An Interactive Simulation Model to Compare an Autonomous Haulage Truck System with a Manually-Operated System

by

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Abstract

This thesis presents a deterministic/stochastic model that was created to compare an Autonomous Haulage System (AHS) to a manual system by calculating and estimating benchmarked Key Performance Indicators (KPIs) such as productivity, safety, breakdown frequencies, maintenance costs, labour costs, fuel consumption, tire wear, and haulage cycle times.

The manual system was verified against data provided by a major international mining company which cannot be identified for confidentiality reasons over a period of operation from Feb. 12 to Feb. 15, 2010. The mine that contributed the necessary data cannot be identified. For purposes of discussion, the mine is referred to as the Lucy mine in this thesis. Only a portion of the Lucy mine haulage system is modeled in this work with two shovels digging ore and waste to achieve a stripping ratio of 0.5.

The results show that an autonomous haulage system is able to increase either production or productivity by 21.3% due to increased utilization. The autonomous mode shows an improvement in fuel consumption of 5.3% for L/cycle and 6.1% for L/t. Tire wear (mm/cycle) also shows an improvement of 7.6%.

Although AHS trucks drive slower than normal drivers, the cycle time is shorter than manual because manual breaks involve assembling at the parking lot for safety purposes. A decrease in queuing time also occurred because of increased driving consistency. The AHS fleet queuing time decreased by 28.7% compared to the manual system.

An economic assessment of an AHS system versus a manual fleet shows an after-tax incremental discounted cash flow rate of return of 48.7% in comparing a 7- truck AHS fleet with a 9-truck manual system both of which were designed to achieve equivalent production.

Preface

The dissertation is an original intellectual product by the author, Parreira, J.

The research project was a collaboration with a large global mining company. This research clearly identifies the student's contribution and ascribes appropriate credit to others.

Parts of the dissertation were published in different conferences. The papers and the conferences names are the following:

Meech, J.A., Parreira, J. (2013) *Predicting wear and temperature of autonomous haulage truck tires*, 15th IFAC Conference on Control, Optimization, and Automation in Mining, Mineral and Metal Processing, San Diego, Aug. 25-28.

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Parreira, J., Meech, J., Mullard, Z. (2009) *How automation and key performance indicators (kpis) contribute to sustainable development in the mining industry. 2nd* Intern. Conf. on Multinational Enterprises and Sustainable Development, ICMESD, Nancy-Mertz, France.

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Nomenclature

Δaf	= random number between $\pm$ 0.005 * $AF_{max.}$
ΔCC	= capital cost difference between two projects.
ΔCF	= cash flow difference between two projects.
ΔCopex	= operating cost difference between two projects.
ΔD	= depreciation difference between two projects.
ΔS	= salvage value difference between two projects.
A	= frontal area of truck (m_2).
$Acc_{movement}$	= acceleration responsible for truck movement.
AF_{max}	= maximum aggressiveness factor of the driver (+1.0).
AF_{min}	= minimum aggressiveness factor of the driver (-1.0).
AHS	= autonomous haulage systems.
BAC	= blood alcohol content.
BHP-Billiton	= Australian Mining Company (sponsors of this research)
BPR	= business process reengineering.
BSC	= Balanced Scored Card.
BSFC	= brake specific fuel consumption.
CAT 793D	= a type of off road Caterpillar truck.
CF	= net cash flows.
COM	= communication system.
Cr	= rolling resistance coefficient.
Cx	= drag coefficient.
Ct	= traction coefficient.
D	= drive axle weight fraction.
DCFROR	= discounted cash flow rate of return.
DoBs	= degree of belief.
E	= engine efficiency.
Fassist	= sum of all forces acting on a truck in the direction of movement.
F_C	= rate of fuel consumption (L/h).
F_D	= aerodynamic resistance forces.
F_G	= force of gravity or grade resistance force.
FMG	= Australian Mining Company - Fortescue Metals Group.
F_R	= force opposing the movement.
F_{RR}	= rolling resistance forces.
G	= grade of the road (%).
GPS	= global positioning system.
GPSS	= general purpose simulation system.
GVW	= gross vehicle weight.
HS	= highly stable.
HV	= highly variable.
k_d	= heat transfer coefficient (1.6 x 10^{-4}).
k_i	= tire temperature exponential constant = 6.836 x 10-7(P+GVW)V^2
K_T	= tire temperature increase coefficient = 8.344 x 10^{-3}(P+GVW)V

kph	= kilometers per hour.
KPIs	= key performance indicators.
KRIs	= key result indicators.
LC	= limited change.
L_F ( )	= engine factor.
LHD	= load-haul-dump vehicle.
M	= truck mass.
M$	= Million of US dollars.
MHS	= manual haulage system.
mph	= miles per hour.
MTBF	= mean time between failure.
MTTR	= mean time to repair.
P (tonnes)	= payload.
P (kW)	= engine power (kW).
Pmax	= maximum power.
PIs	= performance indicators.
R	= rimpull (kg).
Rimpulleff	= effective rimpull.
Ru	= useable rimpull.
RPM	= rotation per minute.
SAP/R3	= enterprise resource planning software.
SD	= standard deviation.
SDLP	= Standard Deviation of Lateral Position (m).
T50D	= Toro 50D (type of underground load-haul-dump vehicle).
T	= time (seconds).
Tatm	= temperature of the atmosphere (°C).
Ttire	= tire temperature (°C).
TKPH	= tonnes-kilometer-per-hour.
TMPH	= tons-mile-per-hour.
total_time	= cycle time (minutes).
tpd	= tonnes per day.
TQM	= total quality management.
Ttire	= temperature of the tire (°C).
V	= truck speed (m/s).
VIMS©	= Vehicle Information Monitoring System.
Vr	= speed of the wind relative to the direction of the truck.
W	= truck weight.
Wear_temp	= tire wear due to temperature.
ΔTi	= temperature increase during a time step (°C).
ΔTd	= temperature decrease during a time step (°C).
ρ	= air density (kg/m3).
% grade	= slope of road segment in %.

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Dedication

To my father ('meu papai'), always by my side.

1 Introduction

1.1 Autonomous Haulage Trucks (AHS)

One of the first areas being explored as a candidate for automation in an open pit mine operation is that of mine haulage trucks. AHS trucks are receiving increased attention by industry with both Komatsu and Caterpillar as leading manufacturers of haulage trucks creating the first systems being used in mining. Initially introduced in Chile in 2005, a total of five mines in the world are known to have used, to be considering use, or currently using this new approach to mining (Dozolme, 2012). These include CODELCO's Radomiro Tomic and Gabriela Mistral mines in Chile, Rio Tinto's West Angelas mine in the Pilbara region of Northwest Australia, Fortescue Metals' Solomon mine in Australia, and BHP's Navajo mine in New Mexico in the United States.

In open pit mining, haulage road width and bench width create limitations, but driverless haulage trucks are being developed to reduce exposure to the risk of accidents that might affect haulage truck drivers or drivers of auxiliary equipment. Wireless communication, object-avoidance sensors, on-board computers, GPS systems, and artificial intelligence software approaches enable haulage trucks to drive themselves, or to be driven by an operator at a control panel well-away from danger (Lewis, 2004). Knowledge about position and speed of the vehicle (especially relative to other vehicles) can prevent accidents and reduce the cost of maintenance and replacement. While driverless haulage trucks are not immune to breakdowns, increased consistency and scheduled maintenance will improve the lifetime of machine components, leading to longer periods between maintenance, and so, costs associated with maintenance will decline. Lost production can be minimized or eliminated as unpredicted breakdown frequency will also decline (Bennink, 2008).

In addition to increased safety and more accurate control of maintenance, driverless haulage trucks operate more consistently – tires, brakes, and other components subject to wear failure that are now properly used and maintained on a 24/7 basis will have longer operational lives (Parreira, et al., 2009). Fuel consumption is reduced when a truck is driven in a stable, consistent manner. Currently human-operated trucks have significantly fluctuating fuel efficiency as drivers have a large influence on fuel economy. Humans tend to become tired towards the end of a 12-hour mining operation shift and are less consistent with their driving. By one account, "Operators typically influence overall fuel economy by as much as 35%" (Bennink, 2008). At the start-up and shut-down of each shift, significant fuel use results as the trucks idle during the change-over of drivers as well as the need to drive to and from the point of shift change-over.

An entirely automated mine ensures minimal idling. Idling is detrimental to fuel economy and can consume anywhere from 1.9 to 5.7 litres of fuel per hour. Fuel economy can improve up to 4% with a 25 to 50% reduction in idle time (Bennink, 2008). Excessive idling not only wastes fuel, but also contaminates oil and increases carbon intake to the combustion chamber of the engine (Bennink, 2008). By reducing fuel use, greenhouse gas emissions, and operating costs, autonomous haulage trucks directly contribute towards the concept of Sustainable Development.

