Excel compared to when simulated in Arena for a system with an exponential inter-arrival and service time.

Main observations made from this model are as follows:

- The Adapted Machine Repair Model can be programmed into Excel spreadsheets. This gives it the ability to be linked with risk calculation packages such as @Risk® program to provide a spread of results and to determine system sensitivities that can be used to plan risk aversive strategies.

- The benefit of using this model to simulate load-and-haul cycles is that it is stable in programs like Excel®.

- It can be expanded to include truck repair cycles.

- A further benefit is that the exact number of tipping bins (R) can be simulated to match real life mine sites and thus be used to motivate additional tipping bins or evaluate the impact of not having the sufficient number of bins.

- In general, engineers use spreadsheets to model aspects of projects and this model can easily interlink with these spreadsheets to deliver results faster.

4 DISTRIBUTIONS

In the previous sections the importance of fitting distributions on cycle variables was discussed. In this section the various types of distributions relevant to shovel-truck simulations and their characteristics will be discussed. There are various types of distributions that can represent the variability of any particular cycle variable. The distributions that this study* will cover are as follows:

- Normal
- Log Normal
- Poisson
- Exponential
- Erlang

*In Chapter 7 the triangular distributions are used to conduct a sensitivity analysis on cycle time variables of the Elbrond and FPC models for the virtual mine using @Risk® program in Microsoft Excel.

In reality cycle time variables can assume any type of probability distribution. These distributions can also represent the return time for service. The reason why only these distributions are examined is due to their higher rate of occurrence based on field observations. There are a number of concepts common to all of these distributions that need to be explained and will serve as a basis for examining the implications associated with these distributions.

4.1 Probability Density Function (PDF)

(Wikipedia, 2006a)

A probability density function (PDF) represents a probability distribution in terms of integrals. Informally, a probability density function can be seen as a "smoothed out" version of a histogram. Should one empirically measure values of a continuous random variable repeatedly and produce a histogram depicting relative frequencies of output ranges, then this histogram will resemble the random variable's probability density (assuming that the variable is sampled often enough and the output ranges are sufficiently narrow). Examples for the probability models used in this document can be viewed in Figure 4.1 and Figure 4.2

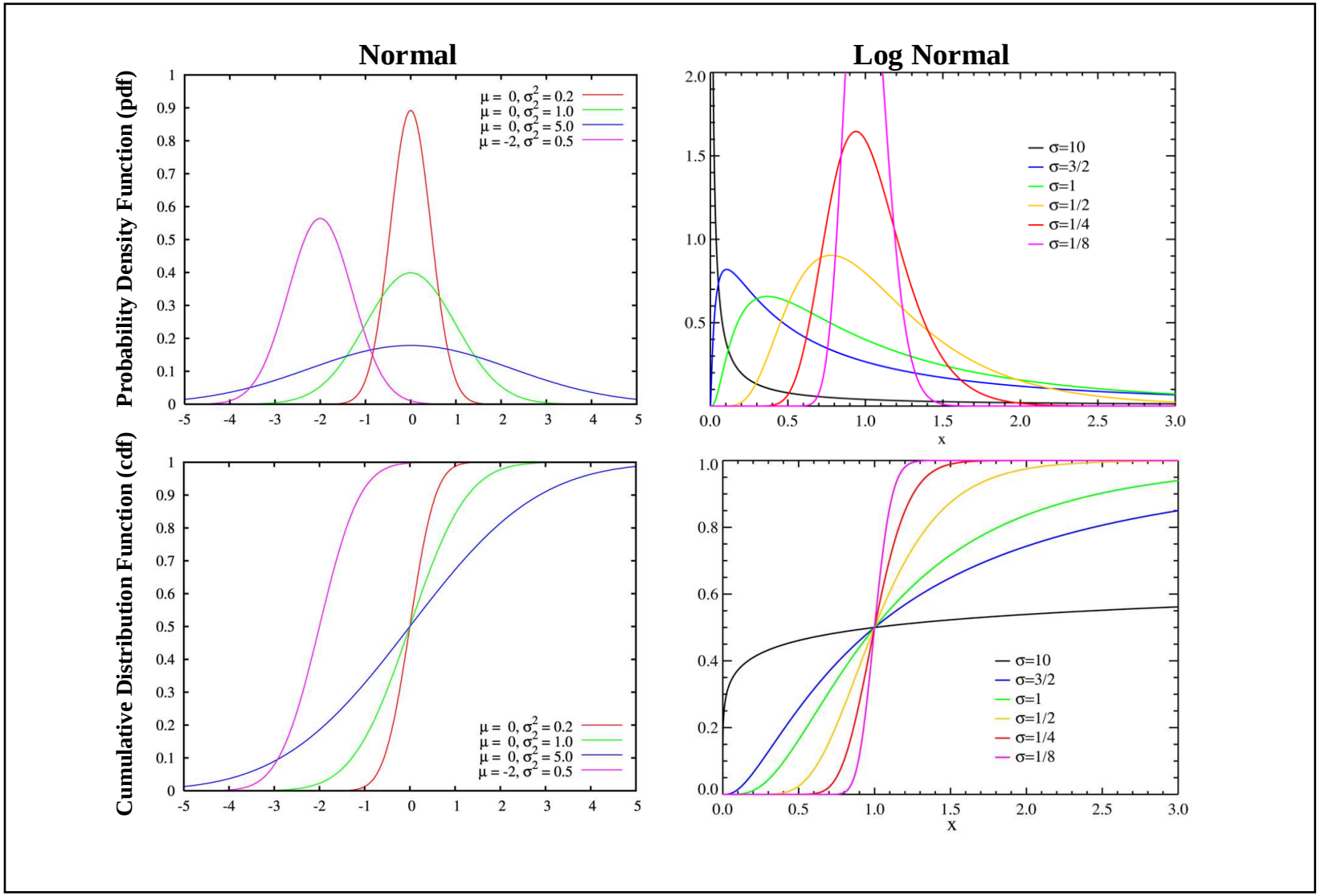


Figure 4.1 PDF and CDF of Normal and Log Normal Probability Models
Normal Distribution (Wikipedia, 2006d) and Log Normal (Wikipedia, 2006e)

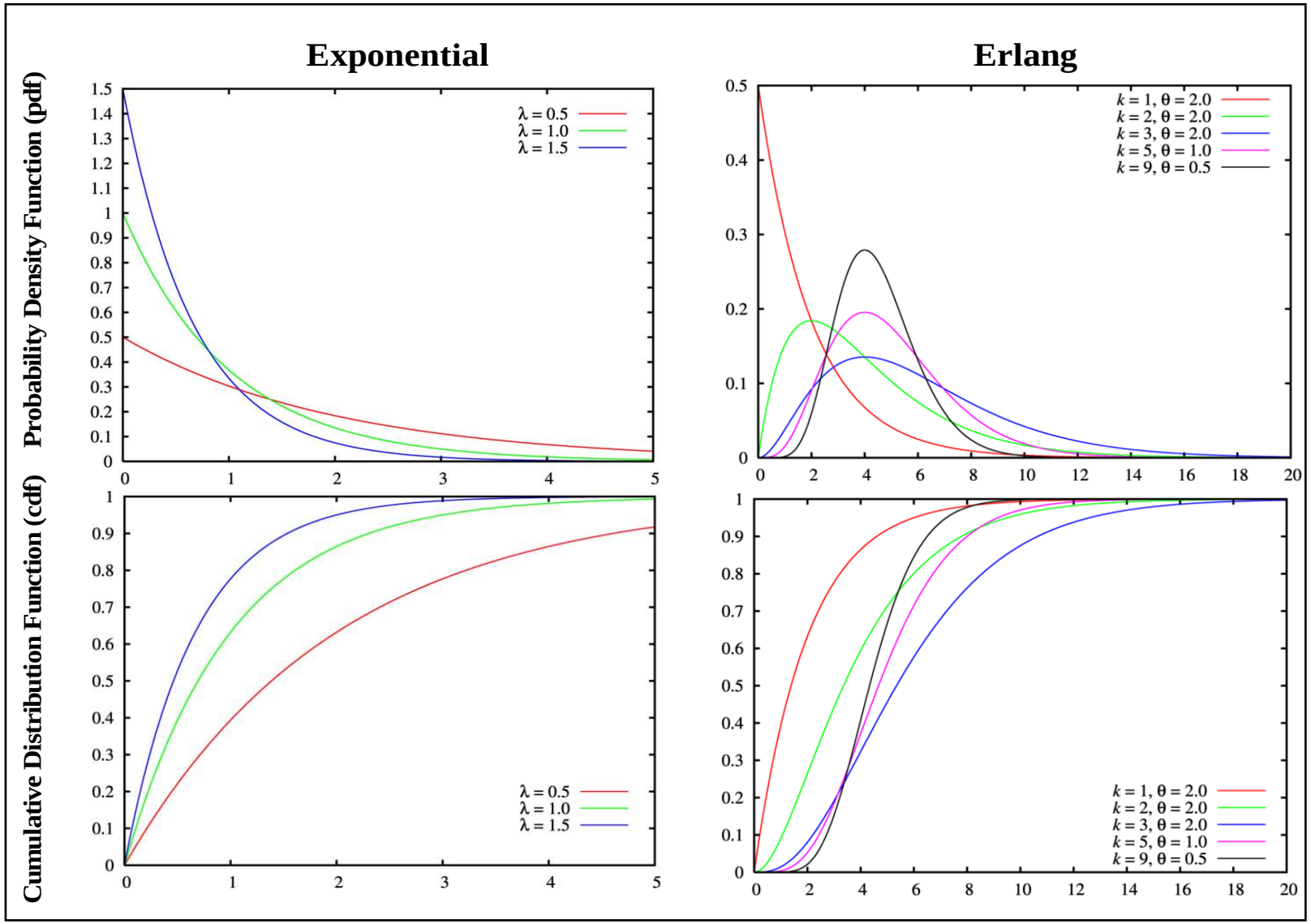


Figure 4.2 PDF and CDF of Exponential and Erlang Probability Models
Exponential *(Wikipedia, 2006f) and Erlang Distribution (Wikipedia, 2006g)*

4.2 Histogram

(Wikipedia, 2006b)

A histogram is a graphical display of tabulated frequencies. It is the graphical version of a table which shows the proportion of cases that fall into each specified category. The categories are usually specified as non-overlapping intervals of some variable.

4.3 Cumulative Distribution Function (CDF)

(Wikipedia, 2006c)

The cumulative distribution function (CDF) completely describes the probability distribution of a real-value random variable such as the cycle time variable. Examples for the probability models used in this document can be viewed in Figure 4.1 and Figure 4.2

4.4 Major Distributions Characteristics

The symbols used in Table 4.1 refer to the mean and variance of any cycle time variable and does not necessarily bear reference to symbols used in Section 3.6. In Table 4.1 the various probability model parameters are shown.

Table 4.1 Major Characteristics of Distributions used in this research

Probability Model	Probability Distribution Function	Cumulative Distribution Function	Mean	Variance
Normal	$\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$	$\frac{1}{2}(1 + Erf\ ^{*}\ \frac{x-\mu}{\sigma\sqrt{2}})$	μ	σ^2
Log Normal	$\exp(-[\frac{\ln(x-\mu)}{2}]^2/2)/(x\sigma\sqrt{2\pi})$	$\frac{1}{2} + \frac{1}{2}\,Erf\ ^{*}\left[\frac{\ln(x)-\mu}{\sigma\sqrt{2}}\right]$	$e^{\mu-\sigma^2/2}$	$(e^{\sigma^2}-1)(e^{2\mu+\sigma^2})$
Poisson	$\frac{e^{\lambda}\lambda^k}{k!}$	$\frac{\Gamma(k+1,\lambda)}{k!}$	λ	λ
Exponential	$\lambda e^{-\lambda x}$	$1-e^{-\lambda x}$	λ^{-1}	λ^{-2}
Erlang	$\frac{\lambda^k x^{k-1} e^{-\lambda x}}{(k-1)!}$	$1-\frac{\gamma(k,\lambda x)}{(k-1)!}$	k/λ	k/λ^2

In Section 4.1 it was mentioned that the probability density function is a “smoothed” out version of a variable’s histogram. In analyzing a variable’s underlying probability distribution Figure 4.1 and Figure 4.2 serve as a visual reference to which a histogram of a variable is compared.

Figure 4.1 and Figure 4.2 also show that the Lognormal and Erlang distribution have, depending on the sample mean and variance, features that resemble the normal distribution and that the Erlang distribution can also closely resemble the Exponential distribution. Any particular variable can be fitted with a specific probability distribution, with the accuracy of this fit measured by the "goodness of fit". Within a truck circuit the individual variables can each have their own unique type of distribution. In general, the decision regarding which model to use to calculate the cycle time will depend on the nature of the inter-arrival time of trucks at a server (loading unit and dumping site) and that of the service times at the servers.

4.5 Chi²-square Goodness of Fit

The Chi-square goodness of fit test will be used to test whether an observed probable type of distribution is in fact a true reflection of a specific distribution model. Pearson's chi-square (Chi²) goodness of fit test statistic *T* is given by:

$$T = \sum_{i=1}^{k} \frac{(O_k - E_k)^2}{E_k} \tag{4.1}$$

Where,

O_k is the observed counts per class, E_k is the expected count per class and k is the number of classes for which counts or frequencies are being analyzed. The test statistic is approximately distributed as a Chi² random variable with k-1 degrees of freedom. Any stochastic variable can thus be classed and compared to a probability distribution function and tested with the Chi² test statistic to determine if there is a correlation between the observed and expected class values.

The Chi² approximation is adequate provided that all of the following hold true:

- Total of observed counts (N) ≥ 10
- Number of classes (k) ≥ 3
- All expected values ≥ 0.25

The following example is from the Orapa Diamond Mine (De Beers) in Botswana.

The following observations of the service time of a Caterpillar 789 Off-Highway Truck (OHT) was made using the onboard Vital Information System (VIMS®, Caterpillar)

loading at an O&K RH200 face shovel in Kimberlite. According to the OEM-Caterpillar (2006, p. 9-7), a 789C OHT being loaded with hard rock with a full bowl liner (metal protective strips) will have a payload of approximately 180 tonnes. The material being loaded has a loose density of about 3.2 tonnes / m³. The O&K RH200 has a 14 m³ bucket fitted and will have a bucket fill factor about 80% since it is hard rock. On average, if a full truck strategy is followed, there should be 5.1 passes per loading cycle and according to manufacturers specification each pass should take about 30 seconds (0.5 min) making the total loading time 2.15 minutes. Figure 4.3 is a summation of $t_1, t_2, \ldots$,7000 observations made:

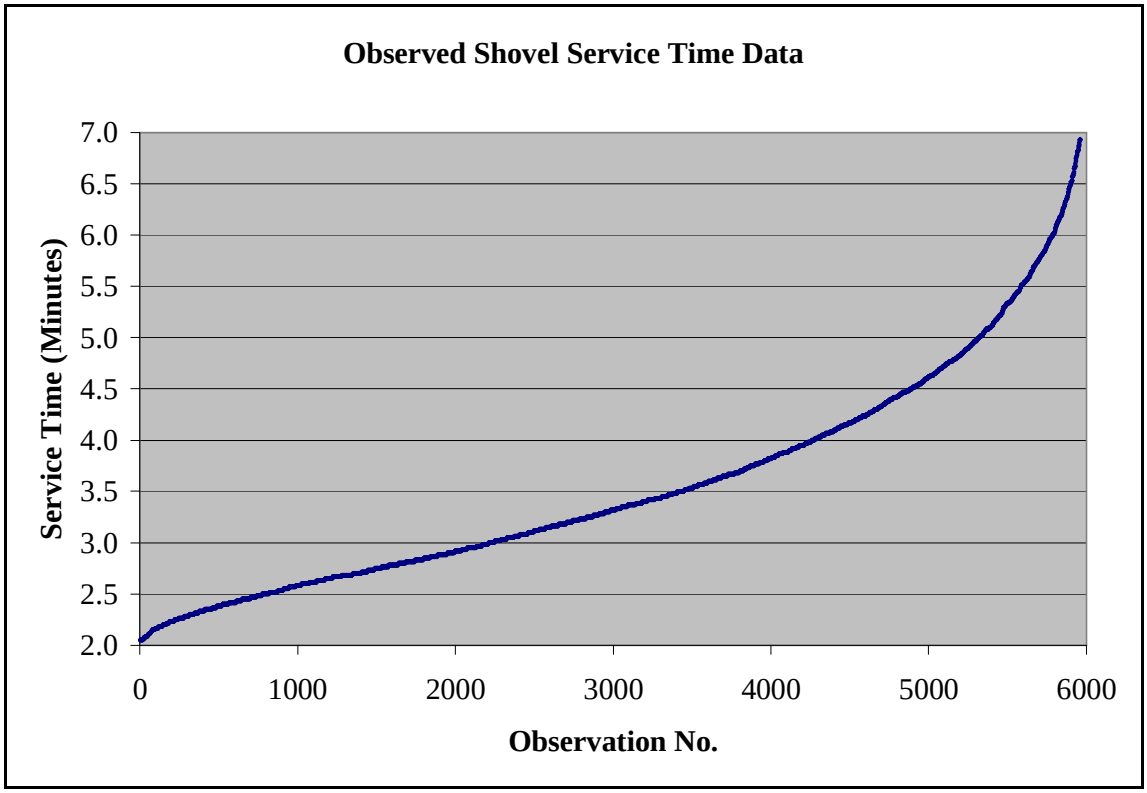


Figure 4.3 Shovel service time observations

In order to answer the answer the question pertaining to what the underlying distribution is within this data 39 categories were constructed (i.e. k=39) categories which is based on population size. We then count the number of observations per category and compare it with various probability density functions. We need to determine the best fit in order to know which statistics will give the highest level of accuracy. Using the Pearson's Chi² test statistic we might be able to answer the question. For the test we specify the level of significance (α) to be 0.05, which implies that there is a 5% chance (or 1 in 20 chance) of being wrong.

The Chi² distribution has one parameter ν referring to the degree of freedom which is calculated as follows:

$$v = k - r - 1 \qquad (4.2)$$

Where,

k =number of classes, and

r =number of parameters needed to estimate the variable being tested (service time).

The α- value is graphically illustrated in the following Figure 4.4 as follows:

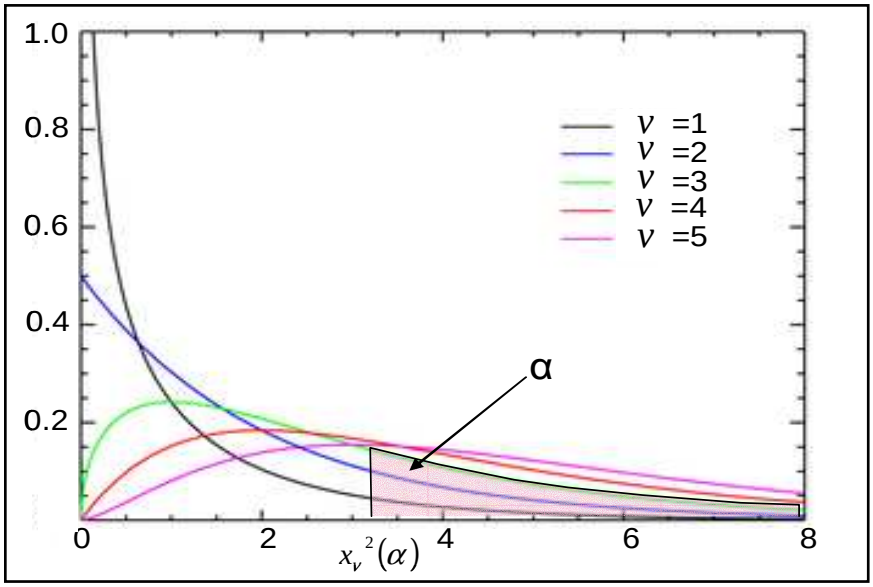


Figure 4.4 Chi² PDF

Depending on the type of distribution evaluated the number of parameters (r) will be:

Normal	$= (\mu, \sigma)$	=2
Lognormal	$= (\mu, \sigma)$	=2
Exponential	$= (\lambda^{-1})$	=1
Erlang	$= (k, \lambda)$	=2

For this example with k = 39, we obtain from regular available percentiles of Chi² tables the $\chi_\nu^2(P = 0.05)$. Levine, Ramsey and Smidt (2001, p. A-10).

Table 4.2 Chi² values for the Orapa load time example

Probability Model	ν	$\chi_\nu^2(P = 0.05)$
	36	51
Lognormal	36	51
Exponential	37	52
Erlang	36	51

Figure 4.5 is a graphical representation of the observed frequencies per category of data and the expected probabilities based on the selected probability density function. The fit of each model to the data can also be observed.

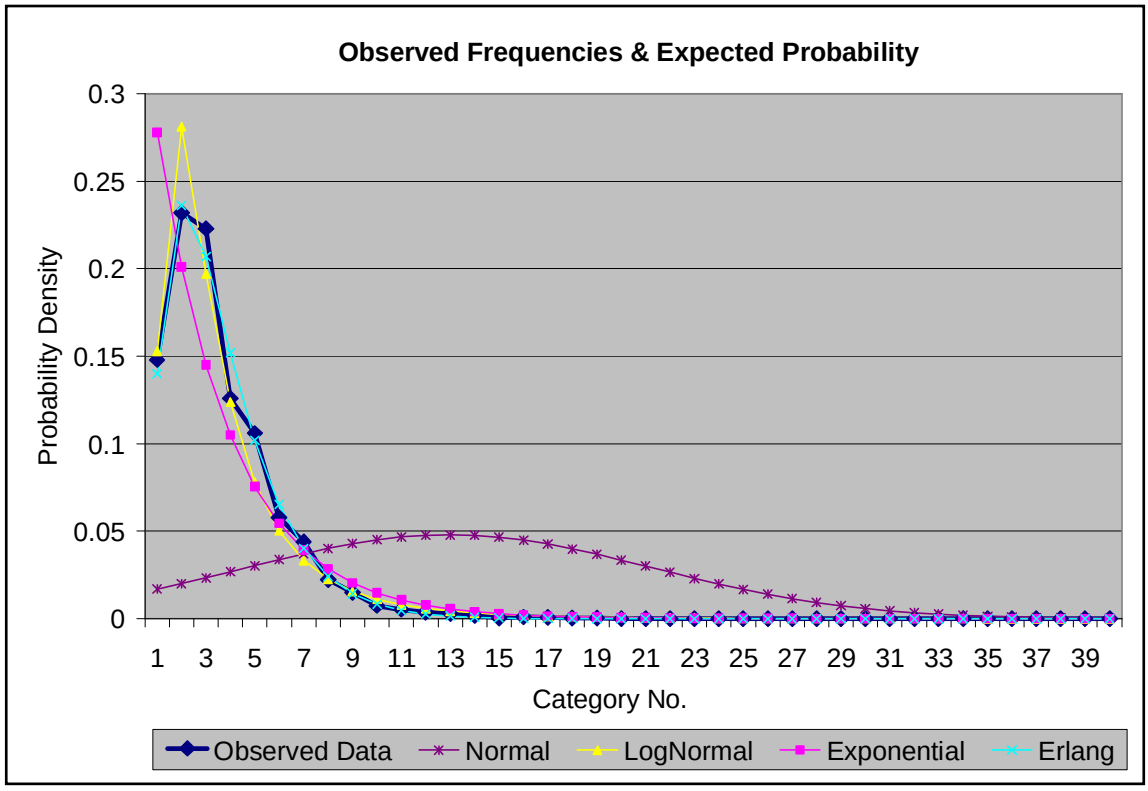


Figure 4.5 Observed frequencies and expected probabilities per category

From Figure 4.5 it can be seen that with the exclusion of the Normal PDF all other probability functions match the data in certain categories and that the Erlang PDF might most probably best fit the data.

In order to determine what PDF "best" fits the data one will use the goodness of fit to test hypotheses about the shape or proportions of a population distribution. The null hypothesis specifies the proportion of the population in each category. Should the alternative hypothesis state that groups are not equal, then the null hypothesis would state that the groups are equal in frequencies. More formally we are interested in testing (for the population of shovel service times) the following hypotheses:

H_0: $t_1, t_2, \ldots, t_n$ is a random sample from a random variable with density $f(t)$

H_a: $t_1, t_2, \ldots, t_n$ is not a random sample from a random variable with density $f(t)$

Given a value of α (the desired Type I error), we accept H_0 if χ^2(observed) ≤ χ^2_{k-r-1} and accept H_a if χ^2(observed) > χ^2_{k-r-1}

For the given example the results in Table 4.3 were obtained:

Table 4.3 Hypothesis test results for the given example

Probability Model	$H_0 : \chi_v^2 (P = 0.05)$	$H_a : \chi^2$ (observed)	**Decision: Accept H_0 ?**
Normal	51	327.17	No
Lognormal	51	0.04	Yes
Exponential	52	0.17	Yes
Erlang	51	0.01	Yes

From the table we accept the H_0 hypothesis for all but the Normal Distribution and conclude that we can accept the hypothesis that the service time could come from a Lognormal, Exponential or Erlang distribution, with:

	Mean	**Standard Deviation**
Lognormal:	3.63	3.48
Exponential:	3.56	12.67
Erlang:	2.78	4.00

Although the means for the distributions that passed the Chi² test are quite close to each other, the standard deviations are not. From Table 4.3 it can be seen that the difference between the observed and expected frequencies is the lowest for the Erlang distribution and in fact this distribution might yield the "best" fit. Another method to examine or rank probability functions that passed the Chi² test is to calculate the Standard Error of the Estimate (S_{xy}).