Autonomous haulage trucks represent only one part of a totally-automated open-pit mine. Drilling and blasting have been automated, but not to the extent of a fully-autonomous system (Thompson, 1999, Girmscheid and Walti, 2001). Digging and loading is a much more complex task to automate. At this stage, installation of sensors to monitor these operations is the state-of-the-art although there are examples of specific elements that are beginning to be controlled automatically (Dunbabin and Usher, 2008). Overall, it is the integration of these systems to attempt to optimize across adjacent processes that will provide the greatest advances (McGagh, 2013). Data and process integration will generate opportunities to know the state of the mine operation on a minute to minute basis generating much more consistent decision-making. The mine of the future will be safer, more productive, more efficient, and more sustainable with the application of automated systems.

1.2 Objectives

This research aims to simulate mine haulage systems in order to compare an autonomous haulage system (AHS) with one in which human drivers operate the vehicles. The specific objectives are as follows:

1. To develop a set of deterministic/stochastic sub-models to study truck movement, fuel consumption, tire wear and temperature, rolling resistance, and driver behaviour.

2. To apply the set of sub-models to produce two models: one using autonomous trucks and the other using manual trucks.

3. To apply the above models to predict Key Performance Indicators (KPIs) such as productivity, equipment failures, fuel use, and tire wear under different road and load/dump conditions for AHS and manual trucks.

4. To investigate the pros and cons of autonomous haulage trucks by simulating the models under different scenarios.

5. To create an incremental economic analysis in order to examine if the additional capital cost of more expensive AHS trucks can be justified through operating cost reductions.

6. To answer the following questions:

   - *What is the level of improvement of AHS technology?*

   - *Are robot trucks more efficient?*

   - *Are mine KPIs efficient and effective to measure performance of this new technology?*

   - *Are mines ready for autonomous haulage technology?*

   - *What are the important aspects to consider changing at a mine before using AHS?*

1.3 Thesis Structure

The thesis consists of 11 Chapters including this brief introduction as follows:

Chapter 2 provides background on Industrial Automation and Mining Simulation.

Chapter 3 provides details on the model design describing those areas that are stochastic and those that are deterministic.

Chapter 4 presents the methodology used to develop the driver behaviour model.

Chapter 5 describes the vehicle motion sub-model detailing the variables that have been included to characterize the forces required to drive a truck up-hill and down-grade within the pit.

Chapter 6 presents the fuel consumption sub-model and introduces the concept of optimizing gear efficiency.

Chapter 7 presents the tire wear sub-model which attempts to predict tire wear as a function of payload weight and vehicle speed. Tire temperature is a major aspect of this model which also depends on these factors together with ambient temperature.

Chapter 8 presents the case studies used to examine differences of the two models (AHS vs. Manual). Comparison of manual results against real mine data is also given to verify the model.

Chapter 9 shows the economic results of these comparisons to quantify the potential improvement in monetary terms of an AHS system over a manual truck fleet.

Chapter 10 presents a discussion on the questions listed above, research contributions, recommendations for future work, and final conclusions.

Chapter 11 presents the Claims to Original Research.

2 Background

2.1 Performance Measures

A **measure** is a number/quantity that shows a directly observable value or performance. For example when measuring 20,000 tpd (tonnes per day), tpd is the defined standard, and 20,000 identifies how many multiples or fractions of the standard are being appraised (IEEE, 1983). A **metric** is defined as a quantitative measure of the degree to which a system, component, or process possesses a given appraised attribute (IEEE, 1990), i.e., a metric involves comparison of two or more measures. An example of a metric is a mine producing 20,000 tpd only three times per week with the other days of the week involving an indicator (deviation) from this metric. An **indicator** is a device or variable set to a prescribed state based on the results of a process (IEEE, 1990). Indicators always compare a metric to a baseline or expected result. In the example above, comparing a mine's weekly productivity to a scheduled measure has a major impact on management decision-making.

To improve its processes, an organization must define the right performance measure. Performance is the sum of all process measures that lead managers to take appropriate actions to create a well-performing organization (Neely, 2002). What are these core processes and how do organizations measure them? Core processes impact direct strategies of an organization. In order to proceed in the right direction, these core processes must be monitored constantly.

There are three types of indicators for monitoring a process. **Key Result Indicators** (KRIs) are essentially a picture that shows what the organization has done from a particular perspective, but they do not provide knowledge of how to improve the results. **Performance Indicators** (PIs) are a set of measures that lie beneath KRIs; they show the organization what is required to meet targets. **Key Performance Indicators** (KPIs) is a set of PIs used to increase performance by resolving issues before they impact the process (Parmenter, 2002).

KPIs are used to develop industry standards to benchmark performance in many different areas such as finance, customer service, internal business, innovation, learning, social, and environment. Global organizations use these standards to create value. Identifying KPIs can be very challenging; they must be dynamic and at the same time aligned with the organization's strategy. There are many performance frameworks that can help an organization identify KPIs for their business processes. Kaplan and Norton (1992) proposed the **Balanced Score Card** (BSC) to evaluate organizational performance by looking at four different perspectives (finance, customer, internal business, and innovation and learning). The main objective of BSC is to align business activities with the vision and strategies of the organization (Kaplan et al., 2004 and 2006). In addition, to address triple bottom-line issues (economic, social, and environmental), Parmenter (2002) says perspectives of employee satisfaction and local environment/community must also be included.

Effort should be given to establishing performance measures since they provide a "warning system" through different comparisons: target performance comparisons, time comparisons (trends), comparisons within the organization, comparisons with competitors and partners (benchmarking), and quality records (Kaplan et al., 2004 and 2006). Organizations must define their KPIs within a BSC framework. Having the right performance measures as well as the right management approach can improve quality, flexibility, resource utilization, and technology (Fitzgerald et al., 1991).

In order to characterize a comparison between manual trucks and AHS systems, the following open pit mining KPIs have been considered according to the Lucy mine.

1- Payload / production / productivity
  - Tonnes per cycle (variance)
  - Tonnes per unit time
2- Cycle performance
  - Number of Cycles per day
  - Cycle time/day
  - Queuing time/cycle
  - Human breaks/day
  - Process delay/day
3- Fuel Consumption
  - L/hour
  - L/cycle
  - L/tonnes

4- Tire Wear
    - mm/cycle
    - mm/ hours
    - tread depth (mm)
    - tire life (hours)
5- % Utilization (actual percent time that the truck operates in the mine)
6- % Mechanical Availability (%time that the truck is mechanically available for work)
7- Maintenance
    - Mean Time Between Failure (MTBF)
    - Mean Time To Repair (MTTR)

As previously suggested, it is important to read the KPIs in a proper way. For example when looking at fuel consumption, AHS may give a higher L/hour KPI, but this does not mean that the technology did not improve fuel consumption. Since AHS trucks drive without any human breaks, this KPI might be expected to rise since the truck will no longer stop for lunch or coffee breaks. To establish any "real" fuel improvement, it is important to examine other fuel consumption KPIs such as L/cycle or L/tonnes. If there is a decline in these two KPIs, then AHS trucks can claim a fuel consumption improvement.

2.2 Automation

Today's organizations face many challenges: high-demand customers, global competition, currency fluctuations, etc. As a result, mining organizations are beginning to look at automated processes to increase plant and production efficiencies. Through automation, benchmarked product-quality and quantity improvements can be achieved, employee safety can be improved, costs can be reduced, and product-delivery performance increased. In mining, automation is playing an increasingly important role due to a scarcity of high demand metals and skilled personnel to operate the processes. Challenging locations and harsh environments are becoming the norm for new ore bodies and mines and so automated systems may become essential.

The Oxford English Dictionary (2005) defines automation as the use of machines to do work that was previously done by people. Automation as such seems to mean loss of jobs (Hornby, 2005). Parasuraman et al (2000) defined automation as full or partial replacement of a function previously carried out by a human operator. Both definitions suggest the main objective of automation is to control the behaviour of dynamic systems and to emulate both physical and intellectual human capacity. Automation can be broken down into several degrees or categories such as controlled, supervised, tele-robotic, semi-automatic, automatic, and fully-autonomous, where less and less human intervention occurs within each higher level of automation (The Royal Academy of Engineering, 2009).

Mining automation may consist of direct tele-operation in which workers control the mining process by computer from a control room; remote operation in which drilling, for example, is performed by workers using joysticks from a safe distance; and autonomous in which equipment such as open pit and/or underground autonomous haulage trucks operate under total instrument and computer control.

Bibby et al. (1975) has pointed to the irony in that even highly automated systems, such as electric power networks, required human-beings for supervision, adjustment, and maintenance during the 1973 energy crisis. As a result, automated systems do not always result in replacement of people; rather, one of the major reasons for implementing an automated system is health and safety, and it will be important that measures are taken and sufficient education given to help people adjust their behaviour around machines. Automation can improve safety and health in the workplace by removing humans from repetitive tasks and positions of danger and to elevate human capacity and abilities by creating new job tasks. Workers need a different set of skills to handle the specialized tasks in automation and the new technical challenges that come into play.

2.3 Applications of Automation in Mining

Automation has been initially promoted in the mining industry to protect the health and safety of mine workers, but it is also clear that a very significant improvement in daily production and/or productivity can be realized. Introduction of automated machines lessens human error by eliminating poor driving behaviours due to tired workers with reduced concentration at the end of a 12-hour shift. Automated technologies are being applied today in both large-scale industrial mines as well as small-scale mining operations. Equipment being automated ranges in size from

300-tonnes mine haulage trucks to automated water monitors in small placer operations. The scale of automation depends on many factors, but it is apparent that operations at all levels of mining are exploring ways to increase efficiency, safety, and production (Mullard, et al., 2009).

Advances in automated tracking systems, control equipment, telemetry and robotics are providing major improvements in the accuracy and safety of mine machinery. Mining processes, such as drilling, are today using wireless technology and GPS to allow an operator to set-up the equipment and drill the ground remotely. This removes the worker from dangerous and noisy locations next to the moving parts of the drill rig. According to Boart Longyear's Product Manager, Craig Mayman, drilling workers suffer the highest percentage of injuries in the industry although this statistic likely extends into exploration and petroleum drilling operations. As such, remote systems can contribute to reaching the goal of "Perfect Zero" or "Zero Harm" in safety performance (Moore, 2009).

Similarly, in an underground mine, a semi-automated load-haul-dump vehicle (LHD) equipped with onboard video systems front and back, allows an operator on surface to view operations in real time. A system of computer-controlled laser scanners allows the trucks to navigate the haulage route autonomously. For example, in 2005, DeBeers Finsch Mine (a diamond mine in South Africa) installed 7 Toro 50D (T50D) automated dump trucks and one Toro 007 semi-automatic LHD to transport ore to an underground crusher. No failures have happened and the trucks operate at 25 kph (~16 mph), significantly faster than human-operated LHDs. With no lost time for driver change-over, the system has allowed Finsch to move about 16,000 tonnes per day (tpd) of ore, compared to about 15,000 tpd for manual operation – a productivity improvement of 6.7%. The economic value of the system has also improved due to reduced maintenance costs as the equipment is being used more consistently and is better managed under computer control. Accidents due to human-error and poor-driving habits have been eliminated (Kral, 2008).

Automation in the mining industry has initially focused on underground mining with telerobotics being the major approach. It is important to realize that these advances do not necessarily have net positive effects on production, but implementation does affect the design and related costs of mining underground. Regardless of automation use or not, mine openings must be sized to allow haul trucks to enter and operate. Roof support and ventilation systems must be engineered with a high degree of safety since, although truck operators may be repositioned to the surface, maintenance personnel will still require access to the equipment if it fails on-the-job. Underground mine design is complex and expensive, and as mines become deeper, requirements become more intensive particularly with respect to dewatering and temperature control. Regardless of whether humans or robots are working at such depths, rock mass stability is still required (Mercer, 1999). In the future, changes in design and operation may be possible through automation (lower-profile machines, different maintenance procedures, etc.), but until these issues are resolved, mining costs will still increase exponentially with depth. As such, at this time, automation is not a universal solution for all challenges faced by underground mining.

Automation is also being adopted on a small scale. While the processes are not highly-computerized, implementation of automated powered equipment can have a positive impact on the quality of the workplace, increasing safety and reducing toxic emissions into the environment (Mullard, et al., 2009). Automation will continue to evolve and its application in all scales of mining operations will help advance mining company contributions to sustainable development through safety and workplace improvements.

2.4 Autonomous Haulage Systems

An existing open-pit mine haulage truck fleet can be adapted to a robotic system. The system would require the following components among many other elements:

- a wireless communication network system
- sensors to provide measurements for navigation and object-avoidance
- local computing hardware on-board each truck to process sensor information to control final-control-elements on the vehicle (accelerator, steering, and brake)
- controller devices to regulate each final-control element
- a central processing system to coordinate all communication among the different pieces of equipment and provide supervision of the vehicles
- a GPS system accurate to <10 cm to provide localization in all parts of the pit
- a software system capable of local and supervisory control

Komatsu and Caterpillar are two equipment manufacturing and supply companies known to be working on autonomous haulage truck development (Komatsu, 2013), Caterpillar, 2013). Hitachi has recently announced development of AHS trucks (Kouketsu, 2012). Komatsu is using the technology at Rio Tinto's West Angelas mine (an iron ore mine in Australia); implementation of this technology is under the program "Mine of the Future©". The main focus of the program is to automate the entire mine. In order to achieve this goal, Rio Tinto has developed a centre for mine automation in Sidney in partnership with the University of Sidney (Rio Tinto, 2012).

In December 2008, Komatsu's FrontRunner AHS fleet began trials at Radomiro Tomic mine following testing of a 5-truck system over a 2-year period. All truck navigation was controlled from a central control room using GPS signals to establish position and speed. During this trial, an incident obliged the Radomiro Tomic mine to temporarily replace its AHS with manaul trucks, after one AHS hit a loader and another slipped down the face of a waste dump. These incidents resulted in no injuries (Dozolme, 2012). After this trial, the technology moved to Gabriela Mistral mine and today the system is running with 18 trucks (Jamasmie, 2009).

The Caterpillar AHS project was set-up as a joint-venture with BHP-Billiton in 2007. The long-term plan was to design for a major open pit mine expansion project in Southern Australia in 2020 with a fleet size of 150 trucks. Due to the economic crisis in 2008/2009, the project was placed on hold, although some initial trials have been executed at BHP's Navajo Coal mine near Farmington, New Mexico in 2011 and 2012 (Russell, 2011).

More recently, Caterpillar announced a joint venture with the Australian mining company, Fortescue Metals Group (FMG), to implement an autonomous mining solution at the new Solomon iron ore mine in Western Australia involving a 45-truck fleet (Fischer, 2011).

Autonomous haulage trucks contribute greatly to reducing losses associated with human elements such as individual performance, personnel breaks, and absenteeism (Zoschke and Jackson, 2000). However, with large automated projects, communication problems can arise. There is a large amount of equipment that relies on control technology and wireless systems that depend on system bandwidth and latency issues (see Appendix 20). Therefore, while a mining company may be attracted to implement an AHS system, to take advantage of many efficiency improvements in a large operation with considerable automated equipment, communication complexity problems can be severe. Continuing research and new key performance indicators are needed (Meech, 2012).

Using autonomous haulage trucks improves safety, maintenance and equipment life, optimizes fuel consumption, and provides streamlined operations with increasingly accurate production systems. Even with these advances, mining companies must work hard to connect this new technology to other organizational processes. The decision to implement an autonomous system in a mine must consider all possible impacts, not only operations (Parreira, et al., 2010).

2.5 Simulating Autonomous Haulage Trucks

How can an autonomous haulage system be adapted to mining? It is important to have models to simulate core processes to examine key variable that may affect future results so performance can be managed and identified (Neely, 2002).

To predict future results, it is important to know the degree to which an autonomous haulage system can approach or exceed a manual system. Past KPIs are not necessarily measurements of future events (Parmenter, 2002). As a result, simulation software can be used to help predict benchmarked KPIs as well as discover new KPIs that might be better at measuring future changes with new technology. This can then quantify the improvements and enable rational and logical decision-making, i.e., determining the level of improvement (Key Performance Indicators) to justify the cost of the technology.

Simulation of mine haulage systems has been around since the 1960s and has been applied to study problems such as: shovel/truck scheduling schemes (dedicated service vs. individual truck rerouting); development of planned maintenance schemes; design of different haulage routes in multiple digging point situations; and optimum truck fleet size (Baiden, 1984), (Bonates, 1992), (Bissiri et all, 1968), (Bozorgebrahim,1964), (Lipsett, 2002), (Ta, 2002), (Sturgul and Yi, 1987). However, there is no open literature on simulation of mine haulage systems applied to determine how fuel consumption, tire life, safety issues and other deterministic measures might change when an AHS system is employed.

Autonomous haulage trucks are only one piece of a complex solution to improve performance. Simulation software should be incorporated into an Autonomous Haulage Truck project for the purpose of improving the technology and making sure that an AHS fleet is smoothly integrated into the organizational process to add value. AHS does not improve all KPIs; in some cases, intelligent driverless haulage trucks may actually produce deterioration in performance with respect to some KPIs. It is important to define the overall improvement across KPIs in the long-run such as productivity, fuel consumption, tire wear, safety, maintenance, cycle-time, etc. The presence of certain attributes or the absence of specific constraints at any particular mine may be necessary to include to ensure overall performance improvement, i.e., weather conditions, topography, geology, etc. all affect overall operations and implementation (Parreira, et al., 2010).