4.6 Standard Error of the Estimate (S_{xy})

The standard error of estimate represents a measure of variation around a fitted regression line and is similar to the standard deviation that measures the variation around the mean.

$$S_{YX} = \sqrt{\frac{SSE}{n-2}} = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n-2}} \qquad (4.3)$$

The sum of the squares of the errors is equal to the sum of the squared differences (SEE) between the observed value *Y* and the predicted value *Y* or the unexplained variation.

For the example the S_{xy} values are as follows:

Table 4.4 Standard error of estimate for given example

Probability Model	S_{xy}
Lognormal	0.00567
Exponential	0.0137
Erlang	0.00499

The S_{xy} values indicate that the Erlang distribution yields the lowest error between the predicted loading times and the observed loading times. When the S_{xy} values are very small and close in comparison, it does not always imply that the smallest value is indeed the "best" fit. In practice the choice as to which model to use will depend on the user's preference for a specific model or be based on computational efficiency within a particular computer programming environment.

Main observations made from Chapter 4 are as follows:

- Cycle variables have a mean and variance that can be calculated from field observations and is determined by the type of probability distribution that best fits the data.
- In determining the best fit, the Chi² square goodness of fit test statistic can generally be used to determine if there is a correlation between the observed and expected class frequencies for a particular probability function. A low correlation will eliminate any particular probability function as a possible match for a certain set of data.
- When a number of probability functions for a specific set of data all pass the Chi² square test, the Standard Error of Estimation can be used to determine which model gives the best fit to the data.

5 DISTRIBUTIONS OF CYCLE VARIABLES (Orapa Case Study)

In this section, the distribution model characteristics of some truck cycle components of the Orapa Diamond Mine (De Beers, Botswana) will be investigated. The goal of the study was to determine the types of distribution models that best fit the main cycle components. The types of distributions found can then provide an indication to the relevance in using any particular cycle time calculation model.

The data on which the observations are based was generated by the Caterpillar VIMS ® system which is built into the trucks. The VIMS system logged about 70,000 cycle transactions on seven trucks (no.5, 6, 7, 8, 9, 10, 12) within a period of 4 years (2002 – 2005). This number of cycle transactions was then reduced (about 20%) by eliminating faulty readings which included readings with a value of zero (distance and time) and inconsistencies between the reported total cycle time and a summation of individual cycle components. The cycle components investigated are: loading time, travel time full, dumping time and empty travel time.

5.1 Process followed

The Arena program's distribution fitting functionality was used to fit all possible probability distributions on a sample of data for the various cycle time components investigated. Sample data was grouped into 3 categories which are based on three half-cycle travel distances being: (1) up to 2 km, (2) between 2 and 4 km and (3) above 4 km. These distances provide a linear scaling of results and are also typical ranges of travel distances observed on operating mines.

The least square error method was used to calculate the error of using a particular probability model in modelling a particular cycle component. The minimum and maximum square error values were calculated and allocated a value of one to the minimum and a value of zero to the maximum error values calculated for a particular model. This weighting process was then used to find the relative deviation of individual models from the minimum square error to establish their accuracy relevance.

5.2 Research Findings on distributions for cycle variables

Observations made based on the results as indicated in Table 5.1 are as follows:

- The difference between the observed data and the various models fitted are very close which is due to the least square error values being very low. The least square error method is not a definitive method for comparing distribution model results and is influenced by the sample population size which might favour any particular model. For this investigation the sample sizes were relatively large which should have lessened this influence.
- The results show a high level of accuracy for the various main cycle components compared.
- The results also indicate that depending on the degree of prior knowledge regarding the various types of distribution models for cycle time variable values, (example, their mean and deviation) the comparative difference or error in selecting any particular model is almost insignificant.
- To improve the accuracy when determining a cycle component's distribution characteristics which is used in cycle time calculation methods, a sufficiently large population of data is required. Obtaining this data is not always possible (green fields projects) or it is complicated by conducting time studies during mine operations.
- It is surprising that no particular method significantly dominated any particular cycle component. A major disadvantage of using the VIMS ® system exclusively on trucks is the loss of destination specifics such as the loading unit identity. The data for a particular truck does not link it with a particular loading unit and with other issues like haulage profile differences which will influence the results.
- The importance of loading unit identity is vital to determine cycle characteristics such as the inter-arrival time and inter-arrival rate which can be used to determine whether any particular probability distribution will yield the best fit.
- The data also indicates that for a particular truck, the probability distributions of the cycle component values are not constant over time. Based on the weighted least squares error method, each cycle component can be represented by more than one distribution type (Table 5.2). These results thus only serve to illustrate the diversity of possible models that can be present at a particular mine and their relative accuracy.

Table 5.1 Weighted Least Square Errors for distribution models applied to Orapa data

	Distibution Model	Square Error		Weighted Difference with minimum Square Error			Average
				One Way Travel Distance (TD), km.			
		Min.	Max.	(0 < TD ≤ 2)	2 < TD ≤ 4	TD > 4	
Load Time	Beta	**0.000**	**0.800**	1%	1%	2%	**1%**
	Erlang			1%	1%	2%	**1%**
	Exponential			3%	3%	4%	**4%**
	Gamma			1%	1%	2%	**1%**
	Lognormal			1%	1%	2%	**1%**
	Normal			1%	1%	2%	**2%**
	Triangular			2%	2%	3%	**2%**
	Uniform			3%	3%	5%	**4%**
	Weibull			4%	3%	5%	**4%**
	Average			**2%**	**2%**	**3%**	
Travel Time Full	Beta	**0.002**	**0.576**	0%	0%	2%	**1%**
	Erlang			1%	0%	4%	**2%**
	Exponential			2%	2%	13%	**6%**
	Gamma			1%	0%	4%	**2%**
	Lognormal			1%	0%	6%	**3%**
	Normal			0%	0%	2%	**1%**
	Triangular			1%	0%	6%	**2%**
	Uniform			2%	2%	11%	**5%**
	Weibull			1%	1%	2%	**2%**
	Average			**1%**	**1%**	**6%**	
Dump Time	Beta	**0.003**	**0.521**	1%	6%	0%	**2%**
	Erlang			3%	5%	2%	**3%**
	Exponential			3%	7%	2%	**4%**
	Gamma			3%	5%	5%	**5%**
	Lognormal			2%	3%	2%	**3%**
	Normal			13%	11%	12%	**12%**
	Triangular			17%	14%	17%	**16%**
	Uniform			19%	16%	19%	**18%**
	Weibull			2%	6%	2%	**3%**
	Average			**7%**	**8%**	**7%**	
Travel Time Empty	Beta	**0.000**	**0.190**	0%	0%	0%	**0%**
	Erlang			0%	0%	0%	**0%**
	Exponential			1%	1%	3%	**2%**
	Gamma			0%	0%	1%	**0%**
	Lognormal			0%	0%	1%	**0%**
	Normal			0%	0%	0%	**0%**
	Triangular			1%	0%	1%	**1%**
	Uniform			1%	1%	2%	**1%**
	Weibull			1%	0%	0%	**0%**
	Average			**1%**	**0%**	**1%**	

Table 5.2 Range of applicable distribution types for cycle variables for Orapa data

Cycle Variable	Distibution Model
Load Time	Beta, Lognormal, Gamma, Erlang, Normal, Triangular
Travel Time Full	Beta, Normal, Gamma, Erlang, Weibull, Triangular
Dump Time	Beta
Travel Time Empty	Beta, Normal, Erlang, Gamma, Lognormal, Weibull, Triangular, Uniform, Exponential

6 MODEL COMPARISON FOR VIRTUAL MINE MODEL

During the investigation of cycle times at producing mines, it was observed that circumstances do occur which influence the outcome of results. An example of such a circumstance is the breakdown of equipment which causes trucks to either be redirected to other shovels or to queue excessively. Such changes will influence the normal level of production and complicate truck cycle times. The primary aim might have been to study a particular cycle component and due to such occurrences more emphasis might be placed on other components causing results to be skewed. It is probably for this reason that those who develop cycle time models took several years to study the nature of cycle time on mines.

The nature of mining technology is also constantly changing the cycle components. For example, improving travel speed might lower travel time but will also change the nature of queue at the end servers. On certain mines there might be various levels of technology such as different truck sizes or models within a haul circuit which complicates the process even further.

Surface mines in South Africa do however have certain limits. Depth is such a limit, the average mine does not normally exceed a depth of about 135 metres with the exception of super pits which can extend down to about 250 metres (Venetia diamond mine, De Beers Co.). When an ore body extends further than these depths the mining method normally changes from open pit to underground, for instance a block caving method (Palabora copper mine, Rio Tinto Co.). Another limit that influences truck cycle times is that of ramp designs. Ramp designs vary in complexity but their main or common variable is GR% which is a function of machine gradeability and retardability. Most trucks can negotiate a GR% of about 10% but due to safety considerations such as over-speed, braking distances and variable road conditions (slipper wet roads), this value normally ranges from 5% to 8%. In this section the various cycle time calculation models will be compared for a virtual mine. The cycle time calculation methods applied to the virtual mine are Elbrond, FPC®, Talpac®, Arena® and the Adapted Machine Repair Model.

6.1 Virtual Mine Layout

The virtual mine (Figure 6.1) has 10 metre benches that extend from the surface to a depth of 135 metres and the ramp is constructed at an 8% up-grade GR% with a 4% RR% kept constant throughout the haul route. The off-highway trucks (OHT) are loaded with a wheel loader (WL) and dump their ore/ waste at either a plant or waste dump.

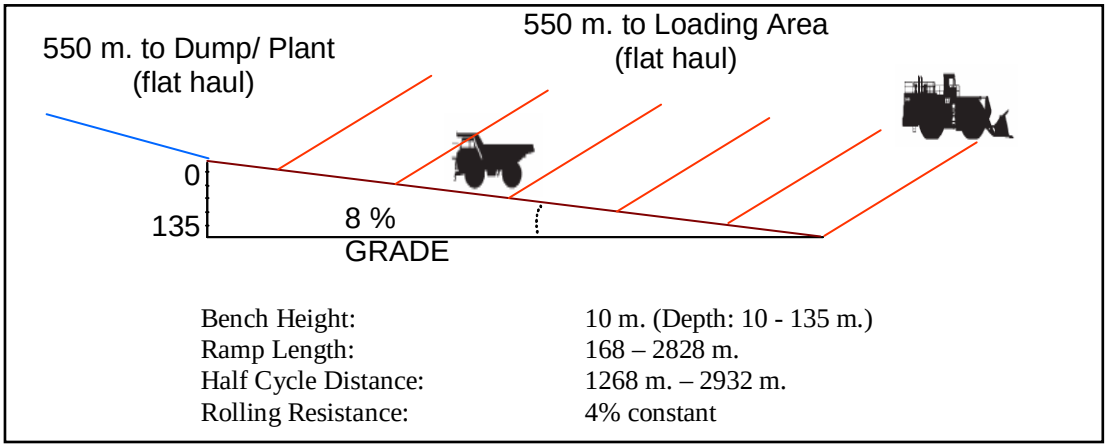


Figure 6.1 Virtual Mine Layout

Figure 6.2 indicates typical working ranges for the mobile equipment, Caterpillar (2006, p. 22-13). The hauling distances for rear dump trucks (off-highway) is seen to vary between 200 metres to 6500 meters, with the virtual mine representing an average mine.

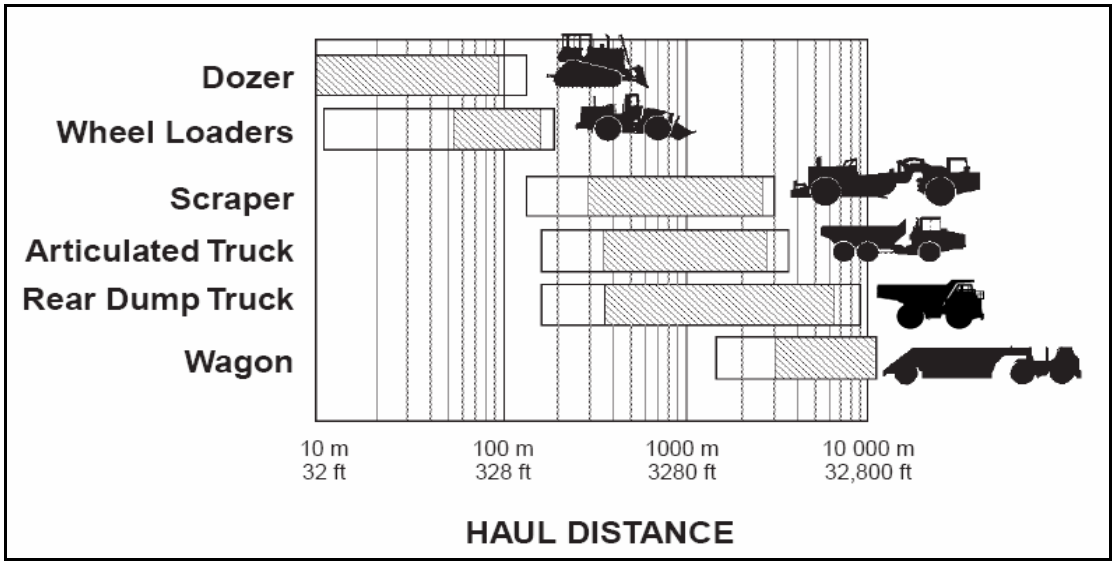


Figure 6.2 Typical hauling distances for mobile equipment

The 4% RR% is based on field observations with loading areas and dumping areas normally having a RR% higher than the best-case scenario of 3%. It might be argued that a 4% RR is high and in general represents a system that is stressed. Caterpillar (2006, p. 27-1) list the conditions associated with rolling resistance levels as shown in Table 6.1

Table 6.1 Rolling Resistance Classification

Underfoot Condition	Rolling Resistance, Percent*			
	Tyres		Track**	Track + Tyres
	Bias	Radial		
A very hard, smooth roadway, concrete, cold asphalt or dirt surface, no penetration or flexing	1.50%	1.20%	0%	1.00%
A hard, smooth, stabilized surfaced roadway without penetration under load, watered, maintained	2.00%	1.70%	0%	1.20%
A firm, smooth, rolling roadway with dirt or light surfacing, flexing slightly under load or undulating, maintained fairly regularly, watered	3.00%	2.50%	0%	1.80%
A dirt roadway, rutted or flexing under load, little maintenance, no water, 25 mm tire penetration or flexing	4.00%	4.00%	0%	2.40%
A dirt roadway, rutted or flexing under load, little maintenance, no water, 50 mm tire penetration or flexing	5.00%	5.00%	0%	3.00%
Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 100 mm tire penetration or flexing	8.00%	8.00%	0%	4.80%
Loose sand or gravel	10.00%	10%	2%	7.00%
Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 200 mm tire penetration and flexing	14.00%	14%	5%	10.00%
Very soft, muddy, rutted roadway, 300 mm tire penetration, no flexing	20.00%	20%	8%	15.00%

*Percent of combined machine weight.
**Assumes drag load has been subtracted to give Drawbar Pull for good to moderate conditions. Some resistance added for very soft conditions.

The main difference between a 3% and 4% RR% (Table 6.1) is the degree of tyre flexing (especially in turns) and a 25 millimetre extra road penetration. The problem associated with tyre flexing can be alleviated by roads cambered in turns and by avoiding sharp turns for loaded trucks. Most mines observed in South Africa generally do not camber main roads and temporary in-pit ramps normally do not comply to GR % standards nor have they adequate turning circle radiuses to prevent tyre flexing. The 4% RR% selection might, from this point of view, provide a more realistic representation of reality.

6.2 Cycle Variables of the Virtual Mine

For the virtual mine three scenarios of loader cycle time were investigated: (1) 3 minutes, (2) 4 minutes and (3) 5 minutes.

Another variable that was investigated is truck payload and thus truck size. Table 6.2 summarizes the machine and cycle variables for the three scenarios.

Table 6.2 Machine an Cycle Variables for Virtual Mine

Machine & Cycle Variables	Units	Scenario 1		Scenario 2		Scenario 3	
		Truck	Loader	Truck	Loader	Truck	Loader
		777D	992G#2 (Hi Lift)	777D	992G#2 (Hi Lift)	793C	994D (Hi Lift)
Machine Number		1,2,…,8	1	1,2,…,8	1	1,2,…,8	1
Target Payload	kg.	90 386	21 772	90 386	21 772	222 904	30 844
Actual Payload	tonnes	87.73	17.55	90.21	15.25	215.46	30.78
Bucket/ Bowl Volume	Loose- m^3	51.61	11.47	51.61	11.47	119.70	18.00
Fill Factor	%	-	95%	-	95%	-	95%
Loader Passes		-	5	-	6	-	7
Material							
- Loose Density	tonnes/ m^3	1.7	-	1.4	-	1.4	-
- Bank Density	tonnes/ m^3	2.2	-	1.6	-	1.6	-
Cycle Time							
Loader Cycle Time	minutes	-	0.60	-	0.65	-	0.7
First Bucket Dump	minutes	-	0.60	-	0.65	-	0.70
Hauler Exchange Time	minutes	-	0.70	-	0.70	-	0.70
Load with Exchange	minutes	-	3.70	-	4.65	-	5.70
Dump & Maneuver	minutes	-	2.5	-	2.5	-	2.5

For the simulation the loads per shift will be used as the base unit for comparison as it is the shortest period within which loading and hauling can occur.

6.3 Simulation in Arena®

The Arena® program was modelled with the Machine Repair Model cycle time characteristics and used as a benchmark against which the other models mentioned in Section 6 were compared. Figure 6.3 illustrates the process flow diagram for this simulation in Arena.

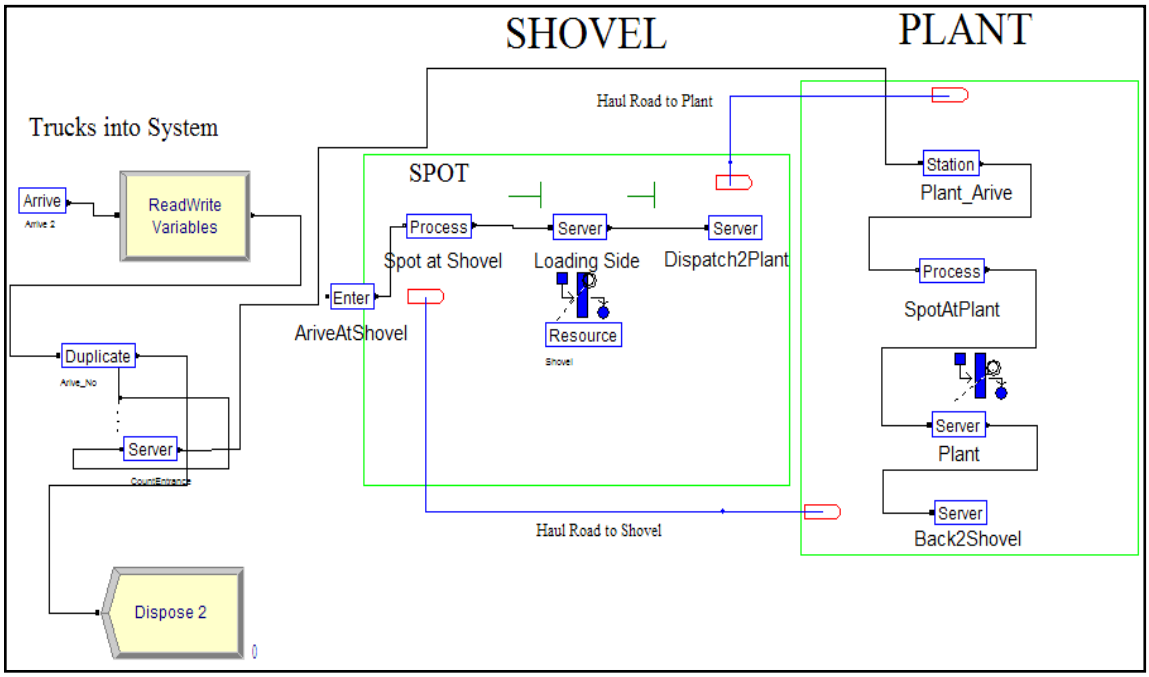


Figure 6.3 Simulation process in Arena®

The Machine Repair Model characteristics incorporated in the model are loading and dumping service times and inter-arrival times of trucks following exponential distributions at the two end-servers (shovel and dumping site). The reason why Arena was modelled in a similar manner to the Adapted Machine Repair Model (A-MRM) is that the other models such as Elbrond, FPC and Talpac are established models while the A-MRM model needed to be benchmarked. Arena is also easier than the other models to programme exponential distributions and the most neutral model for this purpose. FPC does not specify any probability model and Talpac has embedded lognormal distributions.

Arena was not set up to calculate “haul full” time and “travel empty” time values and as such relies on FPC and Talpac travel times for the specified mine design. Trucks are

represented as entities that are processed by resources (shovel/ loader) according to their service times that follow an exponential probability distribution. At the start of a simulation the entities enter the system as it occurs during a shift start-up and servers are programmed with variables such as service time and travel times. The Arena program has, like Talpac, the ability to track each truck's progress throughout the simulation and report the total number of successful loads dumped at the plant. For this simulation, the number of repetitions within which a standard shift is simulated was set at 50,000. The shift duration is 450 minutes (7.5 hours per shift) and the servers were scheduled to stop for 0.5 hours ever 7.5 hours representing non operating shift delays.

The loads per shift results for the Elbrond model are presented in Figure 6.4 while the results for the FPC, Winston, Talpac and Arena models are in Appendix A.

6.4 Model Distribution Fitting

The models are programmed with the following distributions fitted to cycle time variables:

- Elbrond: No distributions are fitted and average values are assumed for the loading and dumping service times as well as for the travel times full and empty. The STS/TS and SRT/RT ratios were set equal to 0.3 (see Table 6.2).
- FPC: No distributions can be fitted with average values assumed (same as Elbrond).
- Winston's Machine Repair model: No specific distributions are fitted and average values assumed (same as Elbrond).
- Talpac: Lognormal distributions on the travel time, dumping time, bucket cycle time and bucket payload.
- Arena: Exponential distribution fitted on the loading and dumping service times, travel times and full and empty (in accordance with the Adapted Machine Repair Model).

The reason why the Elbrond, FPC and Machine repair models were not fitted with probability distributions is that their Excel-based calculations do not require it.

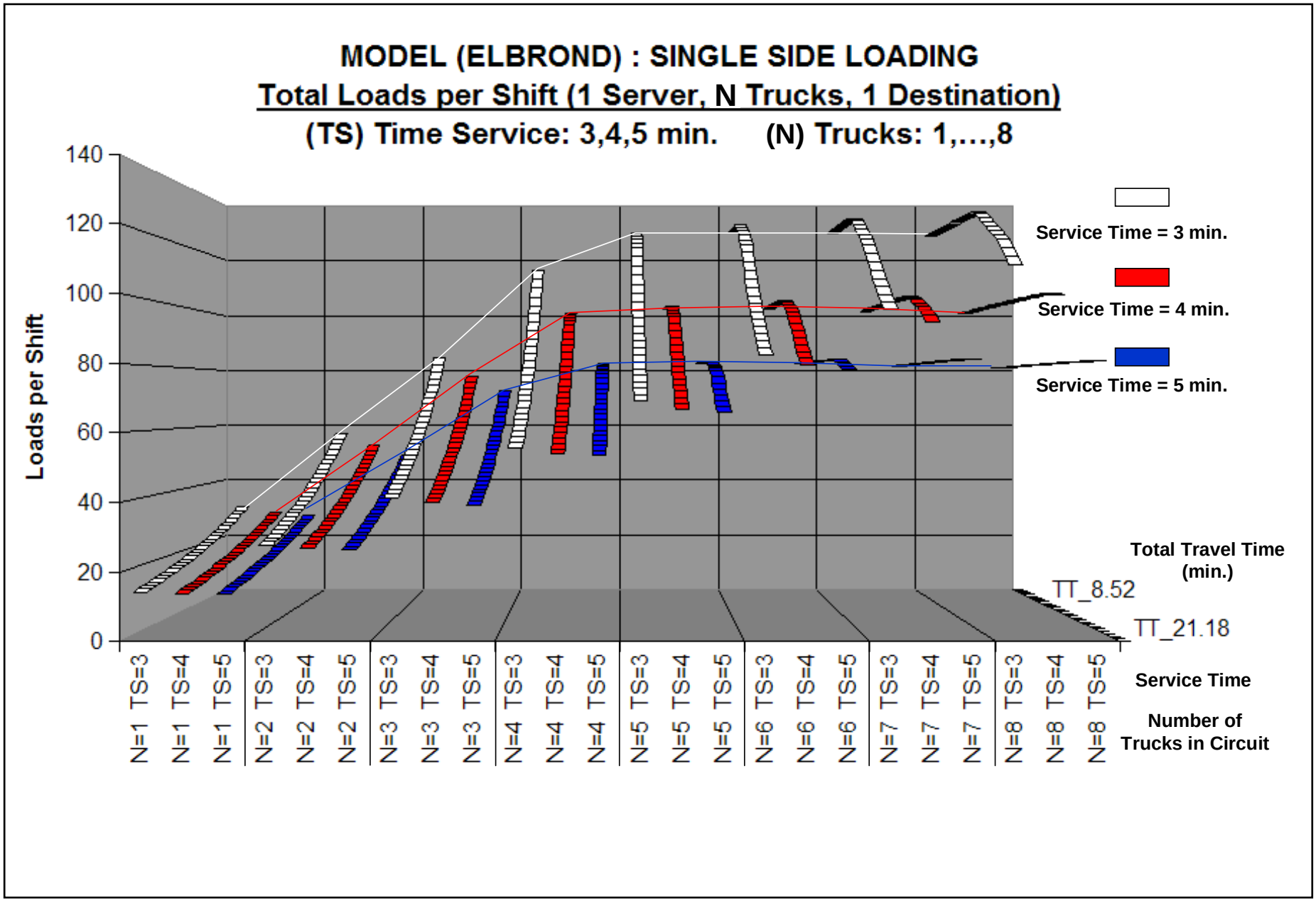


Figure 6.4 Loads per Shift for Virtual Mine using Elbrond Model

6.5 Main Observations in regards to the Loads per Shift

Figure 6.5 depicts the correlation of loads per shift between the various models and Arena for all categories of haul distances per service time at the loader.