2.6 Simulation Package and Operation of the Model

Discrete-event computer simulation has been in use since the late 1960s using a software language called GPSS (General Purpose Simulation System) – see (Bauer and Calder, 1972), (Tu and Hucka, 1985), (Fytas and Wilson, 1986), (Vagenas and Granholm, 1990), (Sturgul, 1995), (Sturgul, 1998). Today, a version of GPSS is marketed by Wolverine Software that requires a graphical user-interface called PROOF to perform system animations (Sturgul, 2010). In addition, AutoMod, Arena, SimFactory, Slam, Taylor II, Simscript III, Simprocess, and Quest are each used as simulation languages to model mining systems among other types of processes.

The simulation package in this research project was chosen based on several criteria such as ease of use, provision of adequate debugging and error diagnostics, capability of integrating data with other software such as Excel and Visual Basic, ability to have animated graphical environments to visualize the simulated mine, and finally, the software cost. Taking into account these criteria, a package called ExtendSim, marketed by Imagine That Inc. in San Jose, CA, was chosen. Appendix 2 describes the basic steps to create an ExtendSim model. Appendix 3 explains the blocks used in the model. Appendix 4 shows some processes such as resources allocation, maintenance, and digging and loading, in order to understand how the simulation package works.

2.7 Discussion

2.7.1 Impact of Mining Automation

The decision to implement an autonomous process in a mining operation must consider a myriad of changes and impacts that such technology will have on employees and on the community at large. Internally, the largest concern is impact on employment and the number of employees hired to work at a mine. Automated equipment does work formerly performed by people, and so, addressing the shifting roles and responsibilities of company employees is of prime importance (Mottola and Holmes, 2009). Automated equipment is ideal to replace repetitive and dangerous tasks, allowing operators to take on the responsibility for more than one machine at a time, leading to improved multi-tasking abilities and creating work cycles with greater reliability and quality (Poole, 1999). Automation also provides new training and employment opportunities for mine personnel. New job categories must be developed to manage intelligent information systems to link mine planning systems with the machines themselves (Mullard, et al., 2009).

The information in turn must be relayed to technicians and authorities responsible for decision-making (Poole, 1999). A company must balance the opportunities and perceived threats of automation and its impact on employment. The first step is through clear and regular communication with stakeholders – within the company and by doing outreach to the community – to indicate the reasons for applying automation and the expected impact on overall operations (Boutillier, 2008). The company must be open to feedback about the impressions, concerns, and ideas of personnel from all levels of the company.

A company can monitor and measure the impact of automation by using KPIs related to personnel productivity, workplace quality, safety issues, and reduction in hazardous exposures. This allows targets to be set for improving working conditions for employees as a result of automation. KPIs can be implemented at the operational level as well as the management level, in order to assess if automation is easing processes throughout the company (Parreira, et al., 2010). It also gives an opportunity to engage affected employees in the implementation process.

One way to manage personnel and community transition into an automated system is through training. Training programs should be developed to provide the new skills that employees will require to operate, monitor, and maintain the automated equipment. If automation is being used to expand an operation, a company should also have a long-term employment scheme that considers the evolving positions that will enable smooth and successful transition and growth (Parreira, et al., 2010). Replacement of employees will occur in any automation program, but it must be done in a way that involves attrition or turnover issues, not the dismissal or lay-off of affected personnel. In a new mine, the implementation is somewhat easier while with an existing mine, there are more challenges related to addressing people's perception and providing proper training (Meech, 2012).

Automation should not be viewed as a solution in itself and failures have occurred due to limited preparation of the employees and community, as well as a lack of management commitment to the long-term implementation cycle. By its very nature, automation means a fundamental change in how the overall mining process will operate. As such, the change is dramatic and can be traumatic. In 1998, INCO’s Sudbury LHD and Drilling Automation program was withdrawn because of insufficient teamwork across the organization between internal R&D groups with divergent philosophies, and a lack of support from head office (Mottola and Holmes, 2009).

In communities where automation is being implemented, often there are cultural barriers and fears related to the idea that an automated process will result in fewer jobs for the community. Employment is an important contribution that a mining company creates for a community, and this forms an important part of the corporate-community relationship, reputation, and social license to operate. When automation enters the system, a long-term strategy and extensive outreach and education program is necessary. While automation will impact the workforce, opportunities exist to compensate these changes through training on specialization of new skills needed for the new technology (Mullard, et al., 2009).

2.7.2 Robot Ethics

The growth in automation across many industries is starting to raise ethical questions, particularly related to responsibility and intention. Presently, most legal systems primarily take a human-centred approach to their perception and conception of legality; however there is an increasing need to explore the issues surrounding rights and responsibility in relation to robots or hybrid agencies (humans responsible for automated systems) (Nagenborg et al, 2008).

One of the major reasons for implementing an automated system is health and safety, and it will be important that measures are taken and sufficient education given to help people adjust their behaviours around machines. Automated haulage trucks are highly complex robots with sophisticated software, different in many ways from other trucks or vehicles. Proper awareness, training and on-going education will be necessary to change people's perceptions and ensure proper safeguards are in place. Developers and producers of machines and software will need to ensure that training and awareness are implemented along with the system itself in order to receive feedback and learn from the early stages of implementing autonomous systems (Nagenborg et al, 2008).

Despite years of innovation and testing, no machine is perfect; all technologies are liable to fail or misbehave at some point, and the ethical or legal issues that arise from an incident may be unprecedented the first time (Royal Academy of Engineering, 2009). It is important that legal systems are up-to-date with new technologies to address questions of liability with guidelines on how to assess responsibility and divide the degree of liability for any harm that may occur because of an automated machine. In addition to the legal system, the insurance industry needs to determine how to deal with insurance issues related to automated machines and vehicles (Royal Academy of Engineering, 2009). Although mining automation is in its early stages, public engagement on the benefits and concerns will help raise awareness and address positive and negative perceptions. Robots are useful not only for conducting specific tasks, but also they provide insight into human behaviour and value systems (Royal Academy of Engineering, 2009). Regulations surrounding automated machines will likely undergo many manifestations around the world, and it will be important that governments, companies and communities share best practices as they gain experience with automation and automated systems.

2.7.3 Implementation of a Successful Project

The field of automation is changing at a fast pace and is revolutionizing diverse industries, so it is vital for experience and best practices to be shared. There are many lessons to be learned from both the successes and failures of implementing autonomous systems. To be successful, an automation project must identify and analyze levels of interest, expectation, priorities, and influence of stakeholders in the early stages, as well as develop a management plan that incorporates quality control, risk management, communication plans, and exit strategies. In order to automate a manual haulage system, it is expected that one or more of the following methods will be considered (Meech, 2012):

- Replace MHS with AHS in one step – no interaction;
- Isolate AHS from MHS: Separate routes, staged introduction;
- Integrate AHS with MHS: Significant safety concerns.

When completely replacing a manual haulage fleet, it is expected that in the beginning, there will not be much improvement as the AHS technology is new and evolving. For safety purposes, cycle times may be longer with trucks travelling more slowly. Each mine has unique variables such as weather, road material type, etc., and as a result, different set points are needed for each AHS project. Once the technology becomes mature, implementation at an existing manual site will be easier. When a company implements new software such as SAP/R3, the company will replace its entire old management tool(s). SAP/R3 has been on the market for many years, training is consistent and the software is reliable; so, KPIs for such a case are expected to improve even in the first months. Such may not be the case with an AHS fleet.

Isolating the AHS from MHS would be the best option for this new technology, as the mining is evolving with the project, workers are able to understand gradually new safety procedures and the technology grows and improves step by step. KPIs are planned by phases, for example: KPIs for route 1 / week 1, 2, and 3; and then, other KPI targets are set for the second phase (route 1 and 2 / week 4, 5, 6). Improvements take place slowly according to knowledge gained and the experience of acceptance by stakeholders.

For safety reasons, integrating AHS with MHS by sharing the same haulage route is not perhaps, a good idea, since the set points of the technology are not yet 100% certain and workers may be fearful of driving in the same environment as robotic trucks. Many issues may arise due to AHS and MHS interactions along the route or at load or dump areas. Driver's thinking, such as: "will I lose my job?" or "Can this robot see my truck?" may cause driver distraction and fatigue.

Safety concerns require careful design and planning, a back-up or fall-back system may be necessary. It is important to develop the following core competences within the mine planning and operations departments to ensure that safety issues and back-up systems are well addressed.

- Process Control fundamentals;
- Understanding control stability;
- Supervisory control hierarchies;
- Software algorithms;
- Artificial Intelligence methods;
- Managing large databases;
- Sensor knowledge and maintenance;
- Remote operation of equipment.

Specialists of each core process are responsible for giving feedback to the other core competences and, in this way, all processes can be interlinked. This form of integration allows more rapid improvement. During each implementation phase, meetings to discuss KPI reports on each core competency can be shared. New indicators can be created in order to monitor the heath and effectiveness of sensors, data collection, etc.

When implementing an AHS project, a mine manager must be on-side with all decisions about the changes. Divergent ideas can ruin the project. It must be expected that the need for new safety/traffic rules, more maintenance, less manual operational activities in the pit, and practices such as drilling and blasting may change.

The mine head office must also change; if there is a need to move control of different mines to a central facility, it must be done with care. All headquarter decisions must support local mine site personnel. Another very important issue is to focus on integrating massive data collections. Data are just numbers unless they are well-structured and analysed. Without analysis, implementation will be slow.

2.7.4 Definitions

A model is *an abstracted and simplified representation of a system at one point in time. Models are an abstraction because they attempt to capture the realism of the system. They are a simplification because, for efficiency, reliability, and ease of analysis, a model should capture only the most important aspects of the real system. Dynamic modeling is the foundation for computer modeling* (ExtendSim, 1997).

In a deterministic model, variable states are determined by parameters in the model. For example, travel times are calculated as a function of the load and speed-rimpull characteristics. For each model step time, acceleration is assumed to be constant, and using fundamental physics, the speed, distance, engine speed, BSFC (break specific fuel consumption) are determined at the end of the time interval.

Discrete Event simulation: the simulated time advances based on events that occur during the simulation. The system will change state only if events happen (Robinson, 2004). As such, the mere passing of time does not have a direct effect on the model. Instead, time advances due to a driven event.

Continuous time simulation: the simulated time is fixed at the beginning of the simulation and will advance in equal time increments or steps (Robinson, 2004). A truck changes its states (position, velocity, etc.) continuously according to a fixed time of 0.1 seconds.

Monte Carlo modelling uses random numbers to vary input parameters; it provides a range of results rather than a single value (ExtendSim, 2007). The inputs for loading and dumping time, maintenance, and mine delays use probabilistic distributions in order to indicate parameter variations. Appendix 22 contains the distributions used in the model.

Cycle time is the time necessary for the truck to complete an operational cycle which includes spotting, loading, hauling loaded, dumping, returning empty, queuing, and road delays. Total truck cycle time is the sum of spotting and loading, hauling loaded, dumping, hauling empty, queuing, and delay times. Total cycle time in the model is expressed as truck operating average time over the cycle.

Operational delays are classified as fixed or variable. Fixed delays have a duration and a time of occurrence. Fixed delays are shift changes, preventive maintenance; predictable driver breaks, refueling, blasting, etc. Variable delays are unpredictable. Unscheduled mechanical delays are variable delays.

Truck utilization represents the actual percent time that a truck operates in the mine. It takes into consideration the time that the truck is running and doing tasks such as being loaded, hauling, dumping, returning, and waiting.

3 Model Design

3.1 Model Structure

This research is based on data provided by a major international mining company which cannot be identified for confidentiality reasons. As well, the mine that contributed the necessary data cannot be identified. For the purposes of discussion, this mine will be referred to as the Lucy mine in this thesis. Only a portion of the haulage system at Lucy mine is modeled in this work with two shovels digging ore and waste to achieve a stripping ratio of 0.5.

The research approach used in this work has been designed to extend shovel/truck simulation into a variety of truck sub-models with the goal of capturing the mechanical complexities and physical interactions of these truck sub-systems within the mine environment on a 24/7 time-based basis. The sub-models can be studied as an integrated part of the system (big picture) or separately (Parreira, 2012). This approach can be beneficial when a new system needs configuration or reconfiguration.

The model simulates the operation of haulage roads at the Lucy open pit mine according to a schedule using either autonomous or manual trucks. Mine delays such as blasting, maintenance, queuing, shift changes and breaks (in the case of manual trucks), and the effect interactions with auxiliary equipment were introduced into the model. The software can show the cost and operational benefits of automation. In cases where certain KPIs of the autonomous trucks are inferior with respect to a manual system, adjustments in other KPIs can be made to reduce the negative impact (Parreira, 2012).

Figure 1 shows the overall model structure. The inputs to the model (see Appendix 24) consist of data from the Lucy mine obtained during two field studies. Data on road characteristics, velocity, acceleration, weather and delays (driver and process delays), and maintenance were gathered during the first visit. Data such as dumping and loading time, production, cycle time, fuel consumption and truck speed were obtained through a VIMS© (Vehicle Information Monitoring System) during the second visit. A system database is used to input model parameters (see Appendix 23). The data is held in an internal ExtendSim database stored with the model to open, save, or close when the model opens, is saved, or is closed respectively. Weather information and road condition are input into the model at the beginning of the run. For ambient temperature, the model has an option to assume a constant value or uses a look up table according to Lucy mine temperature (Appendix 15). A crew make-up of passive, normal or aggressive drivers is assumed at the beginning of the run in order to simulate driver behaviour. Road characteristics of the Lucy mine is input to the model database at the beginning of each run with information such as grade, maximum speed, stop signs and segment length.

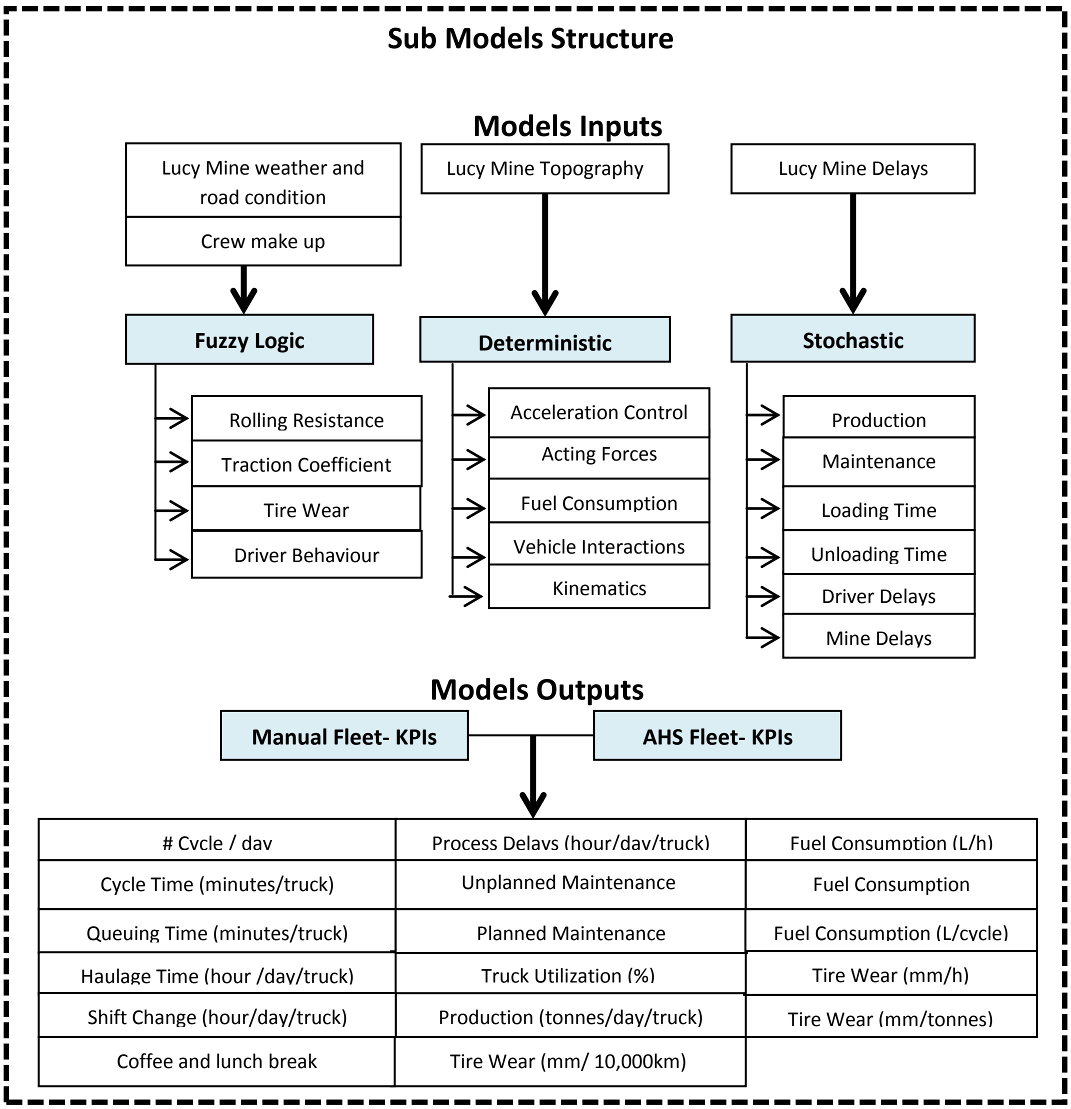


Figure 1. Overall model structure

When the simulation finishes, KPIs (Key Performance Indicators) that were chosen according to Lucy mine standards are exported to an Excel spreadsheet. A comparison between Manual and AHS can be done at this point. The model uses fuzzy logic, deterministic and stochastic approaches. A more detailed description of these approaches will be given in the next chapters.