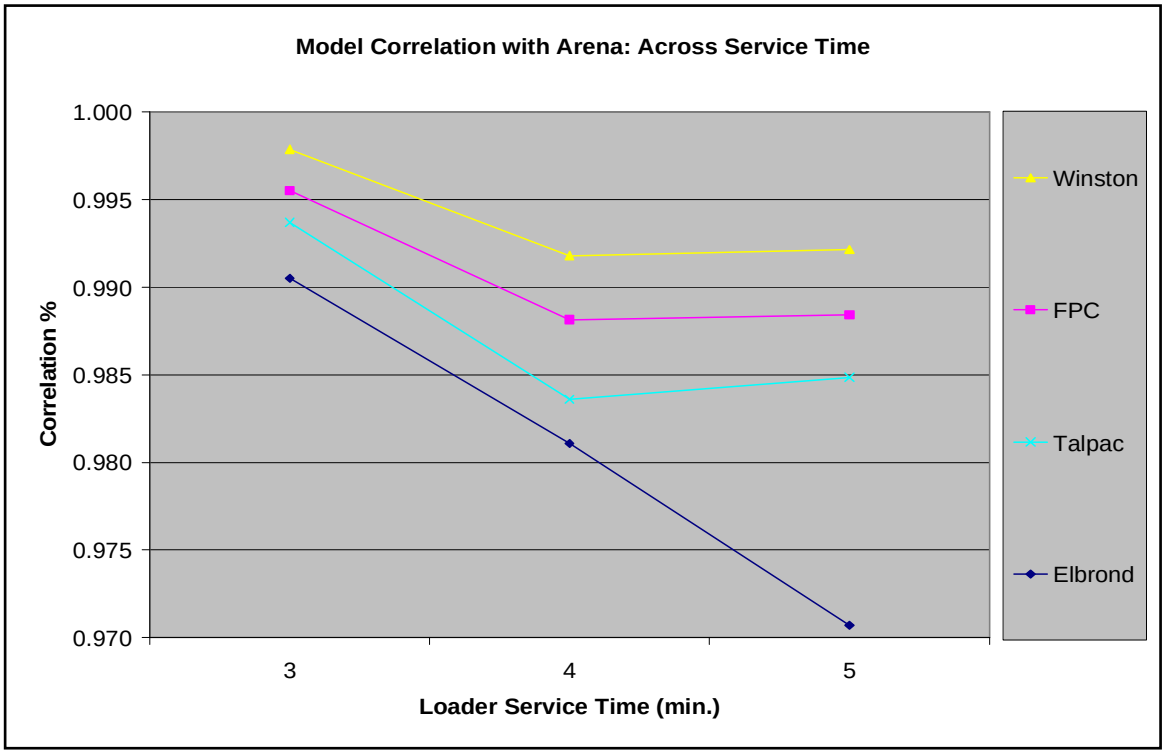


Figure 6.5 Models Correlation with Arena (Virtual mine: loads/ shift)

The following observations are made in relation to Figure 6.5:

- There is a general tendency of relatively high correlations between all models and Arena. (Correlations ranging between 97% - 100%)

- The Talpac model with its predominantly lognormal distributions fitted to cycle variables (standard distribution spreads embedded in program) shows a very high correlation with the predominantly exponential distributions of Winston's Adapted Machine Repair Model.

- Although no type of distribution is specified for FPC, its correlation with lognormal and exponential distribution based models is also very high.

- The Elbrond model has the lowest relative correlation with the other models (including Arena) and this is primarily attributed to it's under-estimation of waiting time for this virtual mine.

- By increasing the STS/TS and SRT/RT ratios from 0.3 to 0.5 the deviation in the Elbrond model decreases and results in this model having a strong correlation with all the other models. This increase in the deviation of the service time and the return time of 20% is quite significant as it signifies a reduction in productivity and an increase in system randomness.

- With an increase in service time the correlation of loads per shift decreases for all models compared to Arena. Arena reported slightly higher loads per shift with the possible explanation being that the models are more conservative in this instance which might be a benefit to any user as it lowers risk in general.

- The structural comments made previously as seen in Figure 2.2 apply to all the above mentioned models.

- The relative improvement in correlation of the Winston, FPC and Talpac models with the Arena Model as a result of the increase in service time from 4 to 5 min. can partially be explained by the difference in machine characteristics between the 777D and 793C OHT's and the difference in the gradeability and retardability.

7 RISK CALCULATIONS FOR THE VIRTUAL MINE

Risk in terms of cycle time calculations is defined as over-estimating or under-estimating cycle time which might include an under estimation or over-estimation of waiting time respectively. The under-estimation of cycle time will in reality result in lower production causing cashflow generation to be at risk which is a major factor influencing any project's feasibility. The following sections focus on risk in cycle time calculations with the financial implication discussed in more detail in Section 7.3

7.1 Cycle Time Variation

There are various reasons why cycle time might be incorrectly estimated, some of the reasons are discussed in the following sub-sections.

7.1.1 Real Operator Proficiency

Over-estimating operator proficiency might result in cycle times that are longer than planned times. Support of operator proficiency is frequently not seen as an integral part of primary production efficiency. For an example, should the wheel dozer operator's not function optimally (or dozer not be available), shovel cleanups can take more time than planned, which can lead to excessive waiting time causing truck cycles to be longer.

7.1.2 Payload Implications

Payload is frequently used as a deciding factor to compare trucks when choosing a supplier to buy from. It was stated earlier on in Section 2.1 that payload is a key factor of production that influences cycle efficiency. Each and every truck is designed for a unique and specific density of material. Linked to that density is the rated payload for that specific truck, if this designed payload is not honoured there can be benefits or disadvantages to the operation. There have been instances where the under-loading of trucks was reported to be a problem. Closer investigation revealed that should the trucks

have been correctly loaded the stresses imposed on the chassis (due to the specific site's poor road conditions) would have seriously affected the future mechanical availability of trucks. Over-loading a truck will increase the normal cycle times. There is a positive correlation between the fuel consumption and the machine life. Overloading might in the short run increase production per cycle but destroy capital and most importantly future cashflows through increased maintenance and equipment replacement.

Payload as factor of production is also a variable that influences the loading strategy and its efficiency. There are primarily two methods or strategies these being full shovel buckets (integer pass number) or full trucks with the possibility of a non integer number of passes to fill the truck. Equal support exists for both methods with valid reasons on each side to support the claim as to which method is best. The full truck strategy will in most cases result in the loading time being longer and will cause the total cycle time to increase. The probability of over-loading trucks which are using this method is also greater. It is the author's opinion that a full shovel bucket strategy is better even with the risk that the full payload might not also be realized. This is due to the benefit of a generally shorter cycle time and lower risk to the truck's structure. Payload is therefore viewed as being subordinate to cycle time yet still a very important factor of production. Over-loading and under-loading causes deviations from the average anticipated payload and cycle time.

7.1.3 Paper Mines

Another reason for why cycle time is frequently over-estimated in reality is due to the difference between planned mine standards and future real time practices. During the design phase a "paper" mine is generated and can include features like cambered roads, low rolling resistance, consistent and optimized ramp grading but in reality the bankable document stipulating such standards are seldom reviewed after financial approval. The recent standards pertaining to resource and reserve classification as defined by the International Valuation Standards Committee (I.V.S.C.) which aims to improve geological modelling might also improve the historical deviation of a mine's production planning in this case.

7.1.4 Dump Site Neglect

Another reason for frequently under-estimating cycle time is dump-site neglect which is more psychological in nature. Globally, most surface mines can be described as waste mines due to their grade characteristics with a by-product being the actual commodity extracted. When platinum miners (for e.g.) are asked what they mine, they almost always answer that they mine platinum. In reality more than 80% of the material mined will be waste. This mindset has resulted in miners neglecting the dump areas in favour of loading areas causing the total cycle time to be higher than anticipated. Quantifying these factors is difficult when planning and simulating a future operation. The following section will investigate the effect of variation in cycle elements as part of a sensitivity analysis to determine its impact on estimating the loads per shift.

7.2 Sensitivity Analysis

A sensitivity analysis was preformed on the virtual mine for the Elbrond, FPC and Winston models to determine the impact the various cycle elements have in affecting the loads per shift. For the sensitivity analysis the @Risk® program was used. @Risk (Palisade Corporation) is an add-in for Microsoft Excel and has the functionality to fit distributions to spreadsheets and perform Monte Carlo type simulations on designed systems. The reason for the exclusion of the Talpac and Arena programs is that they are Monte Carlo type simulations packages with precise calculation algorithms unknown and thus not possible to simulate in Excel.

7.2.1 Distribution Fitting

In Table 7.1 the cycle variables of the Elbrond and FPC models were fitted with triangular distributions where the minimum value, most likely value and maximum value were specified. This distribution type is frequently used to get quick insight into a system. The reason for fitting them with triangular distributions is that the Elbrond and FPC models do not have definite model classifications and it would be biased to force an exponential model on them. The adapted machine repair model's cycle variables listed in Table 6.2 were fitted with exponential distributions for this sensitivity analysis.

Table 7.1 Distributions fitted to cycle time variables for the Virtual Mine

Variable	Triangular Distribution (Min, Avg., Maximum)		
	Scenario 1	Scenario 2	Scenario 3
Loading Time	(3,3.1,4)	(3.9,4,5)	(4.9,5,6)
Spot at Loader	(0.7,0.8,0.9)		
Travel Full	(Travel Full*0.95, Travel Full, Travel Full*1.15)		
Travel Empty	(Travel Empty*0.95, Travel Empty, Travel Empty*1.15)		
Spot at Dump	(0.5,0.6,0.7)		
Dumping Time	(1.8,2,2.5)		
Shift Minutes	(445,450,455)		

In Table 7.1 the minimum loading time corresponds with the minimum loading time specified by equipment manufacturers. In practice loading time can be shorter with trucks being "half" loaded. This will influence the actual payload and thus the production which is not reflected by the loads per shift base unit of measure. Another observation is that of travel time which has a larger spread about the average. This can be explained by a lower operator proficiency which is more dominant than lower cycle times due to trucks being "half" loaded (for instance). The dumping time and shift minutes are both given low spreads and only serve to include more variability into the system.

Figure 7.1 is in fact the loads per shift for the FPC model with the loader having an average loading time of 3 minutes with the number of trucks in the fleet varying from 1 to 8 over a haul course with the half cycle distance varied between 800 and 2300 metres. Figure 7.1 shows typical results obtained from the FPC model for the 20th, 50th and 80th percentile values.

The percentiles values are probability values stating the following:

- 20th: There is an 80% probability values can be higher than its specific value.
- 50th: representing the average value of probability.
- 80th This is the highest calculated value and states there is an 80% chance that the actual value can be lower than its specific value.

The following can be noted in Figure 7.1, on the extremities at 8.53 minutes and 22.1 minutes of a specific service time and truck fleet size series, the percentile values fall within an almost straight line. This is explained by the cumulative probability curve for the same data in Figure 7.3.

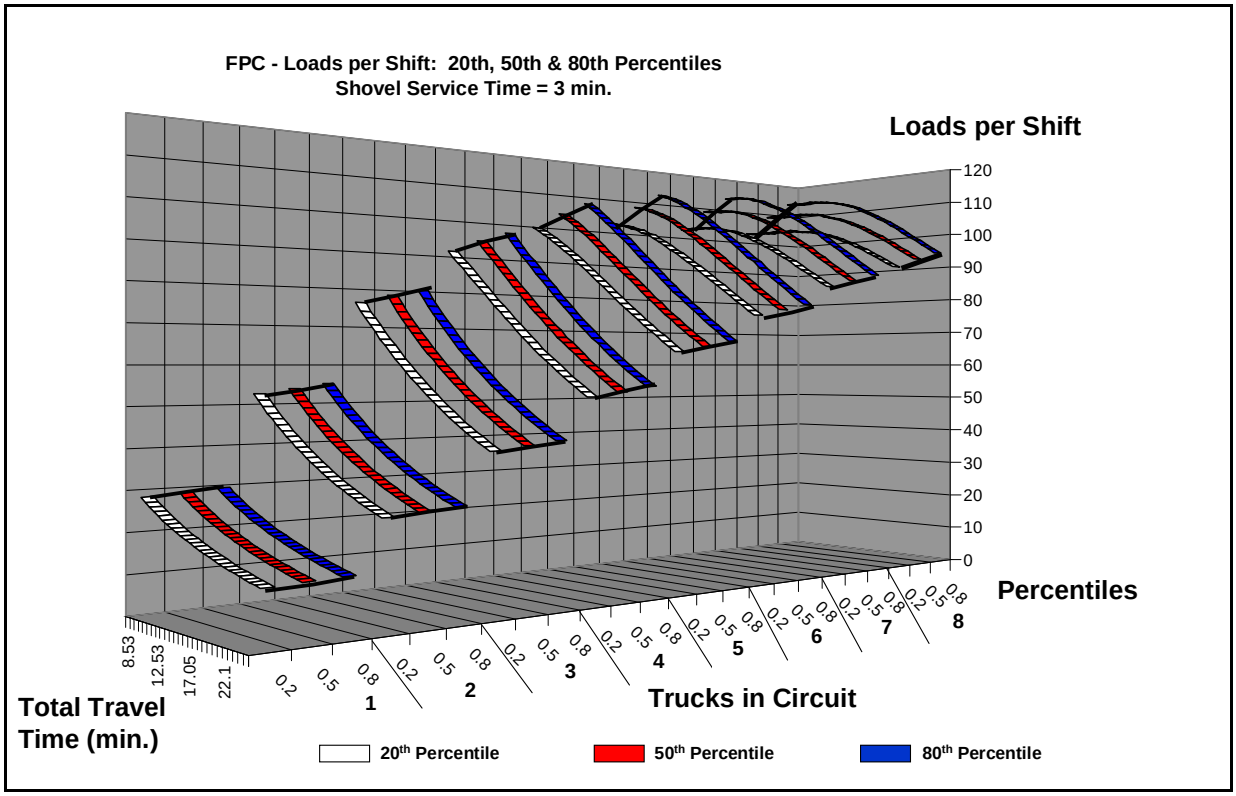


Figure 7.1 Loads per Shift Results of Scenario 1 using FPC for the Virtual Mine

In general, the loads per shift will never be constant and will fluctuate between the minimum and maximum. Of interest is the extent to which it is more likely to vary either side of the 50th percentile value. In Figure 7.2 this difference is measured for the Virtual Mine. Figure 7.3 shows that should the chosen interval on the CDF curve be made smaller, the remaining cumulative probabilities can be expected as to lie on a straight line with an increasingly higher level of correlation. For this chosen interval representing a 60% spread or an interval of 20% higher, 80% lower, the deviation from the 50% probability is given in Figure 7.2.

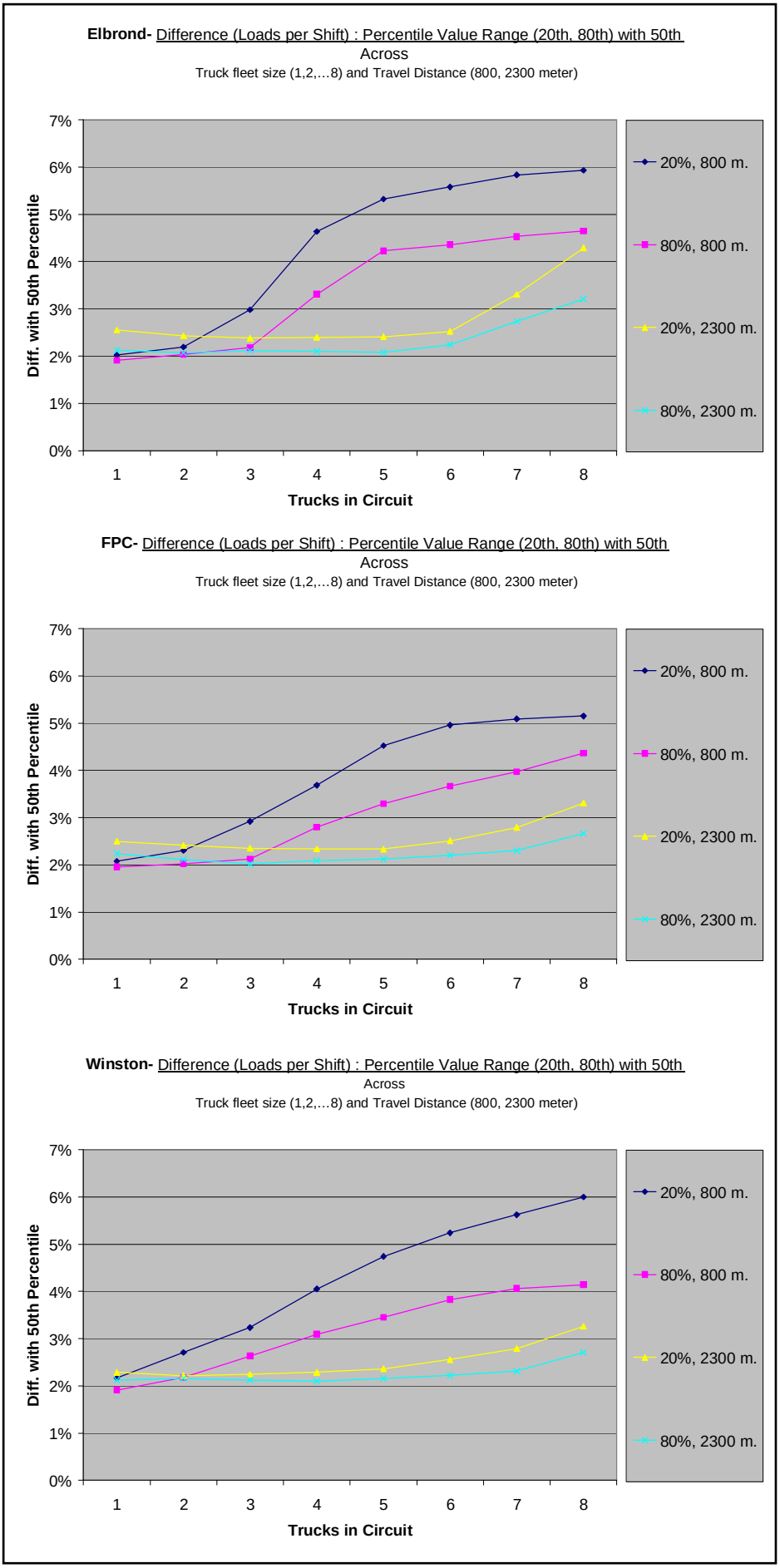


Figure 7.2 Difference in Percentile Values for the Virtual Mine

From Figure 7.2 it can be seen that the deviation around the 50th percentile for the virtual mine is fairly similar for the three models. There is a strong correlation between the deviation and the number of trucks within a circuit, with the deviation increasing as the number of trucks increase. The deviation decreases as the travel distance of the haul course increases. This might be explained by the significance of waiting time that decreases with distance. In general, there is a slightly higher tendency for values to be lower than the average value.

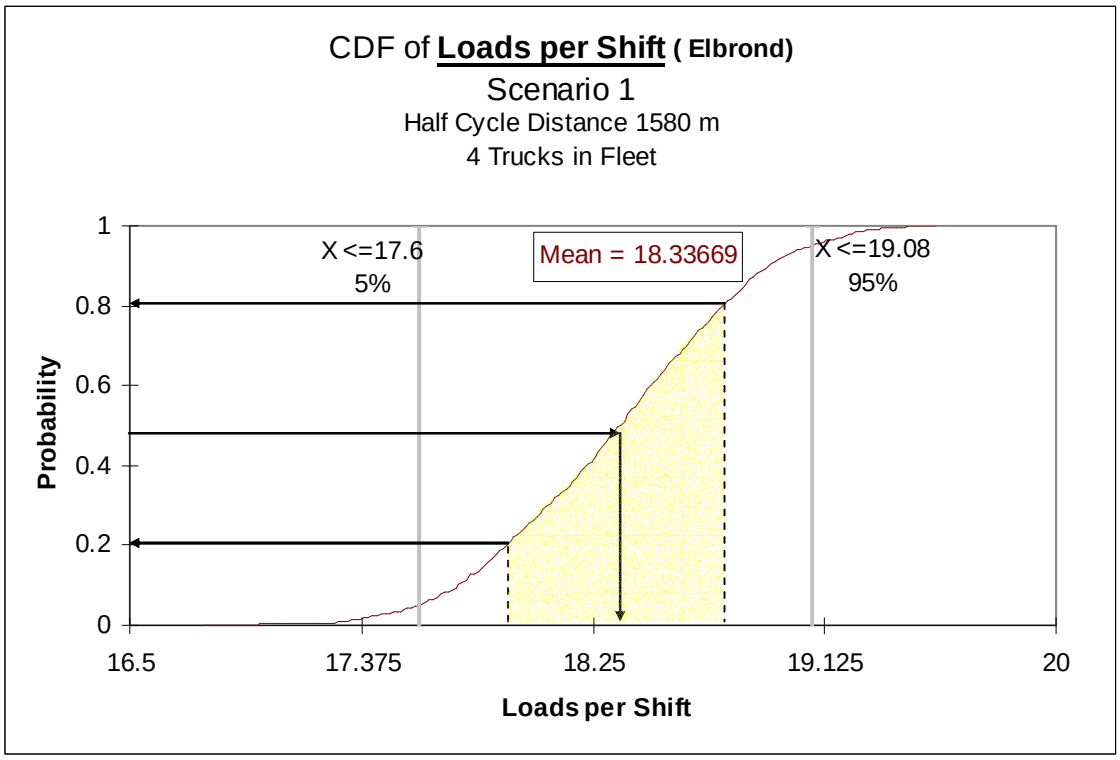


Figure 7.3 Cumulative Distribution Function, Elbrond (Virtual Mine)

Figure 7.3 illustrates how the loads per shift can vary for Scenario 1 (see Table 7.1), based on the chosen triangular distributions for the selected cycle variables within the Elbrond model and specifically with 4 trucks in the fleet.

@Risk also performs a sensitivity analysis on the input variables and presents the results in the form of a Tornado graph. The Sensitivity analysis performed on the output variables and their associated inputs uses a multivariate stepwise regression analysis. The input distributions of the virtual mine are ranked by their impact on the output variable loads per shift. Stepwise regression is a technique for calculating regression values with multiple input values.

The coefficients listed in the @RISK sensitivity report are normalized regression coefficients associated with each input. A regression value of 0 indicates that there is no significant relationship between the input and the output, while a regression value of 1 or -1 indicates a 1 or -1 standard deviation change in the output for a 1 standard deviation change in the input.

7.2.2 Sensitivity Analysis Results

The results of the sensitivity analysis are displayed in Figure 7.4 for the Elbrond model. Results for the FPC and Adopted Machine Repair Model are in Appendix B.

The sensitivity results for the three models: Elbrond, FPC and Winston are set at a specific haul distance of 1580 metre with 4 trucks in the cycle. The models generally have the same degree of sensitivity for the various production variables modelled. The Elbrond model does however show a higher sensitivity for travel time on the lower loader cycle time level and with the increase in loading time compares with the other two models. The increase of shift minutes has a surprisingly high influence in view of the low spread given and highlights the impact of proper shift start-ups and closures. The influence of truck payload is almost negligible as expected as it does not constitute a time value. The high proportion of load time observed within all three models does however support the importance of payload as an important cycle time component. When the travel time was increased, the sensitivity results displayed a similar sensitivity map with one major difference in that the proportion of the travel time decreases with an increase in cycle distance, which can be explained by truck operator proficiency over distance.

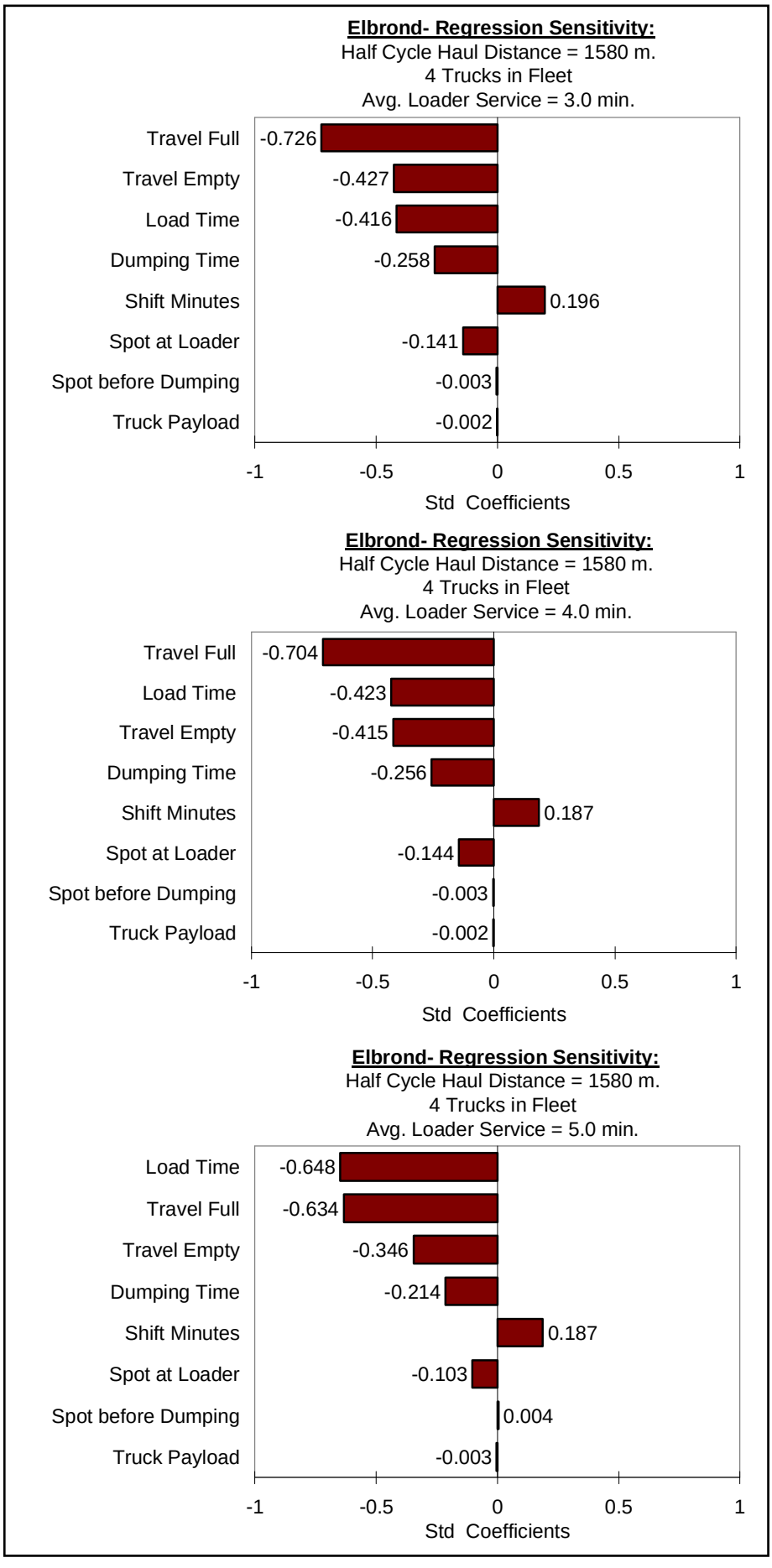


Figure 7.4 Sensitivity Analysis Results: Elbrond (Virtual Mine)

Operator proficiency varies with distance and influences the haulage times as illustrated in Figure 7.5 (FPC Users Manual 2003, p. 104).

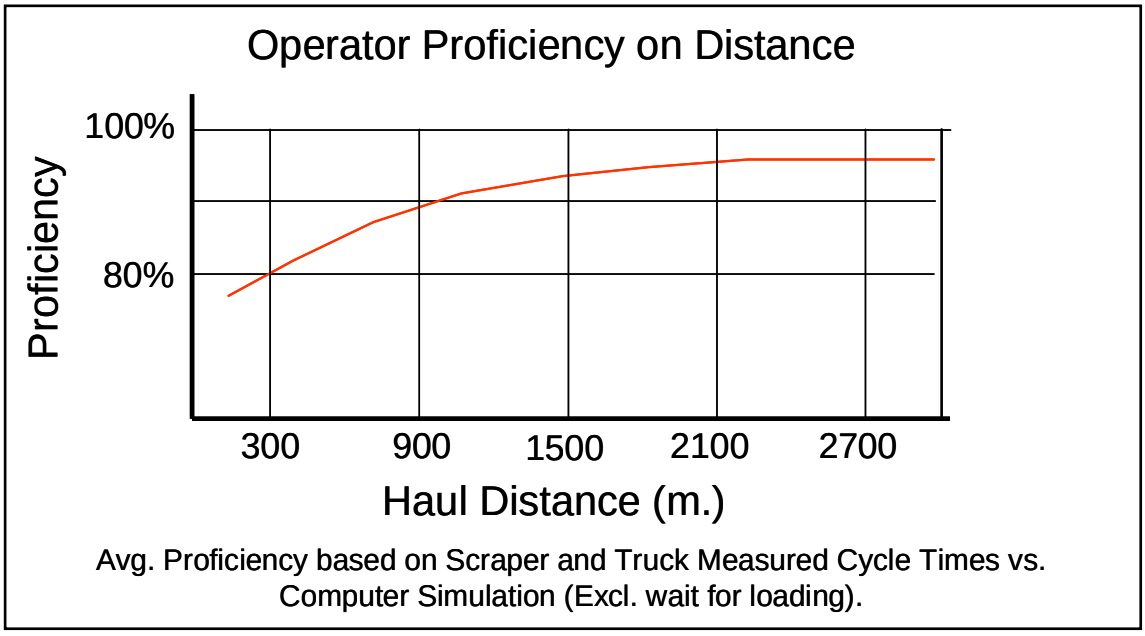


Figure 7.5 Operator Proficiency on Distance (FPC)

Figure 7.5 was developed by the Caterpillar FPC software developers and based on numerous field observations. In general, the operator proficiency will increase with an increase in distance. A possible reason behind this improvement is that over distance there are fewer stops that require truck deceleration and acceleration with the operator having a lower gear shift frequency which improves the potential travel speed and as a result a lower travel time normally realizes.

7.3 Cashflow Risk

The motivation for using the loads per shift as the basis for comparing the various models is to illustrate the "snow-ball" effect which starts with loads per shift and ends with cashflow generation. The basic undiscounted cashflow calculation is as follows:

$$\text{Mining Cashflow} = \frac{Tonnes}{Shift} x \frac{Shifts}{Year} x Ore\ \text{Production}\ \%\ x \frac{Gross.\ \text{Profit}}{Tonne} \qquad (7.1)$$

The nature of all mines varies in regards to their scope of operations (tonnes produced), the type of commodity being mined (revenue per unit, processing cost, equipment capital layout), location (governmental duties, taxes and involvement, transport

requirements) and reserve base (life of mine expectancy and payback period of capital). These are just the most basic variables that will influence the cashflow that is generated by a mine within a variable market (commodity prices and cycles) and that is actually reported. It provides valuable insight into the complexity involved in calculating cashflow. The following assumptions are made for a coking coal example:

- US$ per Tonne: $ 55.00
- Rand: US$ exchange rate R 7.50
- Rand/ Tonne: R412.50
- Profit margin: 25%
- Profit Value: R103.13
- Mining Cost % in Total Value Chain: 35%
- Simulation total cost coverage (assumed): 69%
- Assume Profit/ tonne (simulation): R25/ tonne
- Production period: 5 Years
- Cashflow: Undiscounted
- Site Scheduled Hours: 8480
- Machine Scheduled Hours: 7653
- Machine Operating Hours: 6907
- Operator Combined Proficiency (Truck & Loader): 93%
- Coal Production% 65%
- Truck Inter-arrival Time (Loader & Destination): Exponential
- Service time (Loader & Destination): Exponential

Figure 7.6 illustrates the difference in cashflow (undiscounted) based on the above assumptions between the Elbrond model and Arena. Results for FPC, Winston and Talpac are in Appendix C. The main assumption that inter-arrival time and service-time is exponential has a profound impact on the values displayed and is biased towards the Arena and Winston models (machine repair model) viewing the models in light of these major assumptions. It illustrates the impact each model will have on anticipated cashflows, and can assist in deciding which model to use.

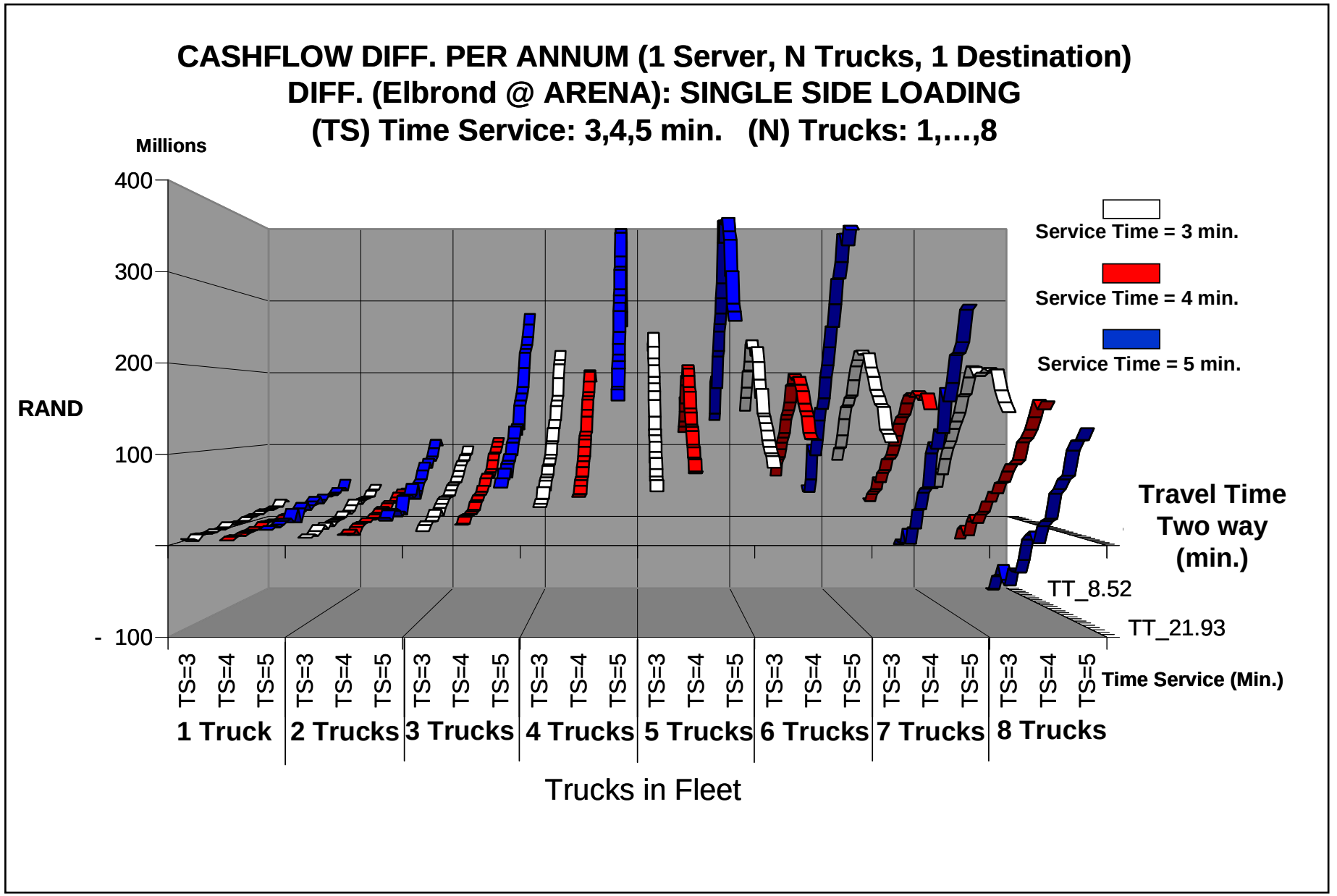


Figure 7.6 Cashflow Difference Results of Elbrond vs. Arena for the Virtual Mine

8 PRODUCTIVITY CALCULATIONS

8.1 Operating Active Hours

Part of the productivity calculation for any load-and-haul system is the calculation of actual productive hours within the cycle. The calculation will determine the production for a specified haulage system and fleet size. The calculation of actual production hours can vary in degree of complexity which is primarily caused by the assumptions made by the person conducting the calculation. These assumptions include machine, operator and destination efficiencies, utilisation and availabilities which will vary in complexity based on the scope and complexity of the operation concerned.

The productivity calculation therefore needs to consider the loading unit, haul unit, operator, destination and most importantly, the availability, utilization and efficiency of the secondary equipment. There is a mindset in the industry that secondary equipment has a secondary role in achieving production goals, and it is for this reason that secondary equipment should rather be referred to as production assist equipment. Numerous studies conducted by Caterpillar and Barloworld have indicated that the absence of production assist equipment can cause production to drop by as much as 20%, which is quite severe when considering the cashflow implication it involves.

In Table 8.1 a typical truck calendar breakdown is shown.

Table 8.1 General Truck Calendar Breakdown

Calendar Hours per Annum	**8760**
Minimum 0ff Time Loss	**3.2%**
Site Scheduled Hours	**8480**
Operator Proficiency- Truck	90%
Proficiency Derated Hours	**7632**
Miss Match/ Bunching/ Queue Loss	15%
Cycle Inefficiency Derated Hours	**6318**
Truck Utilization	80%
Mining Utilization Hours	**5054**
Truck Availability	80%
Operational Hours	**4043**

Table 8.1 indicates that the annual hours are progressively lowered by efficiencies and availabilities to derive the actual operational hours available within which production

will in effect take place unhindered. The off time loss represents losses associated with public holidays or days within which no production will take place. The Machine Hours form part of the operational hours and the breakdown of these hours is based on work done by Ramani (1990) and shown in Table 8.2.

Table 8.2 Machine Hours Breakdown

	hr/yr	%		hr/yr	%
Operational			**Mining**		
Idle	182	3%	Idle	182	3%
Operating, active	3601	57%	Operating, active	3601	57%
Delays, fixed	607	10%	Delays, fixed	607	10%
Preventative Maintenance, Scheduled	251	4%	Standby	666	11%
Repair, Scheduled	262	4%			
Repair, Unscheduled	156	2%			
Standby	666	11%			
Total	**5726**	**91%**	Total	**5057**	**80%**
Maintenance			**Mechanical**		
			Preventative Maintenance, Scheduled	251	4%
			Repair, Scheduled	262	4%
			Repair, Unscheduled	156	2%
Idle	144	2%	Idle	144	2%
Repair	442	7%	Repair	442	7%
Total	**586**	**9%**	Total	**1255**	**20%**
Machine Hours	**6318**	**100%**	**Machine Hours**	**6318**	**100%**

Table 8.2 serves as an example of the two different ways in which machine hours can be broken down i.e. (1) Operational and Maintenance, and (2) Mining and Mechanical time divisions. The fixed delays in Table 8.2 are defined as predictable prior to the time of occurrence. They represent time entities like shift changes, machine inspections, breaks (rest or lunch breaks), refuelling and operations stopped for blasting. Both these divisions have the same Machine Hours and illustrate the importance of mining (or operations) in the time management of equipment.

The Operational and Maintenance division is the most common form normally presented to mine management. By presenting it in this form the importance of Maintenance portion in truck time management can be over-looked which can be as high as 20% of the total machine hours.

Based on Table 8.1 and Table 8.2 the following formulae are used to determine machine availability and utilisation:

$$\text{Physical Availability} = \frac{\text{Operating Active (hours)}}{\text{Machine Hours}} = \frac{3601}{6218} = 57\% \quad (8.1)$$

$$\text{Use of Availability} = \frac{\text{Idle, Operational + Operating, Active + Standby}}{\text{Operational, Total}} = (182 + 3610 + 666) / 5726 = 78\% \quad (8.2)$$

$$\text{Effective Utilization} = \text{Physical Availability} \times \text{Use of Availability} = 57\% \times 78\% = 44\% \quad (8.3)$$

This effective utilisation value of 44% effectively states that with all time available to production for hauling tonnes, only 44% of this time will effectively be used for production purposes. Compared to a conveyor system a load-and-haul system might be less effective and more costly to operate but it is more favoured because of its lower capital cost and high mobility. It also makes projects less sensitive to life of mine concerns such as payback period and changes in the geological layout of a mine. This low value also stresses the importance of accurately calculating the cycle time of a proposed fleet composition as the "window" within which production will actually realise is small. The values are highly subjective and only serve as an indication of the extent to which individual time units can vary within the over-all time distribution.

8.2 Interdependence of System Units

A load-and-haul system's overall efficiency is dependent on each of its components or units functioning at an optimum level and having a high level of availability. The system units are typically the truck, loader, dump, operator and secondary equipment. Productivity can be calculated for an individual system unit such as a truck that is based on machine, operator and loading unit standards. Actual productivity for any particular unit will be a function of all the units and their interaction or alternatively their interdependency. The interdependency is lower for this type of system compared to a conveyor system which can generally be described as a series system with the former having series and parallel links. An example for when parallel links form is when a

loading unit can follow a double sided loading technique or when a dump destination providing more than one server to the trucks feeding it. The lower interdependency of a load-and-haul system also provides it with a higher level of flexibility or lower over-all risk profile compared to a conveyor system where if one belt does not work, the entire system is at risk of not working. Machine availability, utilisation and operator proficiency is part of the total system as the destination also forms a vital part of the system and plays an important role in determining productivity. Figure 8.1 illustrates a typical Load-and-haul System with the various primary production and production assist equipment.

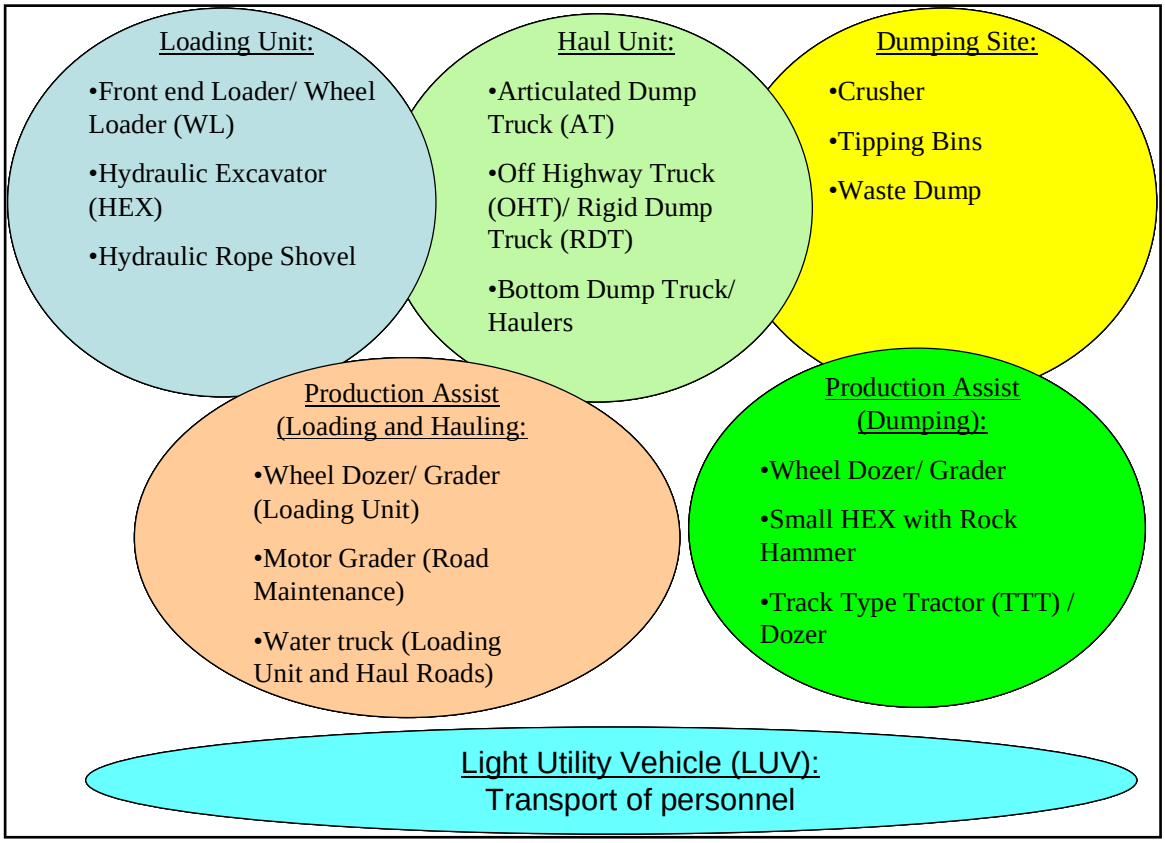


Figure 8.1 Types of machine in Load-and-Haul Systems

Figure 8.1 shows that a load-and-haul system does not just consist of a truck and a shovel but includes production assist machines and can involve a complex plant and dump arrangement. Also very important is the use of a light utility vehicle (LUV) to prevent production equipment from being used as man-carriers. A calculation of actual production hours using a simplistic method is illustrated in Table 8.3, the impact of not accounting for the dump site availability, utilisation and operator proficiency is shown to be 20% compared to the same model which includes the items and represents a over-estimation of production.

Table 8.3 A Simple Calculation of Actual Production Hours

Row No.	Calculation String	Without Dump Site	With Dump Site	Calculation	% Diff. (Without Dump Site)
1	**Calendar Hours per Annum**	**8760**	**8760**		
2	**Min. 0ff Time Loss (3.2%)**	280	280	(1) x 96.8%	
3	**Site Scheduled Hours**	**8480**	**8480**	(1) - (2)	**0%**
4	Truck Utilisation	**95%**	**95%**		
5	Shovel Utilisation	**95%**	**95%**		
6	Dump Site Utilisation	**-**	**95%**		
7	**Machine Scheduled Hours**	**7632**	**7250**	(3) x (4) x (5) x (6)	**5%**
8	Truck Availability	**95%**	**95%**		
9	Shovel Availability	**95%**	**95%**		
10	Dump Site Availability	**-**	**95%**		
11	**Machine Operating Hours (SMU)***	**6888**	**6216**	(7) x (8) x (9) x (10)	**10%**
12	Operator Proficiency- Truck	89%	89%		
13	Operator Proficiency- Shovel	89%	89%		
14	Operator Proficiency- Dump	-	89%		
15	**Actual Production Hours**	**5475**	**4398**	(11 x (12) x (13) x (14)	**20%**

**SMU = Scheduled Machine Units*

The following formulae can be used to calculate production:

Tonnes per Scheduled Hour = Number of trucks
x 60/ Total Cycle Time (minutes)
x Truck Payload (tonnes)
x Combined Utilization % (truck, loading unit, dump)
x Operator Proficiency % (truck, loading unit, dump)
x Combined Availability % (truck, loading unit, dump) (8.4)

Combined Utilisation (%) = Trucks x Loading Unit x Dump (8.5)

Operator Proficiency (%) = Truck Operator x Loader Operator x Dump (8.6)

Combined Availability (%) = Trucks *Avb. x Loader *Avb. x Dump *Avb. (8.7)

Truck Availability (%) = $NC_n(P_a)^n(P_{na})^{N-n}$ (binomial equation) (8.8)

N = Number of units in system

NC_n = Combination of N things taken n at a time ($n \leq N$)

n = Number of units considered (Integer)

P_n = Exactly n units are available

P_{na} = A single unit is not available

Loading Unit *Avb. (%) = (8.9)

$$\frac{\text{Loading Unit Avb. x Loading Unit Scheduled Hours}}{\text{Site Scheduled Hours}}$$

Dump Site Availability (%) = $\frac{\text{Dump Avb. x Dump Scheduled Hours}}{\text{Site Scheduled Hours}}$ (8.10)

**Avb. = Availability*

9 OPTIMUM COLLIERY CASE STUDY

9.1 Background

Optimum Colliery's Kwagga Section is a surface mine belonging to Ingwe Coal Corporation Ltd. and BHP Billiton Co. Overburden bench striping is done with three Marion draglines after which coal is loaded into off-highway trucks and coal haulers using front end loaders. Coal from Kwagga section is mined from 3 areas being: North (Rail), Central and South Sections.

Prior to this study, the equipment fleet complement was:

- 4 x Caterpillar 776D coal haulers
- 7 x Caterpillar 777D OHT
- 2 x Caterpillar 992 G Wheel Loader (WL) with a high lift (HL) arrangement
- 1 x Caterpillar 992 D WL HL

Run of mine (ROM) of about 11.77 million tonnes per year are hauled to 2 tips situated at the Central and South Sections from where two main conveyors feed the washing plant delivering coal to the Hendrina Power Station. This ROM value includes parting material that is not handled by the above fleet, but is contracted to Scharrighuisen Holdings Ltd. The ROM value hauled by the above fleet is about 10.5 million tonnes per annum.

The Central and South tipping points have separately scheduled, weekly maintenance days of an 8 to 12 hour duration taking place on either a Wednesday or Thursday. Material is hauled to stockpiles which are situated at various points connected to the main roads. As soon as a tip becomes available, the stockpile is consumed to lower the risk of spontaneous combustion and to utilise the lower travel distance which will increase the production rate. By consuming the stockpile, a fraction of production is re-handled which lowers the overall utilization of the loaders but increases the overall utilization of the trucks. The aim of this project is to calculate the required number of trucks to reach the tonnes per hour per section targets with the various cycle calculation models and to compare the results. Aerial photographs of the three sections are indicated in Figure 9.1 to Figure 9.3.