Figure 2 shows the overall model flowchart, the inputs, outputs and detailed flowchart of truck movement can be seen in the Appendices 9 and 24. The model assumes two working loaders (shovels), one digging waste and the other assigned to ore production. According to an assumed stripping ratio of 0.5 at the beginning of the simulation, one third of the fleet (9 trucks in total) are set to work with the ore shovel with the other six assigned to the waste shovel. For each segment of each haulage route, movement of each truck and its fuel consumption and tire wear are determined using a deterministic approach. A time step of 100 milliseconds is used in the model which gives a distance of ~0.42 m for a truck moving at 15 km/hr and ~0.83 m for a speed of 30 km/hr. If a greater time step value is selected, trucks may not be where the system believes them to be at each step. Increasing the value of the time step for some segments means that improper simulation of truck braking as well as maintaining a safe-following distance will produce inaccuracies.

The objective is to handle speed and acceleration control issues at any point in time and to calculate fuel consumption and tire wear in simulated real time. The gross machine weight, rolling resistance and drag forces are used to calculate the resultant force that causes a truck to move. For each step change Δt (0.1 seconds), a new force and acceleration is calculated until the truck's cumulative travelling distance equals the total distance of the segment. Chapter 5 gives more details of this approach.

At the end of each road segment, data is initialized for the next segment with simulation continuing until the truck reaches its destination. After a truck reaches the shovel queue, it waits for the shovel and the model stochastically selects values for spotting and loading times based on a probabilistic distribution that represents data from Lucy mine. After loading, the truck leaves the shovel and travels to its unloading site. At the dump or crusher queues, the truck reverses and dumps with values for reversing and dumping times also selected stochastically based on data from Lucy mine.

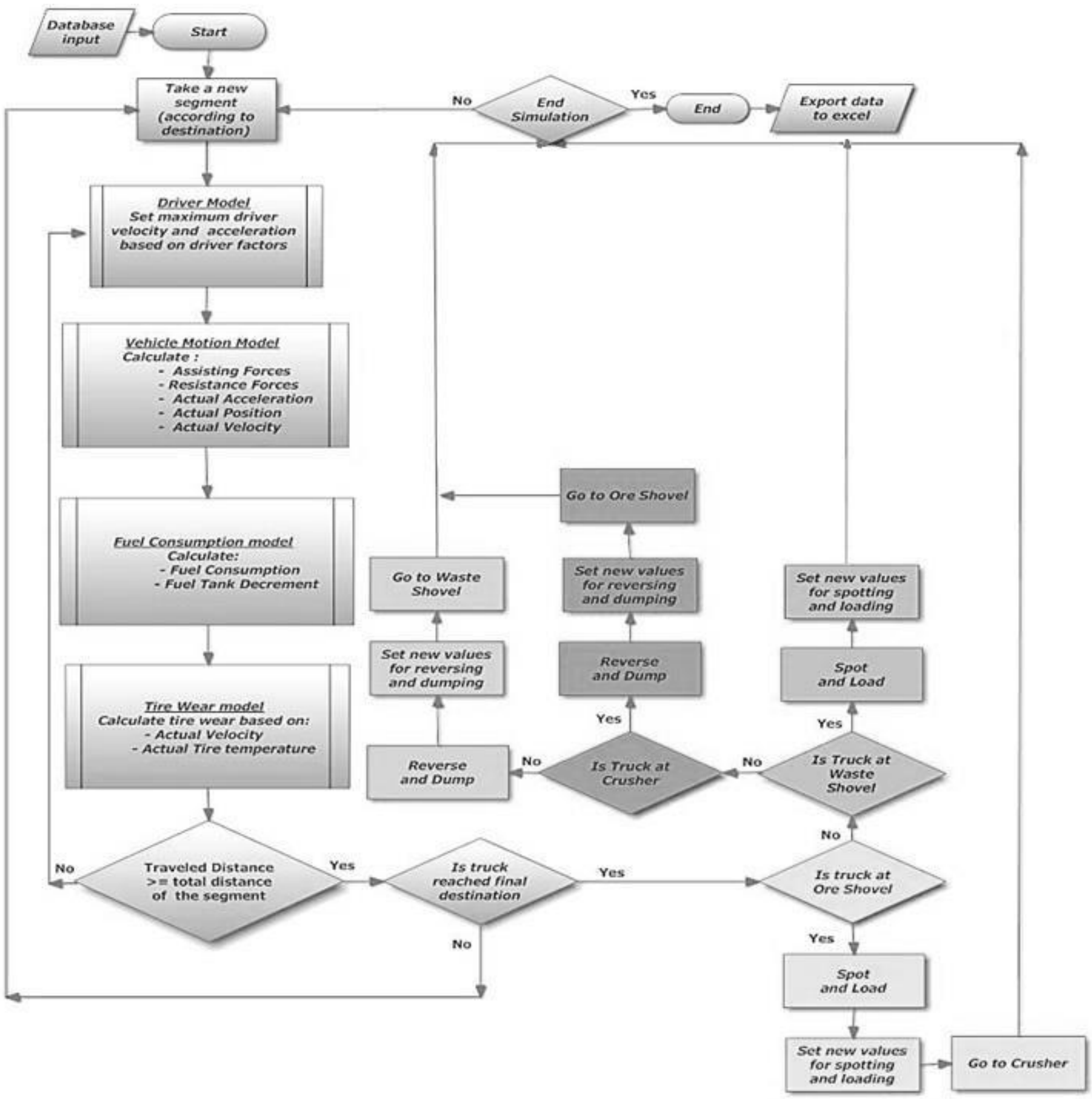


Figure 2. Model flowchart (not showing reassignment schedule component).

All queuing times depend on the presence of other trucks at the loading and unloading sites. Following the unloading routine, the truck returns to its original route if there is no reassignment schedule. It continues in this loop until a break-event happens. Break times and frequency are also based on Lucy mine data.

A refuelling delay takes place whenever the truck's fuel tank level falls below a set minimum value (10% of a full tank). When that happens, the truck completes its current cycle, dumps its payload and proceeds to the refuelling station (parking). If a truck requires maintenance or a driver needs a break (lunch, coffee, or shift change), the truck also drives to parking, but only after it has dumped its load. In some cases for the manual case simulation, a truck goes to parking with its load. This happens if the driver is late for lunch, dinner or for shift change.

After a truck is repaired, the values for MTBF (mean time to failure) and MTTR (mean time to repair) are reset. During the simulation, data is stored and managed in the internal database. The relevant results for the run are exported to an Excel template spreadsheet when the simulation run is completed.

3.2 Layout of the Mine Model

The layout of the model was set to represent a small portion of the Lucy mine. The mine operates with CAT 793D trucks, each having a nominal Gross Vehicle Weight (GVW) of 383,749 kg; a net power of 1,743 kW, and using standard radial tires 40.00R57 (Caterpillar 1, 2007). Instead of simulating the entire mine, 8 haulage routes of the Lucy mine were chosen: Ore Shovel from/to Crusher, Waste Shovel from/to Dump, Dump to Ore Shovel, Crusher to Waste Dump, Waste Shovel from/to Parking, Ore Shovel from/to Parking, Dump to Parking and Crusher to Parking. The last four routes are used for truck maintenance, refuelling, or breaks (shift changes, coffee, or lunch for manual operation).

Figure 3 shows the positions of the two shovels, the dump site, the crusher, and the parking locations used to refuel and perform maintenance during the period February to March 2010 of the Lucy mine. This period represents a longer haulage route layout than other situations.

The map indicates significant points of interaction between the trucks. For example when leaving their respective shovel, waste trucks and ore trucks share the same route up to the first intersection. At the top of the pit where ore trucks arrive for the final leg to the crusher, there is an intersection where interactions occur with waste/ore trucks moving to crusher/parking. Another intersection exists on the leg between trucks moving to and from the crusher and those moving to and from parking.

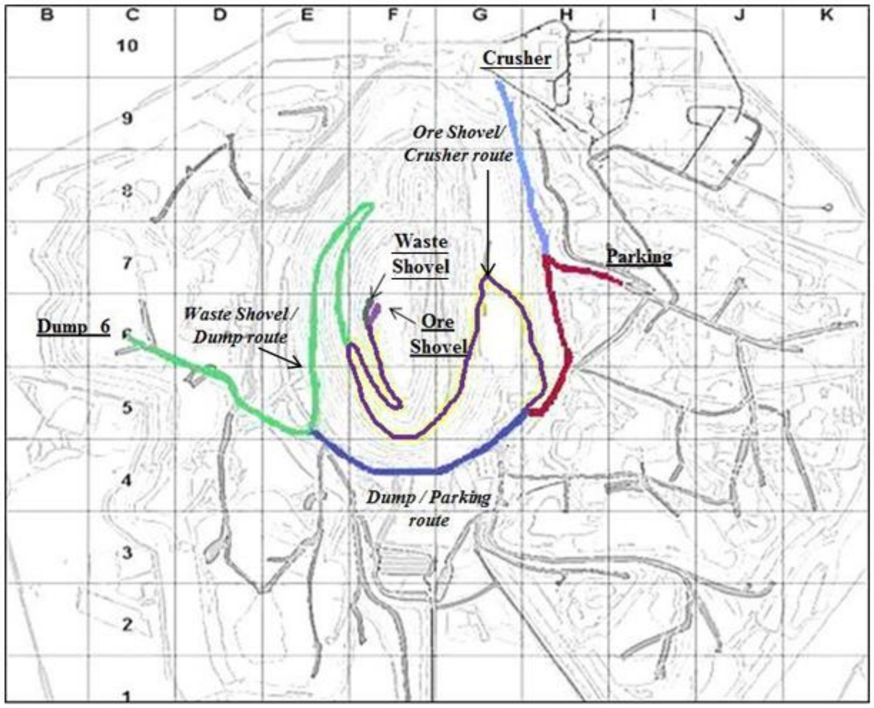


Figure 3. Haulage routes used in the model. scale: 500m x500m grid squares

Table 1 shows the length and number of segments of each route. The grades of each road segment were obtained from the Surpac software system at Lucy mine. The maximum effective grade is 10%. The speed limit on the main haulage segments is 40 kph. The maximum acceleration depends on grade: on a flat section and low grades (= 0% and ≤ +5%), it is 0.42 $m \cdot s^{-2}$; on an uphill segment (≥ +6%), it is 0.21 $m \cdot s^{-2}$; while a downhill road (< 0%) is set to 0.62 $m \cdot s^{-2}$. Maximum deceleration (braking) is set to 0.42 m/s^2. These limits were provided during a visit to the mine site in 2008. These numbers could not be validated during the site visit since acceleration/deceleration variables are not monitored or recorded by the dispatch system, but there is general agreement that these are the designed levels recommended to all drivers. Without monitoring, it is difficult to say whether different drivers actually abide by these guidelines.

In the model, switchback curves of the mine were divided into segments according to grade and maximum speed. At the end of a segment, a truck brakes or accelerates according to the maximum speed of the next segment. Note that truck speeds do not necessarily equal the road speed limit. On a downhill run, for example, speed depends on emergency stopping distance and retarding performance, while uphill, speed depends on payload and road conditions. So, if a truck driving downhill has a safe mechanical speed limit of 14 km/h and the road speed limit is 40 km/h, then safe mechanical speed will be the maximum speed allowed and the road limit is disregarded. The model verifies if a truck is driving above or below the speed limit and whether acceleration or deceleration is too high (this can occur with aggressive drivers).

Table 1. Road segments and lengths of each route from Lucy mine.

Route	Segments	Total Length (km)
Ore Shovel to Crusher	21	5.7
Ore Shovel to Parking	14	3.5
Waste Shovel to Dump	15	5.8
Waste Shovel to Parking	20	5.4
Crusher to Waste Shovel	27	6.2
Dump to Ore Shovel	21	6.2
Crusher to Parking	13	3.9
Dump to Parking	13	3.9

The model runs in either autonomous or manual mode. The model has a simple rescheduling algorithm used to reassign trucks to maintain the stripping ratio close to the set level. If the stripping ratio is trending below target, a truck at the dump is reassigned to haul ore. If the stripping ratio is trending above target, a truck at the crusher is reassigned to haul waste.

3.3 Additional Distances Driven per Day by a Human Driver

It is evident that a manually-controlled haulage system will involve longer travel distances than an autonomous haulage system. There are three factors that contribute to a longer distance travelled by human drivers:

- Distances travelled to parking
- Lateral position displacement (amount and frequency of side-way movement)
- Changes in loading or dumping allocation

On each 12-hour shift, one lunch break, two coffee breaks, and one shift change add a distance per truck equal to about 32 km in this haulage system model since when drivers at the Lucy mine have a break, they drive to the parking lot, adding more unproductive time. This distance is more than one hour of unproductive travel time and about 16% of additional distance. This represents about 1.5 cycles per shift for each driver.

The model also considers variations in road segment lengths due to driver behaviour. A person can drive in a straight line and his/her distance may be exactly that shown for each segment in Table 1; or the truck may travel a longer distance due to rutted road conditions, driver experience, stress, or other driver states that may affect steering. These deviations are known as Lateral Displacement Control and reflect the skill abilities of different drivers.

Considerable research has been done on different performance measures of passenger vehicle drivers that include the impact of drugs, driver distraction, time of driving, and reaction to critical events. Although an ultra-high-capacity haulage truck is considerably different than a passenger car, there are several measures that can scale-up quite naturally into an open-pit situation. These include: distractions; multi-tasking; lateral displacement control; reaction to unexpected events; and length of driving time, among others.

De Waard (1996) performed test work to measure driver behaviour when mental workload increases. His data show a baseline standard deviation of lateral position (SDLP) from a lane centreline of ~20 cm. This means all position data will fall into a window of ±0.6 m around the centre of a lane assuming a normal distribution. Dourlens et al (1998) reported a similar range. Sleep deprivation studies show that as driving hours increase, a significant increase in the range of lateral position in a highway lane occurs (Kozak et al, 2006), while Vester et al (2011) identified that shorter segments show lower percentage SDLP values. This work also confirmed the impact of tiredness due to driving time with an average SDLP of ±23 cm for the first hour rising to ±31 cm after 8 hours.

Vollrath et al, (2008) showed SDLP levels in excess of ±100 cm in simulated driving studies. In a study done to evaluate driver reactions to unexpected events, Schaap (2012) showed SDLP values between 10 and 50 cm with an average of 25 cm. Values were higher during events that occurred when the driver was multi-tasking.

In studies done at Carnegie-Mellon University on semi-truck drivers on the Pennsylvanian Turnpike, Batavia (1998) also reported SDLP values in the range ±60 cm, but more importantly, the data showed lateral position changes every 0.52 seconds at speeds of 90 to 100 kph. At 15 kph, this is equivalent to a travelled distance of 4.32 m, and at 30 kph, a travelled distance of 8.66 m. With a lateral displacement of ±100 cm, the percentage increase in travelled distance would be about 4.9% at 15 kph and about 1.3% at 30 kph. This work also showed that greater variations occur on left-turns with 5 times the range compared to right-turns which gave a range quite similar to straight sections. Botha (2011) has shown that there is considerable difficulty in compensating for yaw effects on lateral position control when cornering in a heavy vehicle with a high centre of gravity even with an autonomous control system.

An analysis of 5 haulage trucks at the Lucy mine has revealed considerable differences in the distances travelled on different cycles by different drivers on the identical haulage route. Comparison was done for longer haulage routes (5.6 - 7.0 km) as shown in Table 2.

Table 2. Average haulage distances for several trucks at the Lucy mine (VIM data).

Truck Number	Distance (km) Empty			Distance (km) Loaded			Distance (km) Total Cycle		
	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.
2020	6.0	4.9	7.2	7.0	6.5	7.4	12.5	11.0	14.0
2109	6.0	5.0	7.0	5.8	5.0	6.6	11.8	10.5	13.3
2013	6.0	5.0	7.0	6.3	5.5	7.0	12.5	10.5	14.5
2079	5.6	4.9	6.1	6.5	5.8	7.2	12.1	10.7	14.2
2016	5.8	4.5	7.1	7.0	6.3	8.0	12.8	10.3	14.2
Average	5.88	4.86	6.88	6.52	5.82	7.24	12.34	10.60	14.04
%Deviation	-	-17.3	+17.0	-	-10.7	+11.0	-	-14.1	+13.8

**Average data per truck for periods of 5 to 9 months from January to July 2011.*

As can be seen the maximum deviation is similar on both sides of the average distance travelled indicating a normal distribution. These trucks show a range of ±17% when travelling empty and about ±11% when travelling loaded, suggesting that the lateral displacement range is lower when travelling slower or when travelling up-grade rather than down-grade. The deviations from the VIMS© database also reflect changes in routes between different shovels and different dumping points since VIMS© does not identify the haulage route; it only gives the distance travelled empty or loaded. It is considered that the extremely large deviations shown in Table 2 are likely due to haulage route changes rather than lateral displacement. Thus, the increased distances due to lateral displacement has been set in the model to the values shown in Table 3. For example, if a driver has normal behaviour and is driving loaded in a segment length of 200 m, the maximum percent deviation is 1 % of this segment length.

Table 3. Maximum percent deviation of segment length travelled by different drivers under different conditions as used in the model.