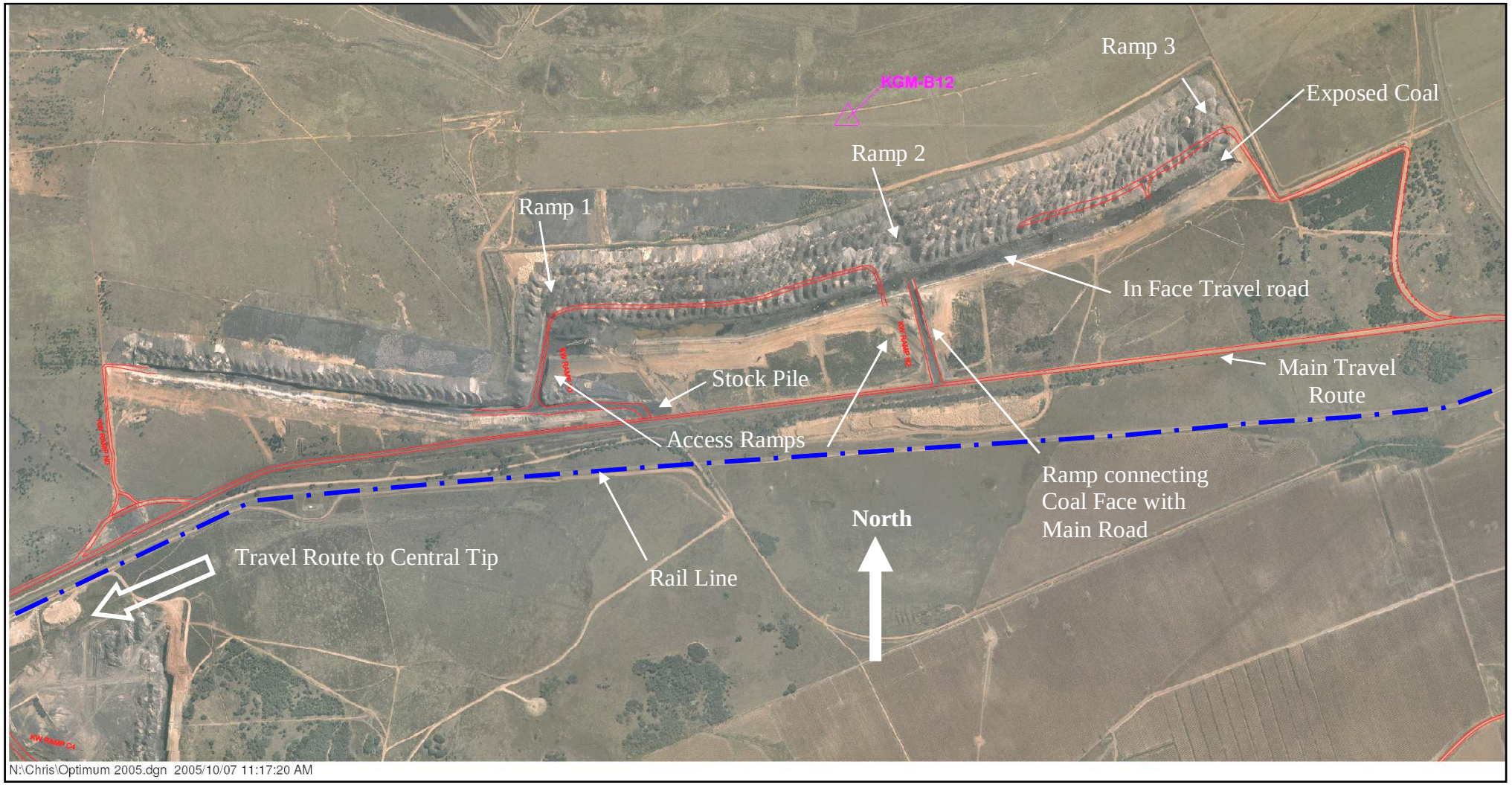


Figure 9.1 Aerial photograph of the North (Rail) Section

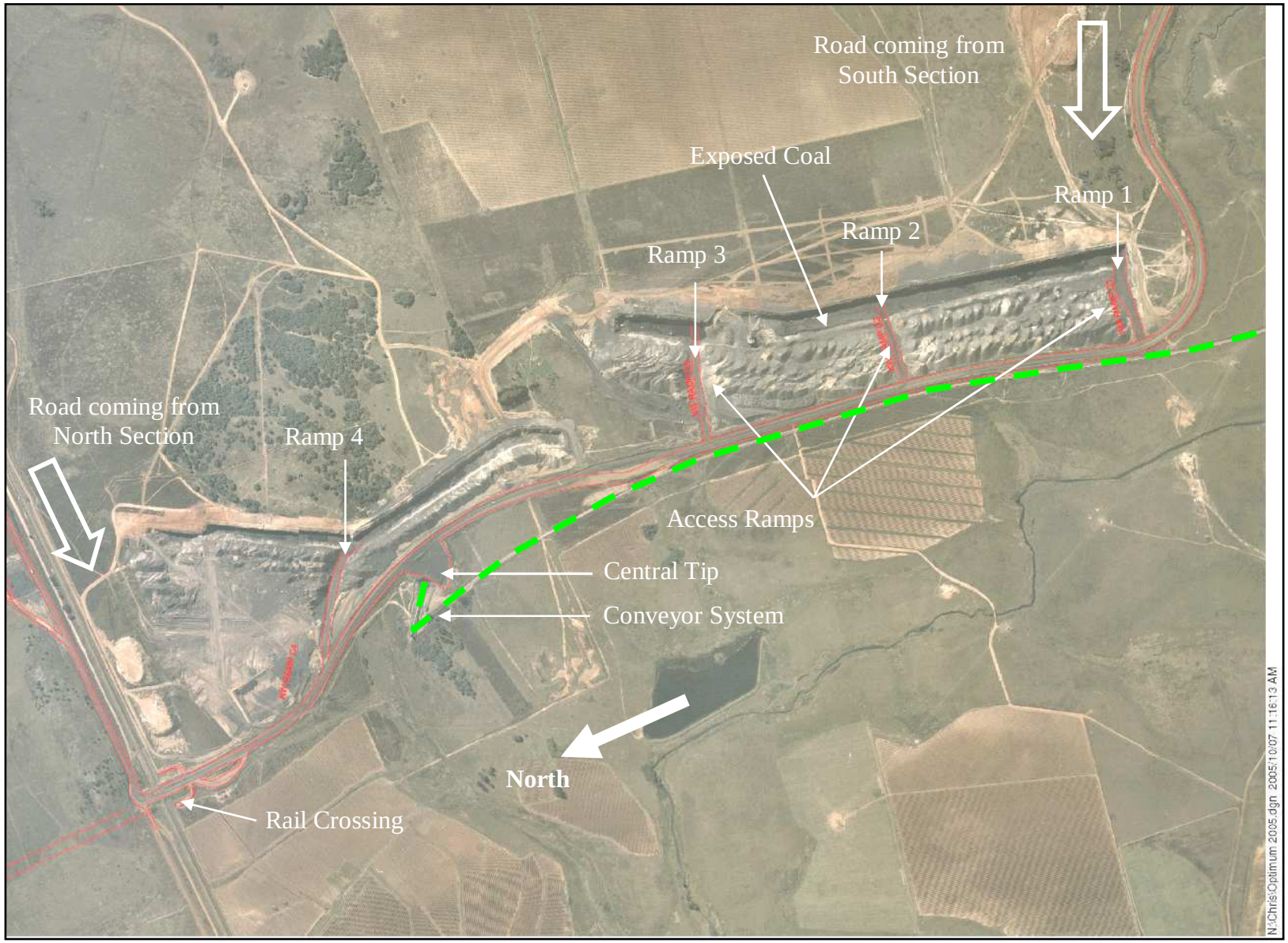


Figure 9.2 Aerial photograph of the Central Section



Figure 9.3 Aerial photograph of the South Section

9.2 Geology

Understanding the geology is important as it influences mine designs, causing the mine haulage profiles to change which directly impacts on the truck cycle efficiencies and therefore the potential production. It further provides valuable information regarding the material characteristics which will be handled by the load-and-haul equipment.

The strata consist mainly of a relatively thick, white, coarse grained massive sandstone layer followed by a thick shale layer below. Thinner alternating shale and sandstone bands occur in places. The top 8 metres consist of soft unconsolidated material.

Four seams of economic importance are present, namely the numbers No. 4L, 2U, 2 and 2A seams. The numbers 2 and 2A seams are the only ones well developed over the entire area.

No major dolerite structures were found in the Southern and Northern areas. A relatively large dyke with a North West strike occurs in the Central Area. The general dip of the floor is slightly South West.

The parting thickness between the No. 2 and 2A seams has an average width of 1 metre. The parting thickness between the No. 2 and 2U seams is more inconsistent with relatively large variations in places.

Based on the geological description the in-face roads are expected to have a slight dip. This in-face dip dictates that the general mining direction should be up-dip so that the gradient can be used to drain water away from the loading operations. The fact that the No. 2 and 2U seams have large variations in their parting thickness periodically causes problems for mine planning as they try to separate the mine's operations from the contractor operations which influences truck cycle efficiency.

Figure 9.4 to Figure 9.6 provide vertical sections through the three production areas illustrating the gradient change of in-face haul roads.

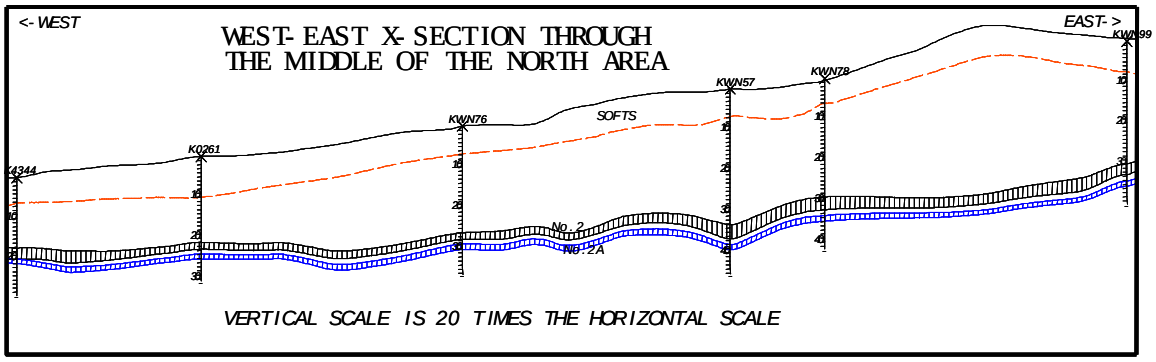


Figure 9.4 Section through North (Rail) Area

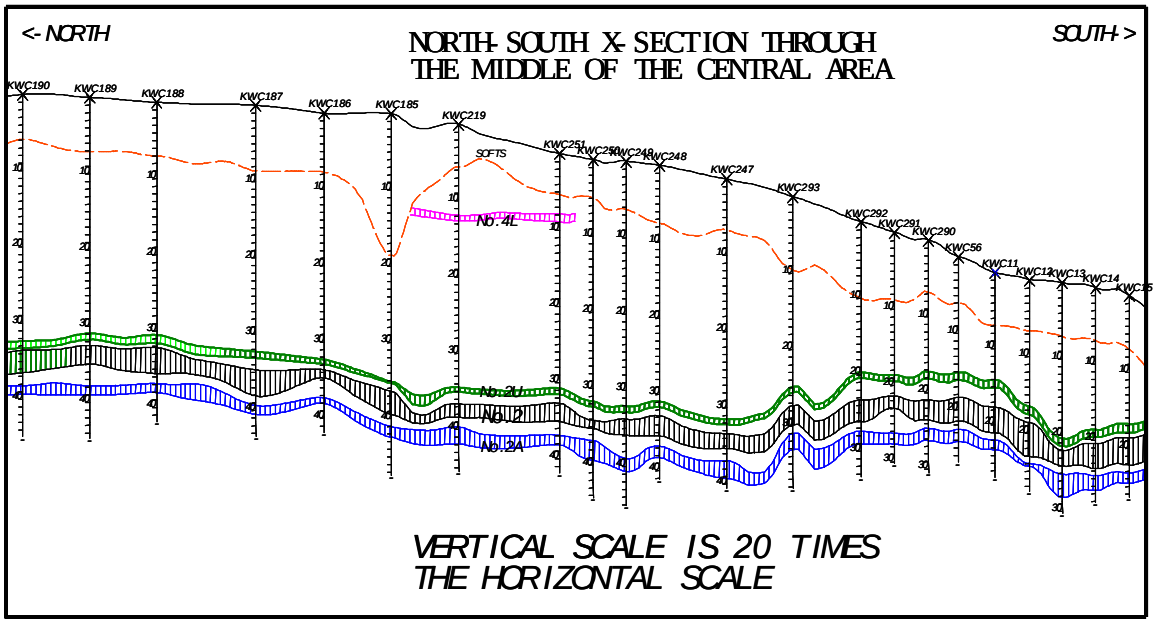


Figure 9.5 Section through Central Area

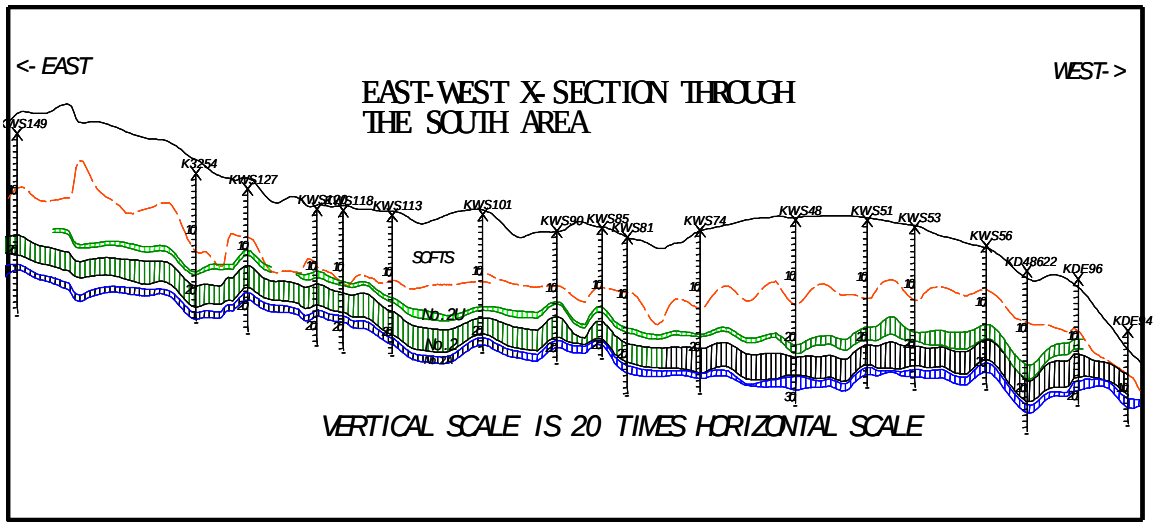


Figure 9.6 Section through South Section

9.3 Material Characteristics

There are two important material characteristics or variables that influence load-and-haul systems, they are the material loose density (tonnes/ m^3) and loader bucket fill factor, which is a function of the material swell factor.

Material Density

Caterpillar (2006, p. 27-4) provides an indication of the various bulk (in situ) and loose densities for various types of material as shown in Appendix D. For this study the material densities obtained from the geology department are:

- In situ density (bank density) 1.5 tonnes/ m^3
- Loose density 1.2 tonnes/ m^3

Bucket Fill Factor

Fill factors on wheel loaders are affected by factors such as the bucket penetration, breakout force, bucket profile and the type of ground engaging tools, for example, bucket teeth or bolt-on replaceable cutting edges. Appendix E provides a good description of bucket filling based on material classification which is used for the study. From Table E- 1 it can be seen that the coal mined is classified as loose material with a fractional size of 24 mm and over. For this study the loader fill factors for both the CAT 992 D and 992 G wheel loaders were estimated by the mine's geology department at 80% for loading the CAT 776D coal haulers and 90% for loading the CAT 777D OHT and are accordingly simulated with the same values. The loader bucket fill factors for the coal haulers are lower than the minimum 85% for this class of material to match the actual payload and number of passes, this being seven.

9.4 Simulation Process

Cycle time data was gathered during a time study conducted on site which was then compared to machine performance standards as suggested by Caterpillar for loader cycle time per pass, truck travel times (full & empty) for the various haul courses (using FPC program) and truck dumping times (dump body raise and lower times). These were

found to have close correlation. The time study was however hampered by adverse mining conditions caused by a two week period of heavy rains prior to the study. As a result the main machine performance standards as suggested by Caterpillar will be used in the FPC, Arena and Talpac programs and also used to construct the Elbrond and Machine Repair models. These variables common to the various models are as follows:

- Loading Time: The number of passes as observed during the time study is used with the 776D OHT having a 7-pass match and the 777D trucks having a 5-pass match. The wheel loaders follow a single side loading process for loading trucks.
- Spotting time at the loaders and at the dumping points is fixed.
- Dumping Time is fixed for all trucks at both tips situated at Central and South Sections.

The remaining cycle components are calculated using the various cycle time calculation models, these components are waiting time at the loading server and dump destination server and travel time. The average travel time (full and empty) as calculated by FPC and Talpac was used for the Elbrond, Winston and Arena programs as they are not programmed with this functionality for this case study. FPC and Talpac calculated their own travel times.

9.5 Machine Standards

9.5.1 Machine Availability and Utilization

Based on historical records and recommendations from the engineering department the machine availabilities and utilization values are as follows:

- All truck Availabilities 88%
- All loader Availabilities 85%
- Utilisation (all machines) 95%

The indicated availability values are somewhat high and relate more to new machines which is not the case for this fleet, but these are nevertheless achievable with well structured machine maintenance practices. The annual machine hours were not provided. This would have enabled a better understanding of the high utilization value.

A good correlation between the two indicates a well managed operation within a very stable production environment.

9.5.2 Cycle Components

The loader bucket capacity for the CAT 992G and D WL is set at 20.4 m³. Table 9.1 indicates the load cycle components for the CAT 776D coal haulers and CAT 777D OHT. This is based on the loading fill factors and material density which will result in a 7-pass and 5-pass match for the CAT 776D coal haulers and CAT 777D OHT.

Table 9.1 Load Cycle Components

Machine & Cycle Variables	Units	Scenario 1		Scenario 2		Scenario 3	
		Truck	Loader	Truck	Loader	Truck	Loader
		777D	992G#2 (Hi Lift)	777D	992G#2 (Hi Lift)	793C	994D (Hi Lift)
Machine Number		1,2,…,8	1	1,2,…,8	1	1,2,…,8	1
Target Payload	kg.	90 386	21 772	90 386	21 772	222 904	30 844
Actual Payload	tonnes	87.73	17.55	90.21	15.25	215.46	30.78
Bucket/ Bowl Volume	Loose- m³	51.61	11.47	51.61	11.47	119.70	18.00
Fill Factor	%	-	95%	-	95%	-	95%
Loader Passes		-	5	-	6	-	7
Material							
- Loose Density	tonnes/ m³	1.7	-	1.4	-	1.4	-
- Bank Density	tonnes/ m³	2.2	-	1.6	-	1.6	-
Cycle Time							
Loader Cycle Time	minutes	-	0.60	-	0.65	-	0.7
First Bucket Dump	minutes	-	0.60	-	0.65	-	0.70
Hauler Exchange Time	minutes	-	0.70	-	0.70	-	0.70
Load with Exchange	minutes	-	3.70	-	4.65	-	5.70
Dump & Manoeuvre	minutes	-	2.5	-	2.5	-	2.5

The first bucket dump value in Table 9.1 indicates that the wheel loader is waiting for the truck to manoeuvre into position with its bucket lifted and indicating where the truck should stop to receive the first payload drop. The lower this value is, the lower the 1st pass time will be. This value only bears reference to the 1st pass. The successive passes last the average cycle time. For this study the 1st pass is equal to the successive passes. In determining the annual production potential for this fleet, the annual change in haulage layout, which will influence the total cycle time for the various fleet combinations per section, needs to be considered. The draglines were fixed at specific positions at the start of the study and followed a fixed sequence, progressively moving up-dip as to utilise the natural gravitational drainage of water.

9.6 Haulage Definition

Figure 9.7 illustrates the various ramp combinations for the three sections scheduled at a constant rate within a specific inter-sectional ratio for a period of one year starting February 2006. These inter-sectional ratios are shown in Table 9.2.

Table 9.2 Annual Production per Section

Section	ROM Tonnes	Production %
North	2 739 769	26%
Central	4 786 857	46%
South	2 918 425	28%
Total	**10 445 051**	**100%**

The various ramp combinations, illustrated in Figure 9.7, influence the fleet cycle efficiency in that the different groupings have different in-face distances, ramp distances and main haul road distances, which are mined with a specific fleet size. This specific fleet size may or may not be able to handle the variable load-and-haul conditions which will influence the dragline efficiency. In reality such efficiency changes, due to the load-and-haul system not being able to handle a specific grouping, will cause the schedule to deviate from plan. Also seen in Figure 9.7 is that, for the various months there are combinations of ramp groupings with varying travel distances. The groupings that involve the highest combined travel distances were selected to calculate the truck fleet size that will reach the respective sectional tonnes per hour requirement. In reality any calculated fleet size will thus be able to handle the maximum production demand and during periods where lower travel distances occur, be able to exceed the required target. This study does not provide for events like accident damage or higher than normal delays caused by rains such as that which was experienced during the time study.

9.6.1 Travel Distance

Table 9.3 shows the haulage profile breakdown for the various sections and section ramps. It can be seen that the rolling resistance is set at 4% for the in-face and ramp-to-haulage roads which is higher than that of the main haul roads which is set at 3%. This is due to the dynamic nature of the primary production areas and the unavailability of proper road building material causing the rolling resistance to be higher which negatively effects the travel times of trucks.

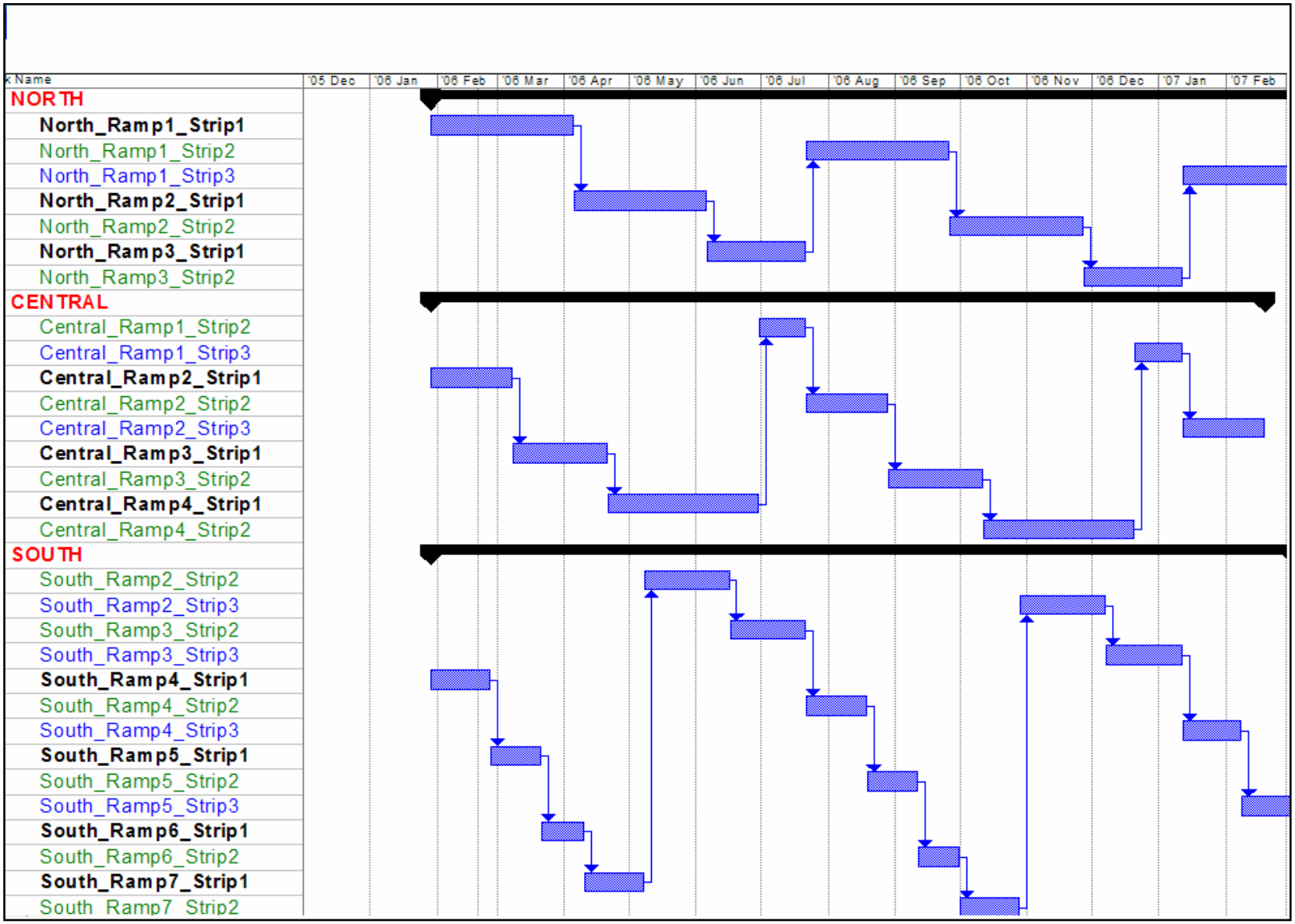


Figure 9.7 Production Schedule (Feb. 06 – Jan.'07)

The travel distances are seen to be moderate for the Central and South sections with the North (Rail) section seen to have long haul distances more suited for the CAT 776D coal haulers. It is for this reason that the CAT 776D coal haulers are predominantly confined to the North (Rail) section.

Table 9.3 Haulage Profile Breakdown

Section	Face to Ramp			Ramp to Haulage			Haulage to tip			Total Distance
	Distance	Grade %	RR%	Distance	Grade %	RR %	Distance	Grade %	RR %	
North										
Ramp 1	1050	5%	4%	800	9.5%	4%	4100	0%	3%	5950
Ramp 2	400	5%	4%	500	9.5%	4%	8715	0%	3%	9615
Ramp 3	Load from Stockpile			600	9.5%	4%	10000	0%	3%	10600
										26165
Central										
Ramp 1	200	5%	4%	400	9.5%	4%	2000	0%	3%	2600
Ramp 2	350	5%	4%	450	9.5%	4%	1300	0%	3%	2100
Ramp 3	400	5%	4%	400	9.5%	4%	700	0%	3%	1500
Ramp 4	650	5%	4%	500	9.5%	4%	400	0%	3%	1550
										7750
South										
Ramp 2	500	5%	4%	1000	9.5%	4%	1000	0%	3%	2500
Ramp 3	450	5%	4%	700	9.5%	4%	400	0%	3%	1550
Ramp 4	350	5%	4%	700	9.5%	4%	400	0%	3%	1450
Ramp 5	300	5%	4%	400	9.5%	4%	1100	0%	3%	1800
Ramp 6	250	5%	4%	600	9.5%	4%	1500	0%	3%	2350
Ramp 7	350	5%	4%	700	9.5%	4%	1900	0%	3%	2950
										12600

Distance = Travel in metres (One Way)
Grade % = Grade Resistance %
RR % = Rolling Resistance %

9.6.2 Speed Restriction

The mine has a code of practice which limits the travel speed of trucks as shown in Table 9.4.

Table 9.4 Speed Restriction

Grade Resistance %	Haul Distance (metres)			
	450	600	900	1500
	Speed Limit (km./hr.)			
4% to 5%	50	50	50	50
6% to 8%	50	50	40	30
9% to 10%	40	40	30	20
>10%	30	20	20	10

These speed restrictions were used to program the FPC and Talpac programs. The only two haulage cycle time calculation methods that have the ability to calculate travel time, which is used in this report, is FPC and Talpac. For the remaining models the average

travel time of FPC and Talpac will be used to complete their respective calculations of the total cycle time and is shown in Table F- 1 Optimum case study travel time. In this table the travel times for the North section is seen to be almost double that of the Central and South sections. It can also be seen that the relative difference between the FPC and Talpac results is about 16%.

9.7 Operator Proficiency

For this study the operator proficiency for the trucks, loaders and destinations are fixed at 92% which is relatively high in terms of industry standards but is supported by the results of the cycle time study conducted at the case study site.

9.8 Calendar Hours Breakdown

The break down of the calendar hours for the FPC and Caterpillar's EIA programs is shown in Table 9.5.

Table 9.5 Calendar Breakdown (FPC and EIA)

Shift per Year Calculation					
Row No.	**Model**	**FPC**	**EIA**	**Calculation**	**% Difference**
1	**Calendar Hours per Annum**	**8760**	**8760**	-	
2	**Min. 0ff Time Loss (5%)**	**438**	**438**	(1) x 5%	
3	**Site Scheduled Hours**	**8322**	**8322**	(1) - (2)	**0%**
4	Truck Utilization	**90%**	**90%**	-	
5	Shovel Utilization	**90%**	**90%**	-	
6	**Machine Scheduled Hours**	**6741**	**6741**	(3) x (4) x (5)	**0%**
7	Truck Availability	**88%**	**88%**	-	
8	Loader Availability	**85%**	**85%**	-	
9	Loader Availability Adjust	-	**81%**	(6) / (3)	
10	Combined Machine Availability	**75%**	**61%**	(7) x (8) x (9)	
11	**Machine Operating Hours (SMU)**	**5042**	**4084**	(6) x (10)	**23%**
12	Operator Proficiency- Truck	**92%**	**92%**	-	
13	Operator Proficiency- Shovel	**92%**	**92%**	-	
14	**Actual Production Hours**	**4268**	**3457**	(11) x (12) x (13)	**23%**

From Table 9.5 the actual production hours for the EIA program are seen to be 23% lower compared to that of the FPC calculation method. The Loader Availability Adjust value has no scientific proof but indirectly resembles an adjustment factor which tries to incorporate the destination availability which lowers the system availability. For this

study the breakdown of the calendar hours will be based on the EIA calculation method (see Chapter 8).

9.9 Productivity Calculation (TPH)

9.9.1 Site Scheduled Hours Distribution

To calculate the tonnes per hour (TPH), the site scheduled hours per section per ramp will be used to calculate the percentage of site scheduled hours allocated to it. The site scheduled hours per section is thus divided amongst the various ramps. The tonnes per annum per section per ramp are shown in Table 9.6.

Table 9.6 Site Hours Distribution (Tonnes per Annum per Area)

Section	Site Schedule Hrs	Tonnes per Annum Planned
North		
Ramp 1	3177	1 046 093
Ramp 2	2951	971 373
Ramp 3	2194	722 303
Sub-Total	**8322**	**2 739 769**
Central		
Ramp 1	1040	598 357
Ramp 2	1820	1 047 125
Ramp 3	2081	1 196 714
Ramp 4	3381	1 944 661
Sub-Total	**8322**	**4 786 857**
South		
Ramp 2	1891	663 278
Ramp 3	1702	596 951
Ramp 4	1324	464 295
Ramp 5	1135	397 967
Ramp 6	946	331 639
Ramp 7	1324	464 295
Sub-Total	**8322**	**2 918 425**
Total	**8322**	**10 445 051**

9.10 Cycle Time Breakdown

The cycle time breakdown for the Elbrond model is shown in Figure 9.8 and the results for the FPC, Talpac, Arena and Winston Models are shown in Appendix G. Several observations are made from these figures as follows:

- The loading, spotting and dumping times are equal for the 776D coal haulers and 777D OHT respectively.
- The travel times for the Talpac program are higher than that of FPC and the other model travel times are equal to the average travel times of the FPC and Talpac programs.
- The Elbrond model does not report any waiting time for the coal haulers compared to the other models that report varying degrees of waiting time at the loading units.
- The Talpac program reports, in general, the highest levels of waiting time and total cycle time for both truck types.
- The South Section reports minimal levels of waiting time by all the models and this is explained by its independence from the North and Central Sections.

In Table 9.7 the TPH simulation results for the various models are shown.

Table 9.7 Tonnes per Hour Results

Model	Section	TPH		TPH Required		TPH (Total)	TPH (Difference)
		776D	777D	776D	777D		
Elbrond	North	891	-	793	-	3436	415
	Central	-	1526	-	1385		
	South	-	1020	-	844		
FPC	North	848	-	793	-	3232	210
	Central	-	1426	-	1385		
	South	-	958	-	844		
Winston	North	900	-	793	-	3203	181
	Central	-	1413	-	1385		
	South	-	890	-	844		
Arena	North	892	-	793	-	3173	151
	Central	-	1392	-	1385		
	South	-	890	-	844		
Talpac	North	843	-	793	-	3196	174
	Central	-	1463	-	1385		
	South	-	890	-	844		
TPH Required						3022	

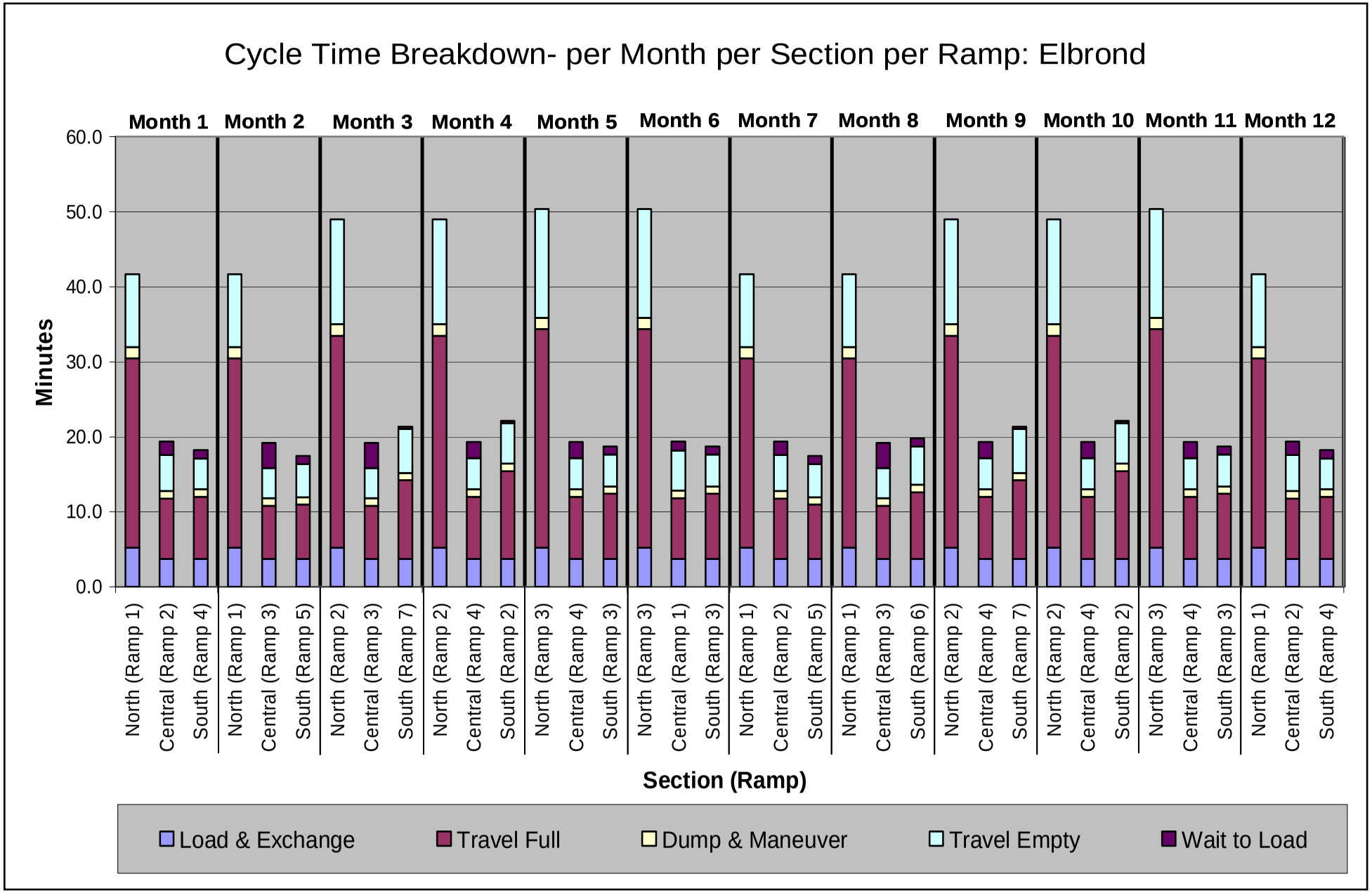


Figure 9.8 Cycle time breakdown results for Optimum using the Elbrond Model

Table 9.7 depicts the TPH results for the various models. The simulated excess capacity amounts to between one and two truck loads per hour for the various models. These results are quite close to the desired TPH requirement in view of the numerous unforeseen events that can lead to the loss of this excess.

The results show discrete tonnes per hour values as none of the models have the capability to report a spread of values. For this case study the Excel® based @Risk® program was not available to assist the Elbrond, FPC and Winston models in generating cycle time results spreads. In reality there will be a spread of results as discussed in Section 7.1 which can be used to qualify and compare individual model results.

9.11 Simulated Truck Requirement

In Table 9.8 the individual truck requirements to reach the desired production target are shown. All of the models calculate production (or tonnes per hour) based upon a fixed number of trucks within a specified load-and-haul system. The required number of trucks to reach a production requirement was progressively increased for the respective load areas to reach the tonnes per hour level as shown in Table 9.7

Table 9.8 Simulated Truck Requirement

Model	Section	Truck Type		Total Truck No.	
		776D	777D	776D	777D
Elbrond	North	6	-	**6**	**9**
	Central	-	5		
	South	-	4		
FPC	North	6	-	**6**	**10**
	Central	-	6		
	South	-	4		
Winston	North	6	-	**6**	**9**
	Central	-	5		
	South	-	4		
Arena	North	6	-	**6**	**9**
	Central	-	5		
	South	-	4		
Talpac	North	7	-	**7**	**10**
	Central	-	6		
	South	-	4		

Table 9.8 shows that the Arena and Winston models, which are both based upon exponential cycle variable distributions, yield the same truck requirements and so does the Elbrond model. Although the Elbrond model yields the same result, its TPH difference is approximately twice that of all the other models. This can directly be attributed to it reporting a zero waiting time for the coal haulers at the loaders. FPC and Talpac reports, relative to the other results, an extra truck required for the central section with Talpac requiring an extra coal hauler for the North Section.

9.12 Discussion of Simulation Results for Optimum Colliery

The various cycle time calculation models yielded their own unique results. In general, with the main cycle time variables like travel time, loading time and dumping time fixed, the difference in results will occur due to the underlying probability distributions of the individual cycle time components. This simulation showed that the Arena model with exponential distributions fitted to the cycle time components yielded similar results to the Winston model. The Elbrond and FPC models, which do not have a user specified distribution model and can be described as field models, yielded similar results compared to that of Arena and Winston. Travel time which is a component of cycle time (one of the three main production factors) showed to play a vital role in the simulated results. The FPC and Talpac models are the only two models with in-built cycle travel time functionality for this case study. The FPC travel time (full and empty) is on average 15% lower compared to Talpac and as a result required less trucks to meet the production target. The results from this Optimum Mine case study showed that there are differences in the production results by selecting a particular model but that the relative difference in the truck fleet requirement is actually quite small. In general, it might be wise to use three or more cycle time simulation models to calculate and estimate fleet size requirements.

Subsequent to the study, the Optimum colliery decided to purchase two extra CAT 777D OHT trucks which brought the total 777D fleet to 6. They also decided not to supplement the coal hauler fleet due to a change in the North Section mining strategy. This decision was supported by a road improvement strategy using mobile crushers to provide sound underfoot conditions. This improvement will result in a reduction of the rolling resistance and travel time and thus total cycle time and the number of coal haulers required.

10 CONCLUSION

The three main production factors of a load-and-haul system, namely payload, cycle time and operator proficiency are inter-related. These production factors are important because they represent the three main components of any load-and-haul system i.e. the machines, the production area and the operators.

The different cycle time calculation methods each have their own underlying assumptions regarding these production factors and as a result each yields their own unique solution for a specific system. These assumptions can be based on the overall nature of truck inter-arrival times and server service times at the various servers (the loader or dumping destinations) as with the Winston iterative exponential model (Machine Repair Model) or the calculations can follow a purely stochastic method.

The Talpac and Arena models use a Monte Carlo (stochastic) approach. Talpac can be programmed with the five core cycle time variables: (1) truck travel time (2) truck dumping time (3) truck availability (4) loader cycle time and (5) loader bucket capacity. Arena can be programmed with probability distributions fitted to all cycle time components.

The second type of cycle calculation method is based on field observations and can either be iterative such as Elbrond's Model or it can have fixed scaling factors such as FPC's fleet match and bunching correction factor.

Any particular cycle time variable can assume any particular probability function. The Chi Square goodness of fit test can serve to rank the various probability distribution models in determining the "best fit" but has its own limitations. Where more than one probability model yields tolerable results, the standard error of estimate can further serve to rank these models and is similar to the standard deviation that measures the variation around a mean value. The results of obtained from the VIMS data from the Orapa open pit diamond mine failed to associate individual truck data with specific loaders and as such can be seen as controversial. It did however, indicate that in selecting any particular probability distribution to represent a cycle time variable there will be an initial error due to a lack of sufficient data for instance. The Orapa case study

further indicated that in time the main cycle time components vary between the different probability distributions. The precise reasons as to why this happens and the tendency or frequency of these changes are not known. The migration between probability distributions will most probably be site specific and thus relate to factors like the common use of trucks between production areas (different material characteristics and course profiles) and sub-optimal fleet compositions (truck and loading unit miss match) and might warrant further research. The conclusion made from the Orapa study is that in selecting any probability distribution or cycle time calculation model there will be an initial error, but due to this migration of cycle time variables the average error in selecting any distribution or model will be almost the same.

The degree of variation around the mean of the main cycle time variables for the Virtual Mine using @Risk's® sensitivity analysis indicates that the values above and below the average are relatively equal. This result states that the risk in calculating the average cycle time or productivity by using the Elbrond, FPC and Winston models will be balanced. The reason behind why this was examined is because all the models only report discrete values. The Elbrond and Winston models are however spreadsheet based models and as such can be integrated with the @Risk program to calculate the distributions of these results and to produce statistical descriptions such as cumulative distribution functions and Tornado graphs.

The Optimum Colliery case study involved estimating the truck requirement for a bench striping coal mine operation using draglines. The estimation involved the various cycle time calculation methods which each yielded their own unique production result. The truck estimation results showed a close correlation with the exception of Talpac model that required a slightly higher truck number due to its travel speed calculation method that yield higher travel times.

This study showed that waiting time as a cycle time variable is a very natural component for a load-and-haul system and its inclusion is vital in completing the total cycle time calculation. Estimating cycle time is important as it estimates production which is necessary to estimate product revenue and cashflow.

Appendix A: Loads per shift for the Virtual Mine

Figure A- 1 Loads per Shift for Virtual Mine using FPC p 103
Figure A- 2 Loads per Shift for Virtual Mine using Winston p 104
Figure A- 3 Loads per Shift for Virtual Mine using Talpac p 105
Figure A- 4 Loads per Shift for Virtual Mine using Arena p 106

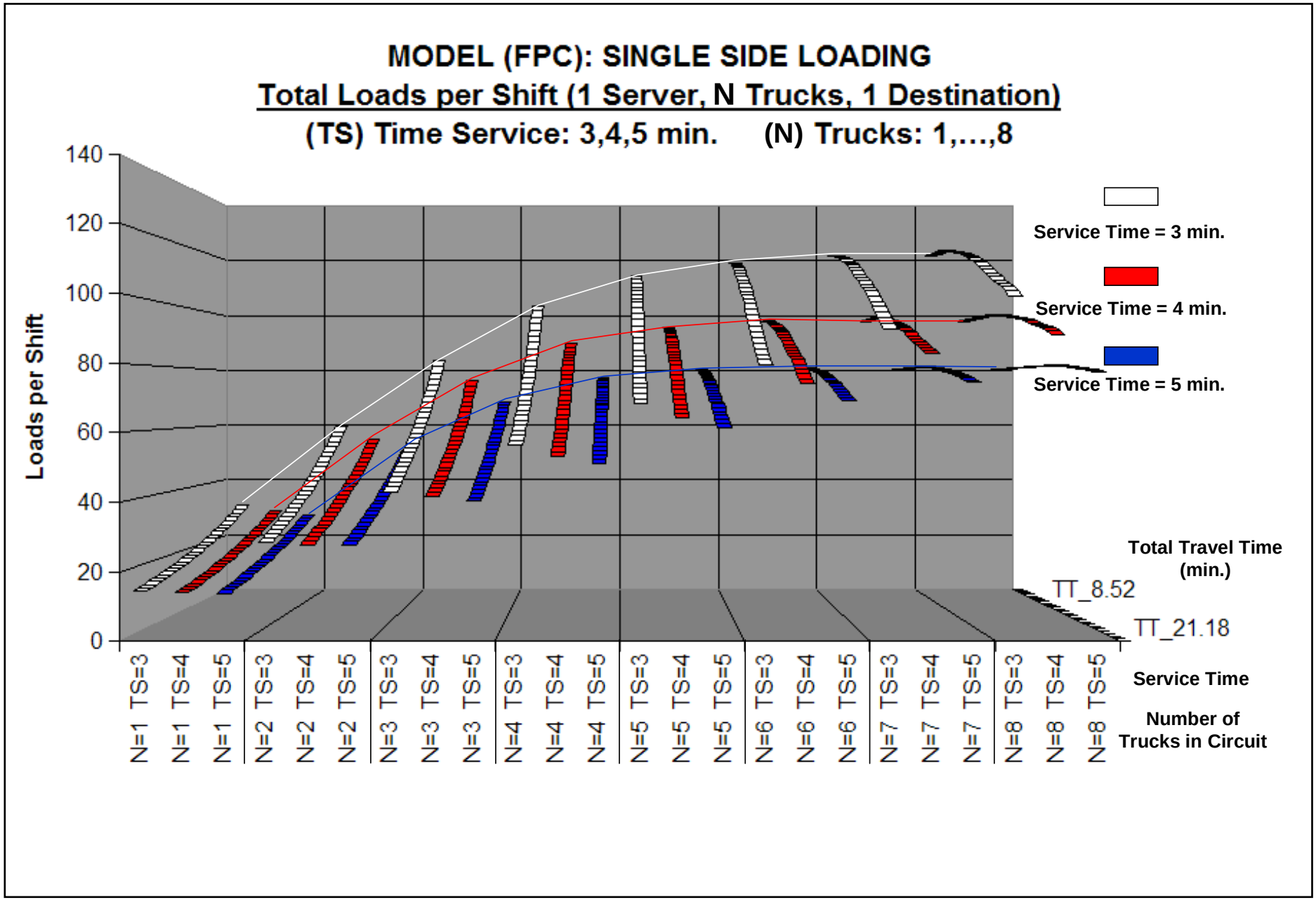


Figure A- 1 Loads per Shift for Virtual Mine using FPC®

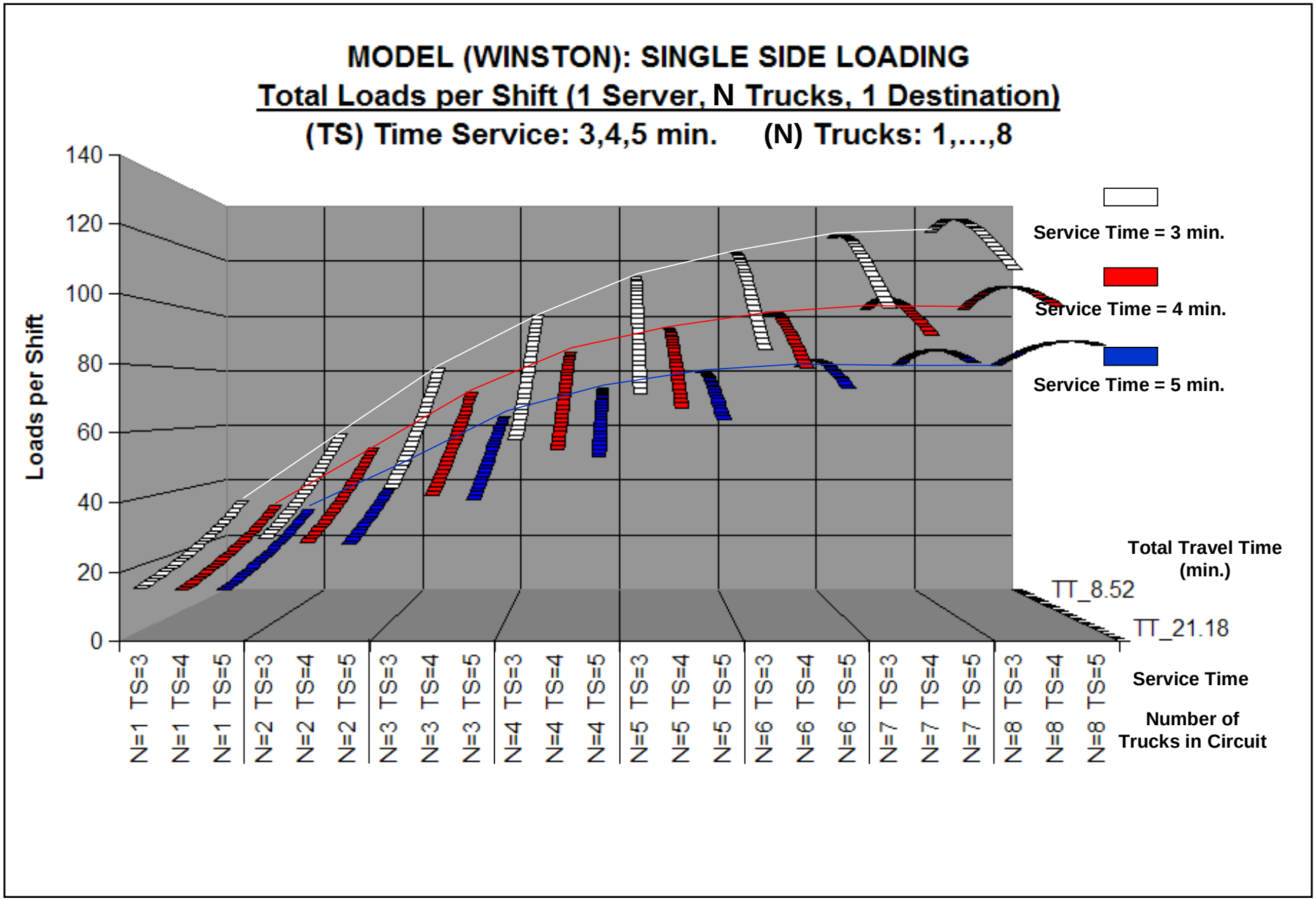


Figure A- 2 Loads per Shift for Virtual Mine using Winston

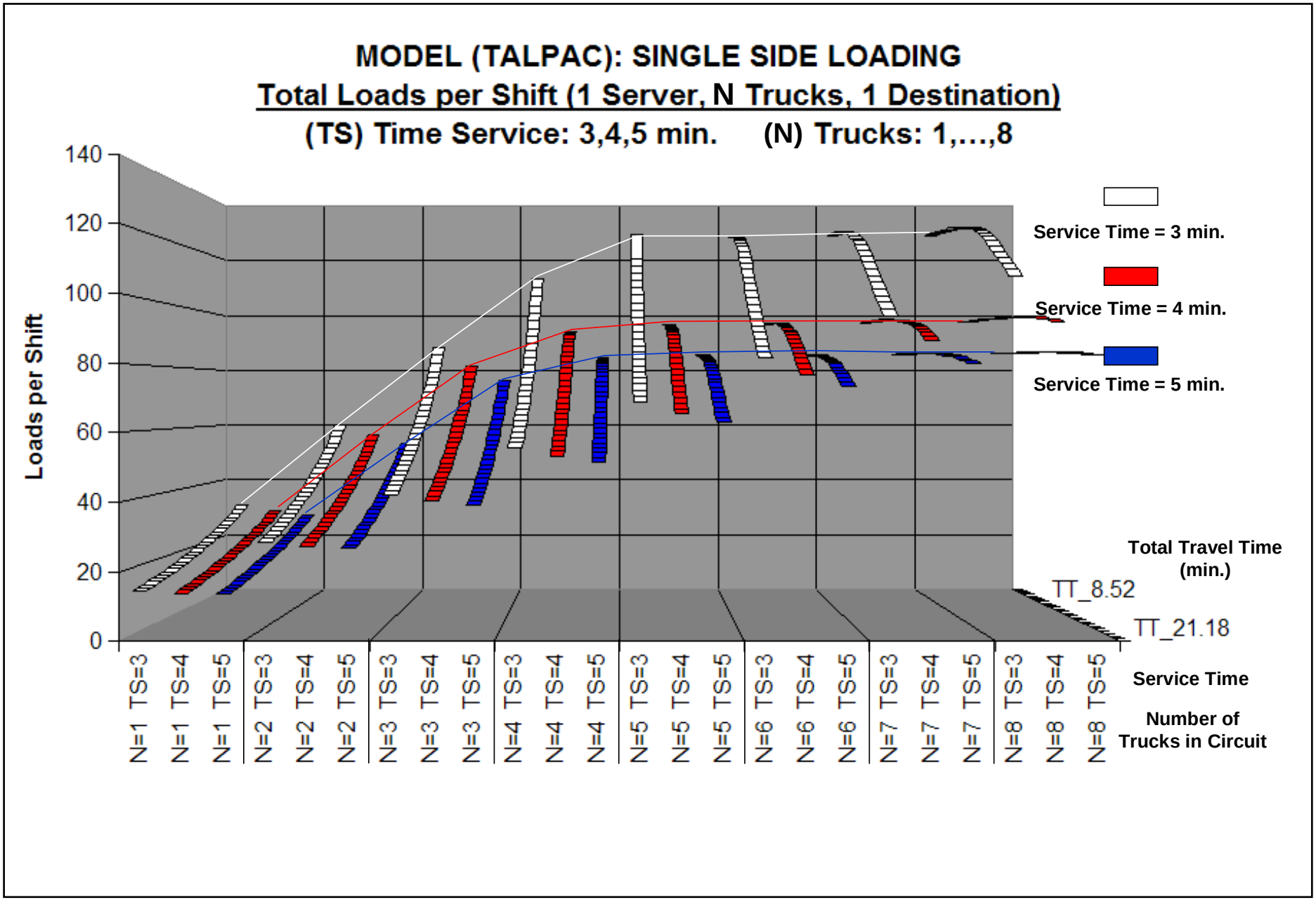


Figure A- 3 Loads per Shift for Virtual Mine using Talpac®

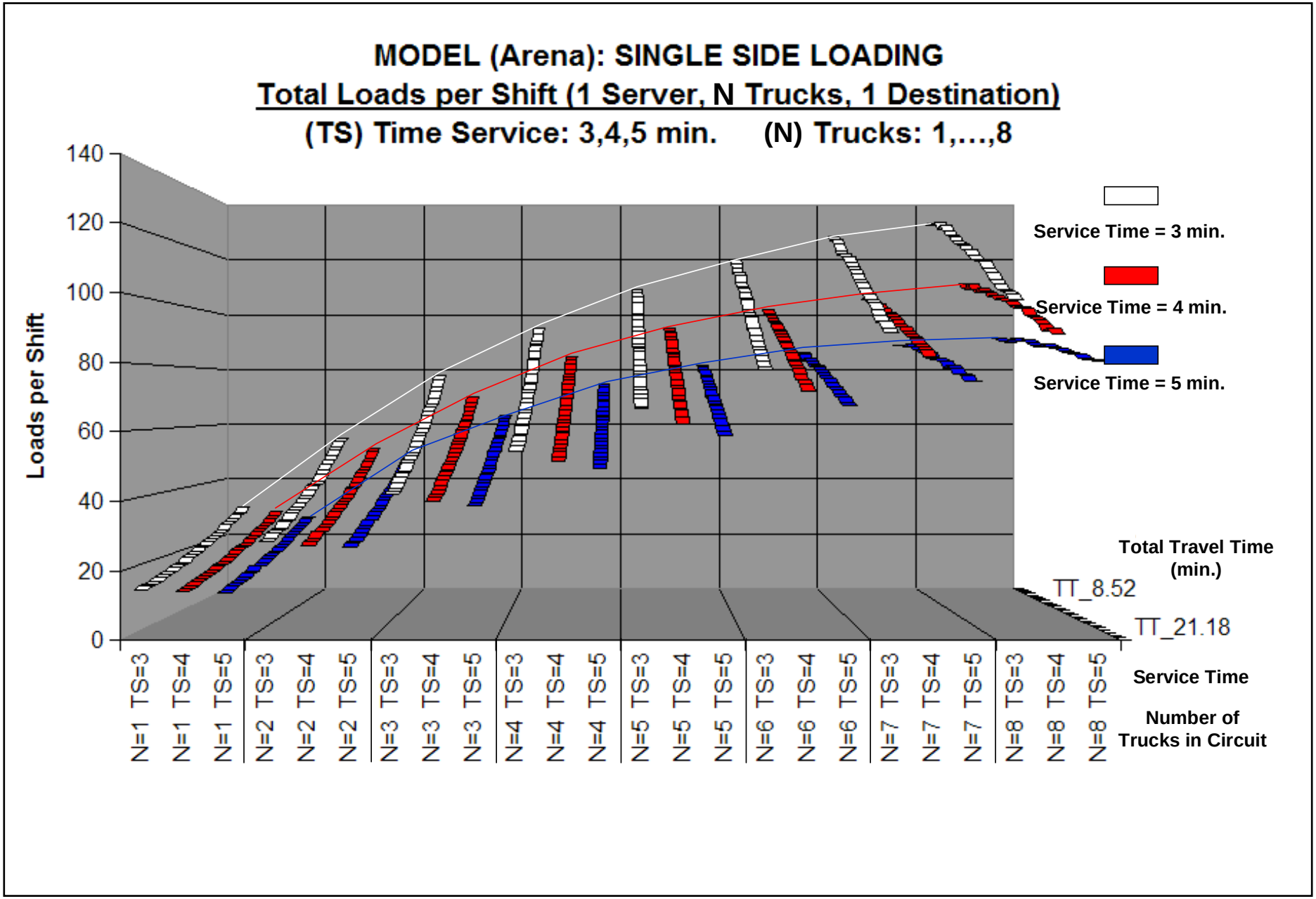


Figure A- 4 Loads per Shift for Virtual Mine using Arena

Appendix B: Results of Sensitivity using @Risk®

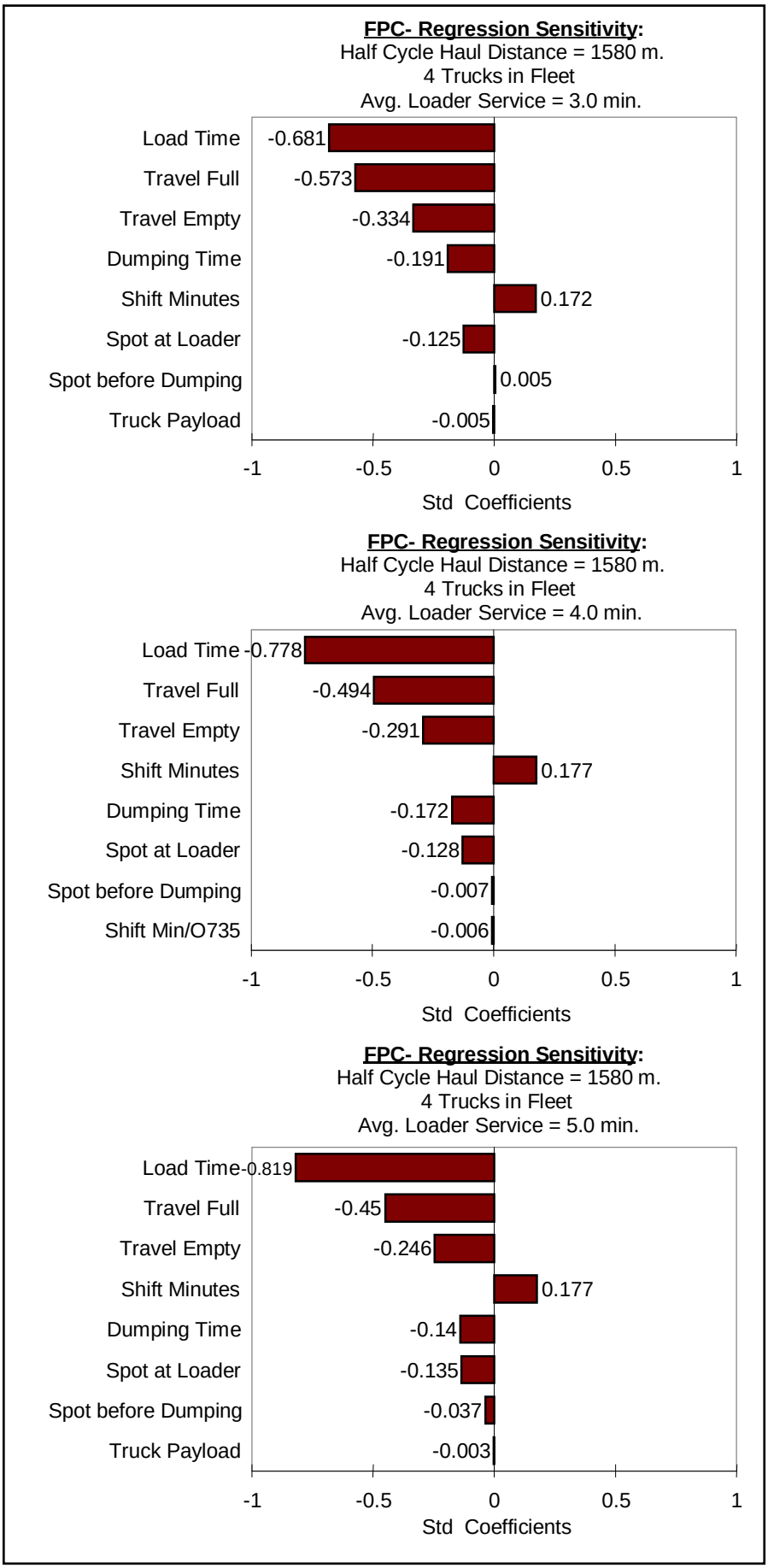


Figure B- 1 Sensitivity Analysis Results for Virtual Mine using FPC Model

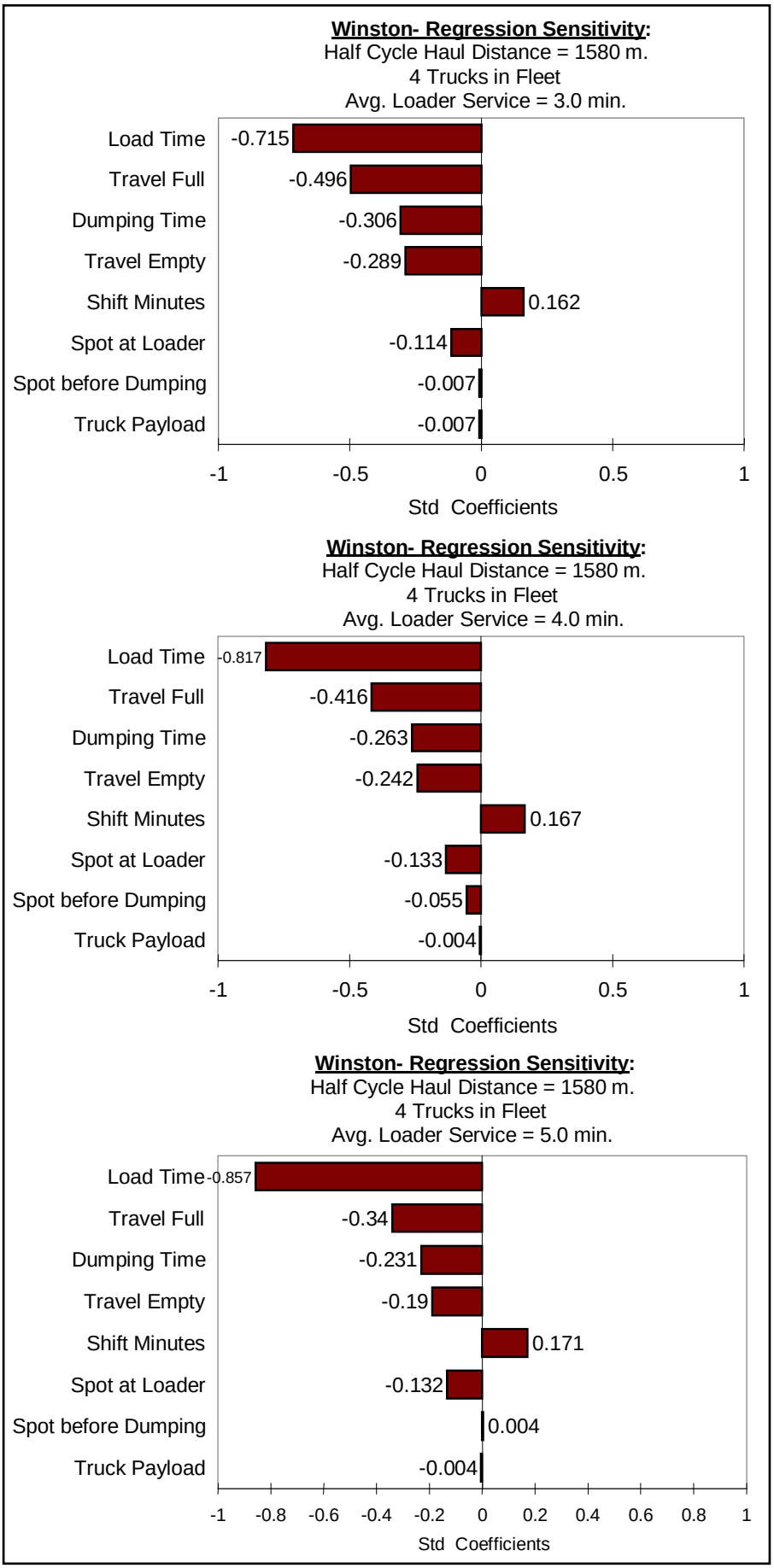


Figure B- 2 Sensitivity Analysis Results for Virtual Mine using Winston Model

Appendix C: Cashflow Results for the Virtual Mine

Figure C- 1 Cashflow Difference Results of FPC vs. Arena for the Virtual Mine p.110
Figure C- 2 Cashflow Difference Results of Winston vs. Arena for the Virtual Mine p.111
Figure C- 3 Cashflow Difference Results of Talpac vs. Arena for the Virtual Mine p.112

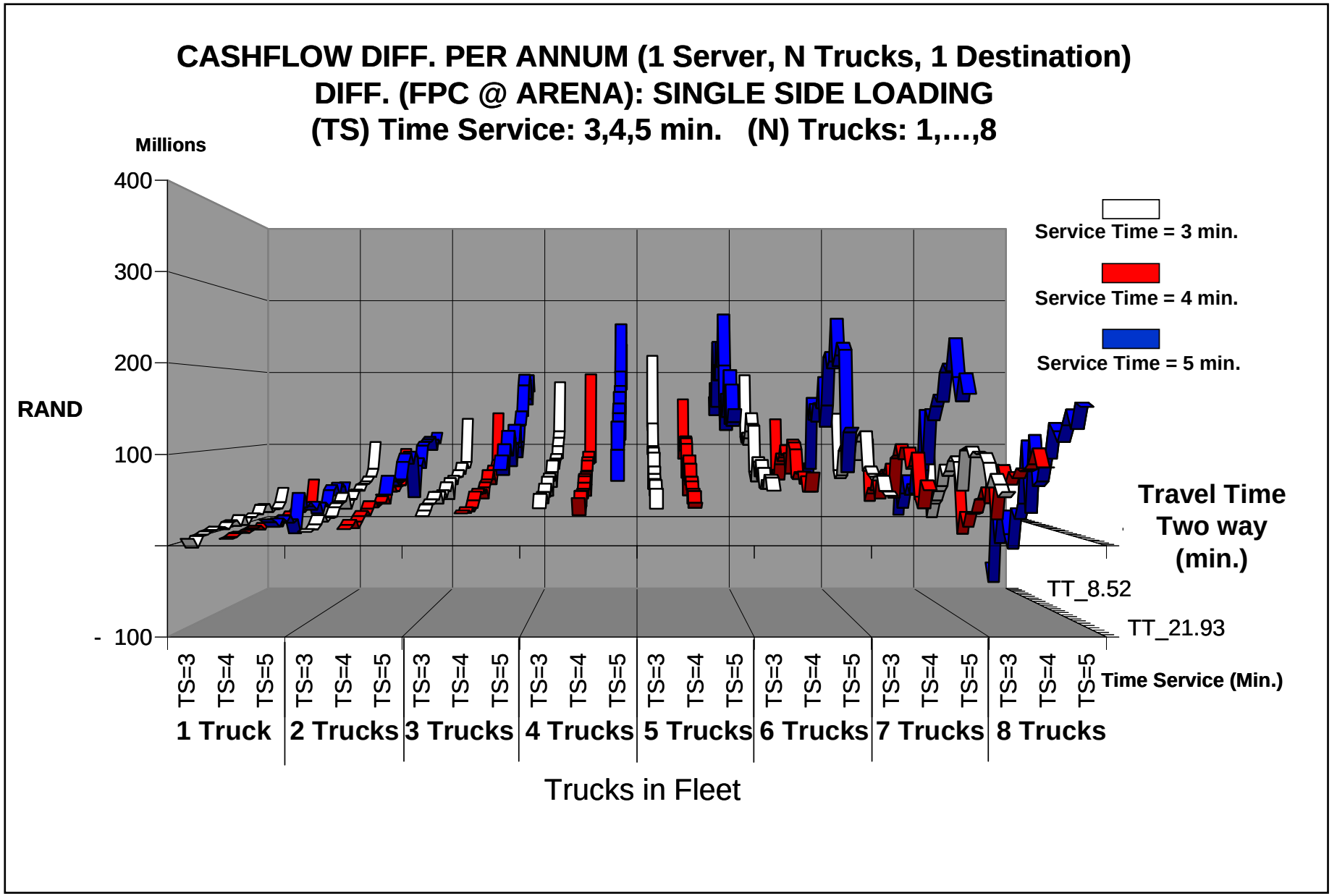


Figure C- 1 Cashflow Difference Results of FPC vs. Arena for the Virtual Mine

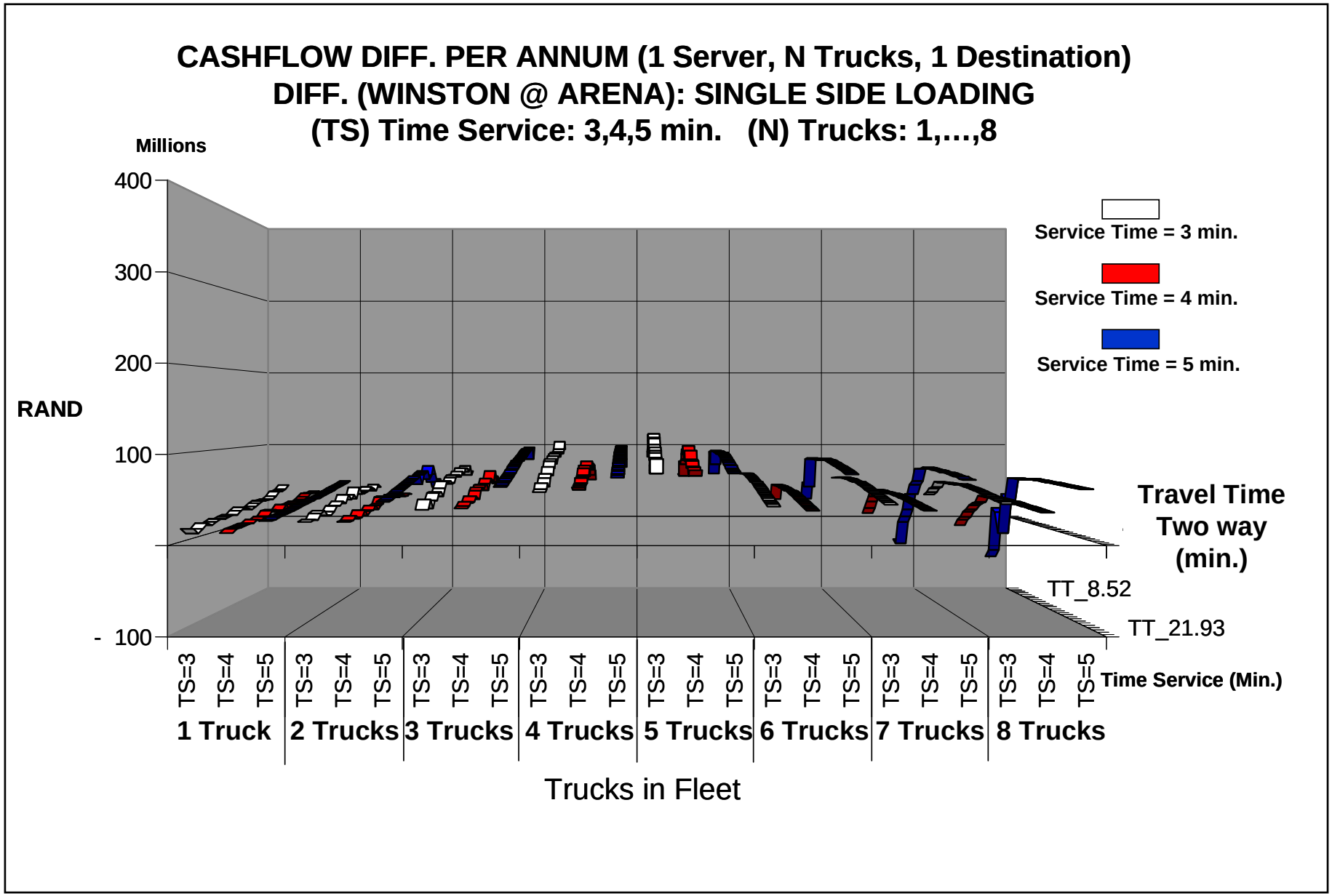


Figure C- 2 Cashflow Difference Results of Winston vs. Arena for the Virtual Mine

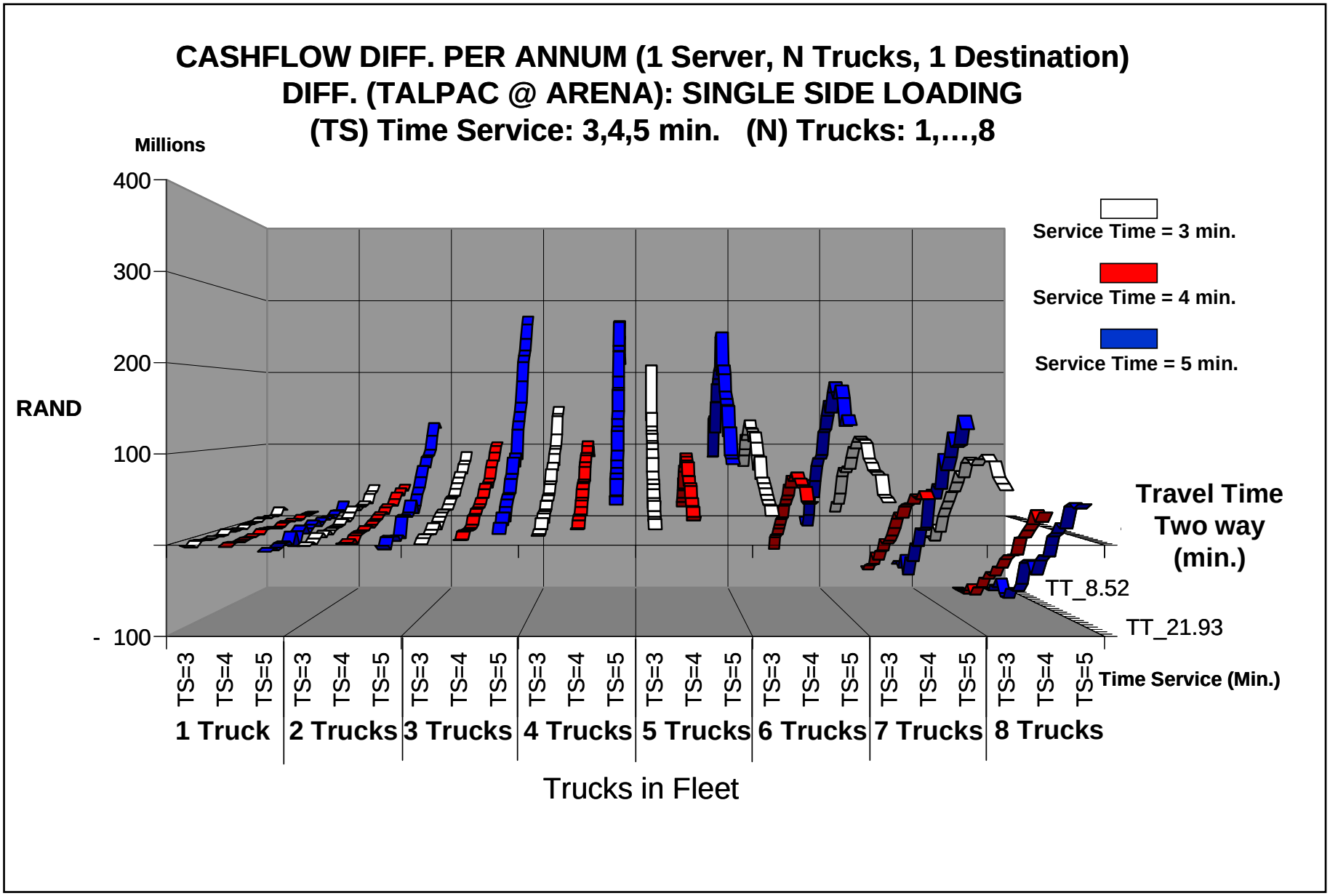


Figure C- 3 Cashflow Difference Results of Talpac vs. Arena for the Virtual Mine

Appendix D: Material Densities

(Caterpillar Performance Handbook, 2004)

Table D- 1 Material Densities

Material Type	Loose	Bank	Load Factor
	kg/m³		
Basalt	1960	2970	0.67
Bauxite, Kaolin	1420	1900	0.75
Caliche	1250	2260	0.55
Carnotite, uranium ore	1630	2200	0.74
Cinders	560	860	0.66
Clay — Natural bed	1660	2020	0.82
Dry	1480	1840	0.81
Wet	1660	2080	0.8
Clay & gravel — Dry	1420	1660	0.85
Wet	1540	1840	0.85
Coal — Anthracite, Raw	1190	1600	0.74
Washed	1100	1200	0.74
Coal — Ash, Bituminous Coal	530-650	590-890	0.93
Coal — Bituminous, Raw	950	1280	0.74
Decomposed rock —			
75% Rock, 25% Earth	1960	2790	0.7
50% Rock, 50% Earth	1720	2280	0.75
25% Rock, 75% Earth	1570	1960	0.8
Earth — Dry packed	1510	1900	0.8
Wet excavated	1600	2020	0.79
Loam	1250	1540	0.81
Granite Broken	1660	2730	0.61
Gravel — Pitrun	1930	2170	0.89
Dry	1510	1690	0.89
Dry 6-50 mm (1/4"-2")	1690	1900	0.89
Wet 6-50 mm (1/4"-2")	2020	2260	0.89
Gypsum — Broken	1810	3170	0.57
Crushed	1600	2790	0.57
Hematite, **iron ore**, high grade	1810-2450	2130-2900	0.85
Limestone — Broken	1540	2610	0.59
Crushed	1540	—	—
Magnetite, **iron** ore	2790	3260	0.85
Pyrite, **iron** ore	2580	3030	0.85
Sand — Dry, loose	1420	1600	0.89
Damp	1690	1900	0.89
Wet	1840	2080	0.89
Sand & clay — Loose	1600	2020	0.79
Sand & gravel — Dry	1720	1930	0.89
Wet	2020	2230	0.91
Sandstone	1510	2520	0.6
Shale	1250	1660	0.75
Slag — Broken	1750	2940	0.6
Stone — Crushed	1600	2670	0.6
Taconite	1630-1900	2360-2700	0.58
Top Soil	950	1370	0.7
Taprock — Broken	1750	2610	0.67

Appendix E: Bucket Fill Factors

(Caterpillar Performance Handbook, 2004)

Table E- 1 Bucket Fill Factors

Material Type	Minimum	Maximum
Loose Material		
Mixed Moist Aggregates	95%	100%
Uniform Aggregates up to 3 mm	95%	100%
3 mm-9 mm	90%	95%
12 mm-20 mm	85%	90%
24 mm and over	85%	90%
Blasted Rock		
Well Blasted	80%	95%
Average Blasted	75%	90%
Poorly Blasted	60%	75%
Other		
Rock Dirt Mixtures	100%	120%
Moist Loam	100%	110%
Soil, Boulders, Roots	80%	100%
Cemented Materials	85%	95%

Appendix F: Travel Times in Optimum Colliery Case Study

Table F- 1 Optimum case study travel time (in minutes)

FPC								
Section (Ramp)	**Travel Empty**		**Travel Full**		**Total Travel**		**Travel Time Diff with Talpac**	
	776D	**777D**	**776D**	**777D**	**776D**	**777D**	**776D**	**777D**
North								
North (Ramp 1)	9.25	-	21.87	-	31.12	-	-7.55	-
North (Ramp 2)	13.44	-	24.21	-	37.65	-	-9.09	-
North (Ramp 3)	14.16	-	25.01	-	39.17	-	-8.92	-
Central								
Central (Ramp 1)	-	4.85	-	7.73	-	12.58	-	-1.66
Central (Ramp 2)	-	4.26	-	7.67	-	11.93	-	-1.78
Central (Ramp 3)	-	3.53	-	6.7	-	10.23	-	-1.76
Central (Ramp 4)	-	3.62	-	7.86	-	11.48	-	-1.82
South								
South (Ramp 2)	-	4.91	-	11.26	-	16.17	-	-1.87
South (Ramp 3)	-	3.68	-	8.31	-	11.99	-	-1.77
South (Ramp 4)	-	3.56	-	7.91	-	11.47	-	-1.73
South (Ramp 5)	-	3.89	-	6.88	-	10.77	-	-1.72
South (Ramp 6)	-	4.61	-	8.48	-	13.09	-	-1.73
South (Ramp 7)	-	5.36	-	10.06	-	15.42	-	-1.78
Talpac							**Travel Time Diff with FPC**	
North								
North (Ramp 1)	10.18	-	28.49	-	38.67	-	7.55	-
North (Ramp 2)	14.49	-	32.25	-	46.74	-	9.09	-
North (Ramp 3)	14.87	-	33.22	-	48.09	-	8.92	-
Central								
Central (Ramp 1)	-	5.86	-	8.38	-	14.24	-	1.66
Central (Ramp 2)	-	5.33	-	8.38	-	13.71	-	1.78
Central (Ramp 3)	-	4.6	-	7.39	-	11.99	-	1.76
Central (Ramp 4)	-	4.69	-	8.61	-	13.3	-	1.82
South								
South (Ramp 2)	-	5.98	-	12.06	-	18.04	-	1.87
South (Ramp 3)	-	4.75	-	9.01	-	13.76	-	1.77
South (Ramp 4)	-	4.62	-	8.58	-	13.2	-	1.73
South (Ramp 5)	-	4.94	-	7.55	-	12.49	-	1.72
South (Ramp 6)	-	5.65	-	9.17	-	14.82	-	1.73
South (Ramp 7)	-	6.42	-	10.78	-	17.2	-	1.78
Average Travel Time (FPC & Talpac)							**Travel Time %Diff with Talpac & FPC**	
North								
North (Ramp 1)	9.72	-	25.18	-	34.90	-	12%	-
North (Ramp 2)	13.97	-	28.23	-	42.20	-	12%	-
North (Ramp 3)	14.52	-	29.12	-	43.63	-	11%	-
Central								
Central (Ramp 1)	-	5.36	-	8.06	-	13.41	-	7%
Central (Ramp 2)	-	4.80	-	8.03	-	12.82	-	7%
Central (Ramp 3)	-	4.07	-	7.05	-	11.11	-	9%
Central (Ramp 4)	-	4.16	-	8.24	-	12.39	-	8%
South								
South (Ramp 2)	-	5.45	-	11.66	-	17.11	-	6%
South (Ramp 3)	-	4.22	-	8.66	-	12.88	-	7%
South (Ramp 4)	-	4.09	-	8.25	-	12.34	-	8%
South (Ramp 5)	-	4.42	-	7.22	-	11.63	-	8%
South (Ramp 6)	-	5.13	-	8.83	-	13.96	-	7%
South (Ramp 7)	-	5.89	-	10.42	-	16.31	-	6%

Appendix G: Cycle Time Results for the Optimum Colliery Case Study

Figure G- 1 Cycle time breakdown results for Optimum using FPC Model p.117
Figure G- 2 Cycle time breakdown results for Optimum using Talpac Model p.118
Figure G- 3 Cycle time breakdown results for Optimum using Arena Model p.119
Figure G- 4 Cycle time breakdown results for Optimum using Winston Model p.120

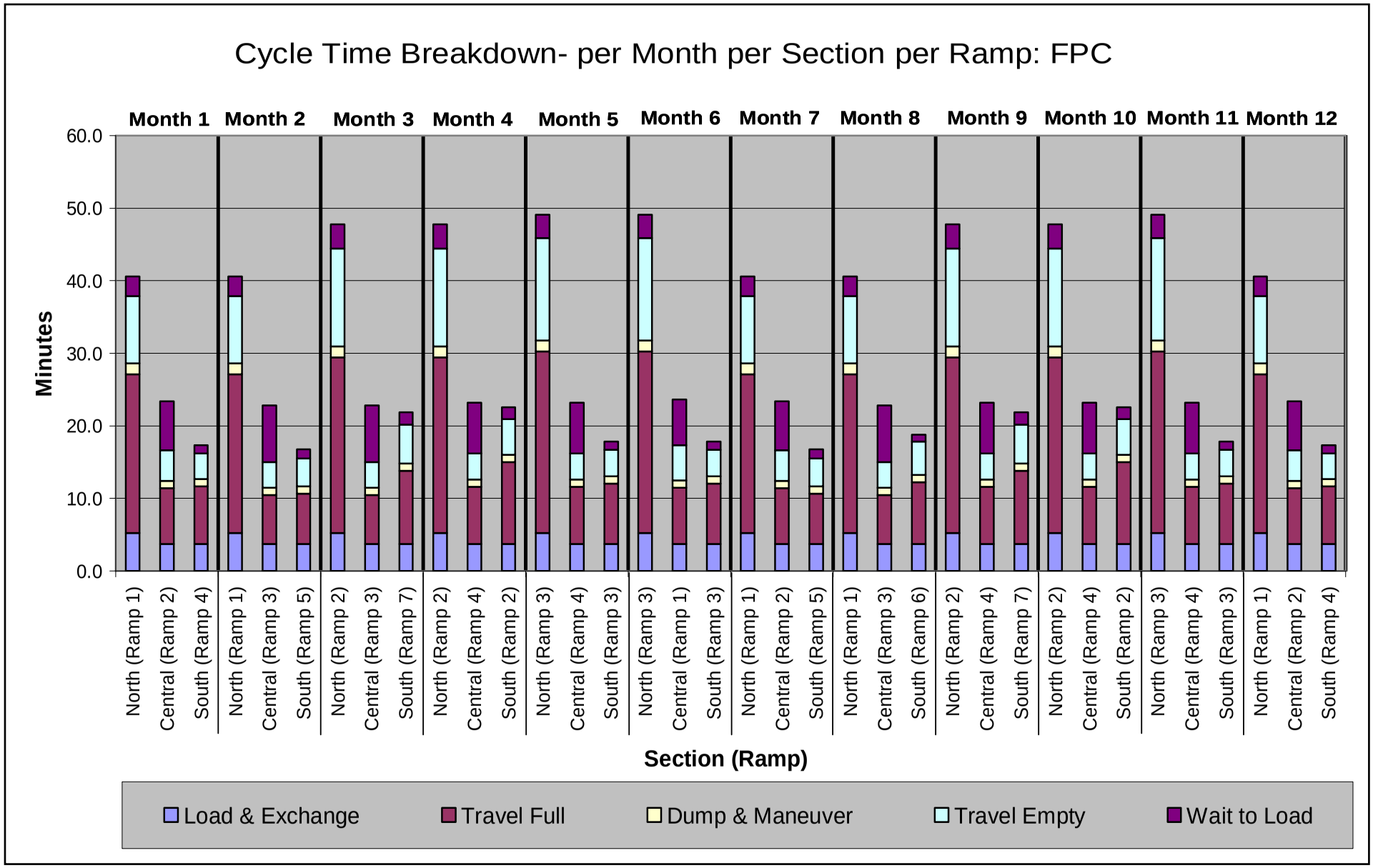


Figure G- 1 Cycle time breakdown results for Optimum using FPC Model

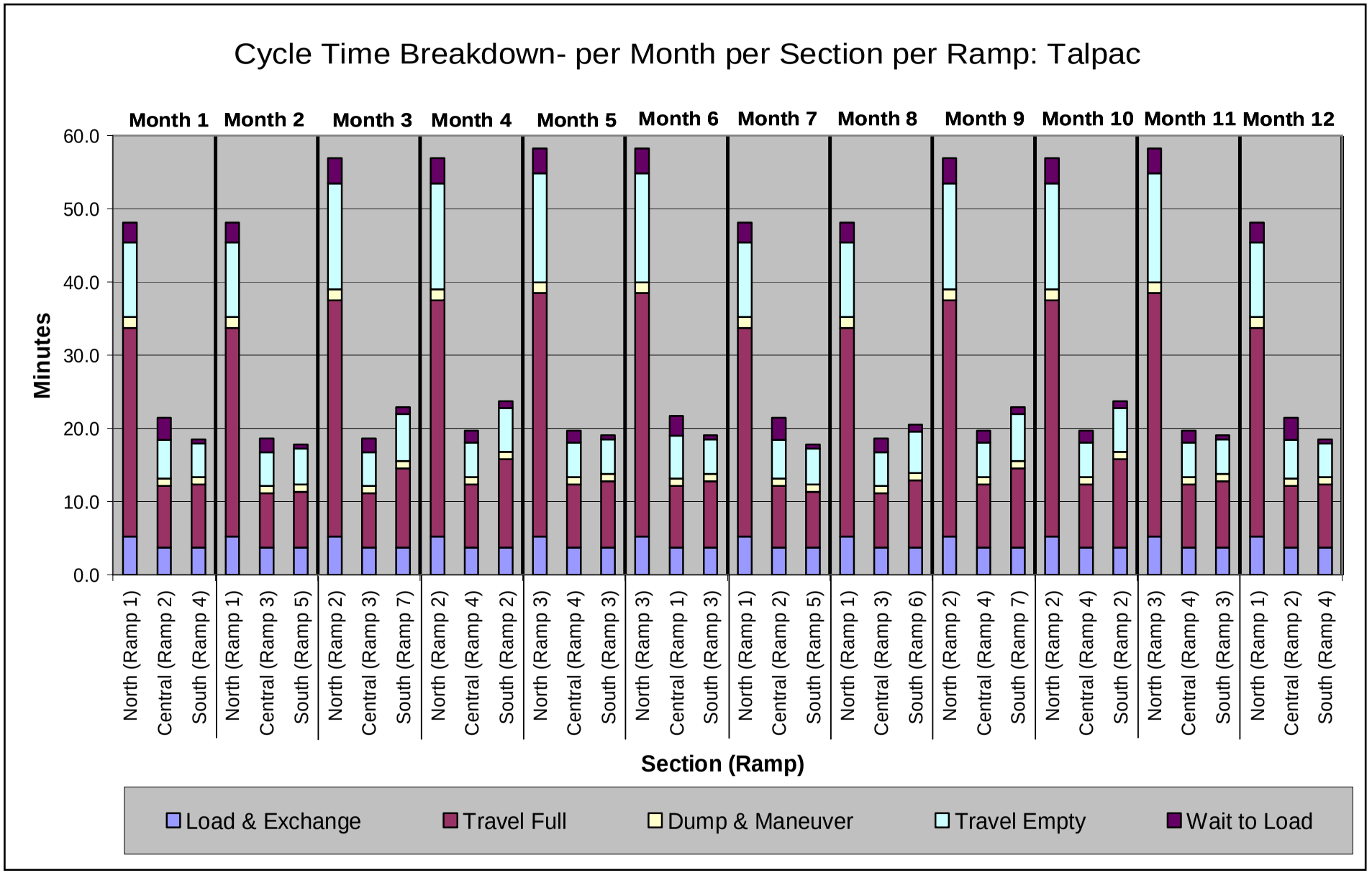


Figure G- 2 Cycle time breakdown results for Optimum using Talpac Model

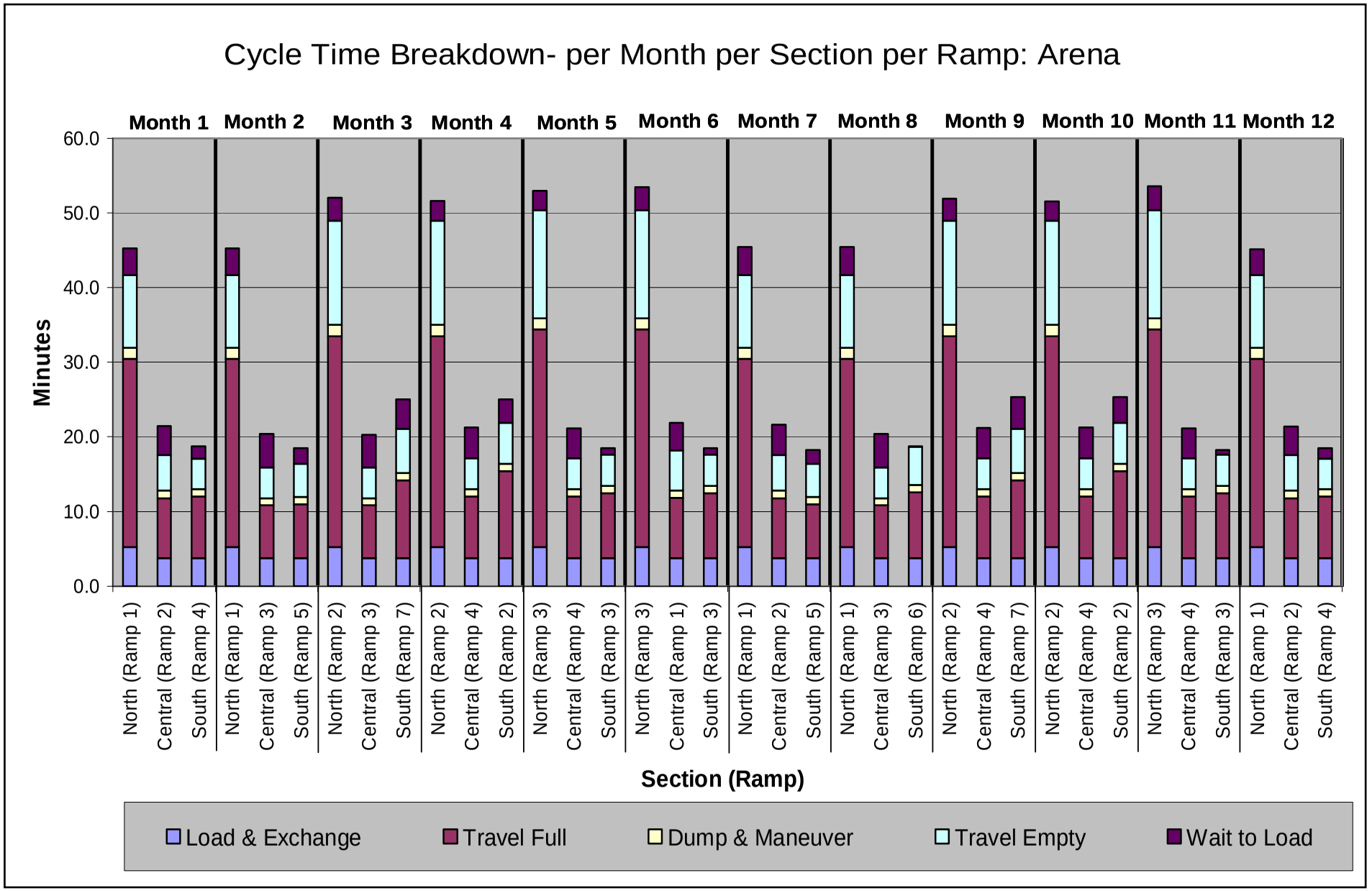


Figure G- 3 Cycle time breakdown results for Optimum using Arena Model

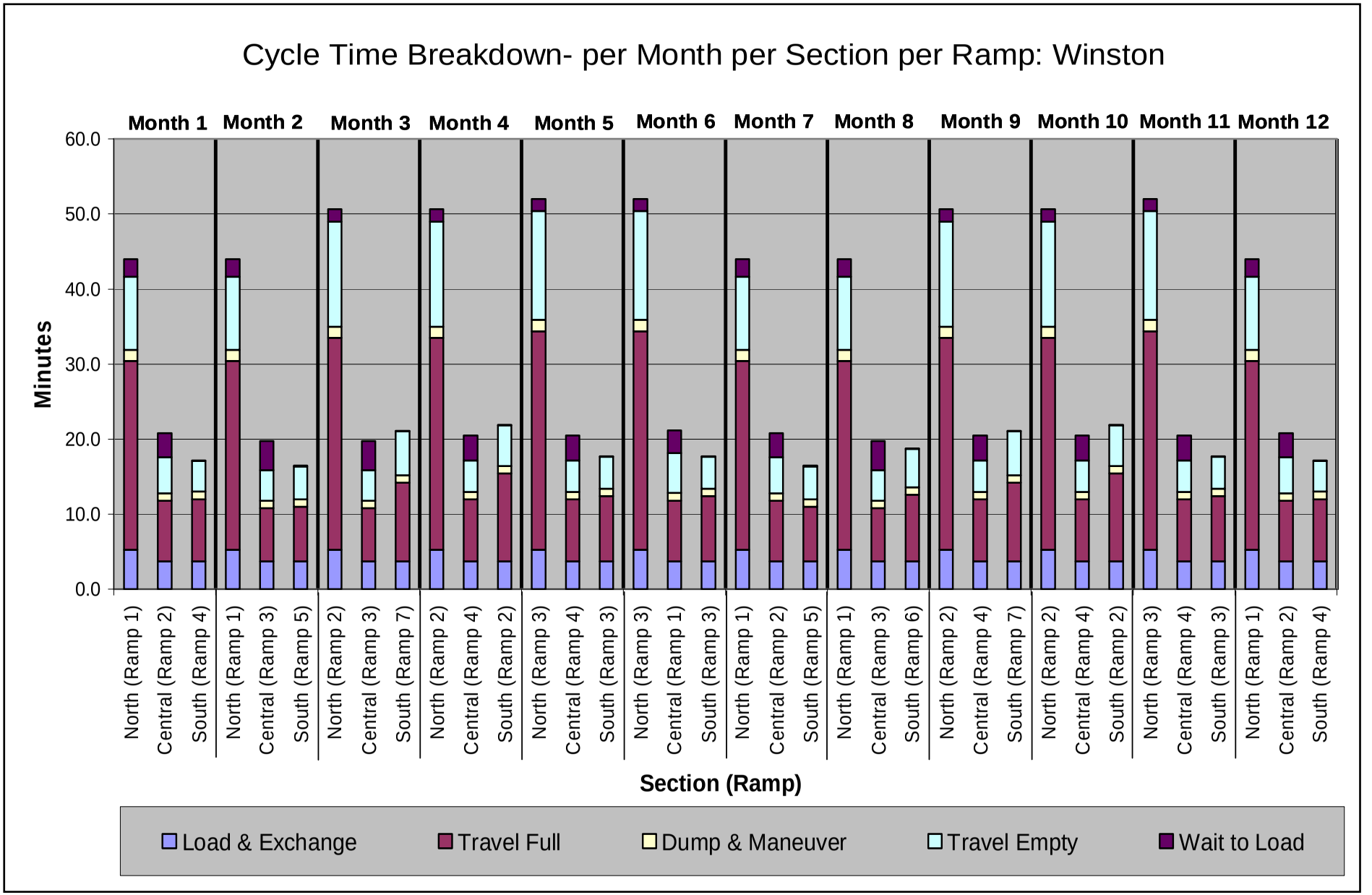


Figure G- 4 Cycle time breakdown results for Optimum using Winston Model

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