Driver Type / Segment Length	Passive		Normal		Aggressive	
	Empty	**Full**	**Empty**	**Full**	**Empty**	**Full**
0 - 50 m	6.0	3.0	4.0	2.0	2.0	1.0
50 - 500 m	3.0	1.5	2.0	1.0	1.0	0.5
500 - 2,000 m	1.5	1.0	1.0	0.5	0.5	0.25
> 2,000 m	1.0	0.5	0.5	0.25	0.25	0.10

3.4 Stochastic Aspects of the Model

The data from Lucy mine such as loading and dumping, refuelling, breaks, and maintenance is used in the model to provide random delays. The distributions of these variables were chosen after plotting and analysing the Lucy mine data (see Appendix 22).

The model uses an ExtendSim block called *Queue* to record queuing delays at the dumping and loading points. This block holds-up an item until there is downstream capacity; the first item arriving at the queue is the first to leave. Upon leaving, queue lengths and waiting times are determined (Sundarapandian, 2009).

Maintenance in the model is based on a probabilistic distribution based on the Mean Time between Failures (MTBF) of the main failure types of the Lucy mine. These were grouped into major and minor failures. In the model, when a random failure is triggered, a truck goes to parking after unloading at the dump or crusher. Table 4 shows the MTBF and Mean Time to Repair (MTTR) used in the model. The maximum, minimum and average values of the unplanned maintenance distribution were based on Lucy mine data. Maintenance assumptions in the model have held delay times due to repairs in the AHS system relatively close to those measured for the manual model. The impact of an AHS system on scheduled maintenance is not a focus of this research.

Each truck begins the simulation with a full fuel tank. As fuel is consumed, the tank level decreases and when it declines below 10% of fuel tank capacity, the truck unloads and then goes for refuelling with an average time of 13 minutes to complete the activity (Table 4). A random time to perform the first minor/major maintenance is also set at the beginning of the model. The model uses triangular distributions to simulate the refueling and maintenance data of the Lucy mine. Table 4 shows the minimum, average, and maximum values used in the distributions.

Table 4. Lucy mine delays data due to refuelling and maintenance.

Delays	Time between Events (hours)			Mean Time to Complete *		
				Minimum	Average	Maximum
Refuelling	**Deterministic approach**			5	13	27
Maintenance	**Minimum**	**Average**	**Maximum**			
Minor	-	3	6	3	19	58
Major	-	126	252	360	840	1,440

** Table in minutes. The model uses triangular distribution to create a refuelling/maintenance delays and uniform distribution to create time between events.*

In order to account for loading, unloading, and productivity in the model, data from the Lucy mine was obtained from the VIMS© (vehicle information monitoring system) from 12-Feb-10 to 15-Feb-10 (See Appendix 16 for VIMS© and ExtendSim data). VIMS© is a tool for machine management to provide information on a range of vital machine functions (Caterpillar 2, 2007).

The Lucy data was filtered in order to use only long haul routes that range from 4.6 to 6.0 km and then the data was analysed and plotted. Figure 4 shows that the data in Blue (Lucy mine) has a lognormal distribution with an average of 2.8 minutes. Based on this information, the model uses a probabilistic distribution to better represent the Lucy mine data. Note some events take more than 5 minutes due to shovel break-downs.

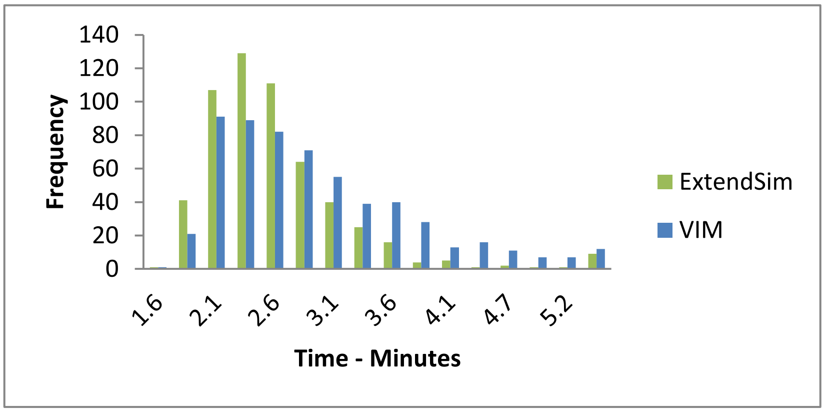


Figure 4. Loading times.

Figure 5 shows the unloading data from Lucy mine (in blue) and the model data which was obtained by a similarly-shaped probabilistic distribution. The unloading time average for the VIMS© data is 4.61 while for the ExtendSim model it is 4.37 minutes. The unloading time includes reversing time before dumping. Unloading and loading data used in the model is the overall unloading and loading time measured at the Lucy mine over a period of 4 days.

In the manual model, delays due to human breaks (lunch, coffee and shift changes) are considered based on Lucy mine data. Each driver has two stops for bathroom/coffee of 9 minutes and one lunch/dinner break of 54 minutes during a shift (Table 5). There are two types of shift change delays, for each 12-hour period, driver shift-change produces a daily delay of 1 hour on average. When the driver completes 14 days of work, it is time to fly-out of the camp. Shift change for the last day of this period is 2 hours instead of 1 hour. This reflects on Lucy mine production (Table 5).

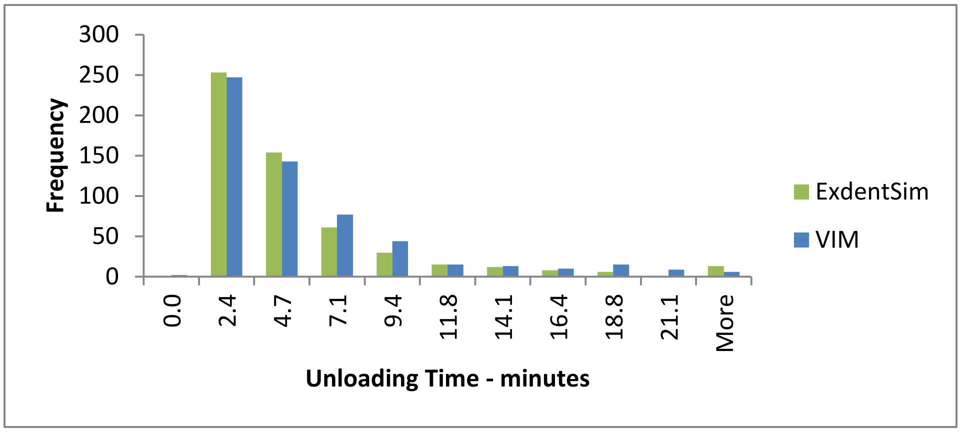


Figure 5. Unloading times.

Note that delays for lunch and coffee breaks are not constant in the model. If a truck breaks down for more than 2 hours near the beginning of the shift, then the driver has spare time, so the model assumes the driver does not need to stop again for coffee. The same happens with a failure close to lunch time if the breakdown time overlaps the lunch break, so the driver does not need to stop again for lunch. Regarding shift changes, the system treats these delays according to the current time of the simulation. If the total cycle time is about 45 minutes, then when the truck is unloaded, the system checks to see if the driver has enough time before the shift ends, to do one more cycle considering as well the time to drive to and park at the parking lot. If the driver does not have time, the driver goes to parking immediately even if loaded. For the long shift change, the system will follow the same logic, but it will send the driver to parking an average of 1 hour earlier than the short shift change.

Table 5. Delays due to breaks and shift changes from Lucy mine.

Breaks	**Scheduled Time in shift (hours)**	**Duration (hours)**
Lunch	6	0.9
Coffee	3 and 9	0.15
Shift Change	**Cycle time (hours)**	**Ave Downtime (hours)**
Short (24 hours)	12	1
Long (14 days)	336	2

The model considers unavoidable delays that are known to occur at the Lucy mine. In order to account for these delays, the model uses a triangular distribution to simulate the downtime shown in Table 6. These values were also gathered at the Lucy mine. When one of these events occurs, the mine shuts down and the trucks wait at the parking lot. The same thing happens in the model. The AHS model also considers these delays.

Table 6. Unavoidable delays per truck at Lucy mine.

Item	Cycle time (hour)	Downtime (minutes)*		
		Min.	Ave.	Max.
Blasting	48	30	60	84
Scheduling	24	40	75	120
Safety/Equipment Checks	24	2	10	15
Emergencies (monthly)	672	30	60	180
Spillage/Cleanup (weekly)	168	5	10	20
Other (weekly)	168	0.5	1	10

**Triangular distributions are used in the model to account for unavoidable delays*

Regarding truck payload, a probabilistic distribution is set in the model based on Lucy mine data. Figure 6 shows payload data at the Lucy mine in Blue from 12-Feb-10 to 15-Feb-10. In order to input these data into the model, a probabilistic distribution that gives a similar shape to Lucy data was used.

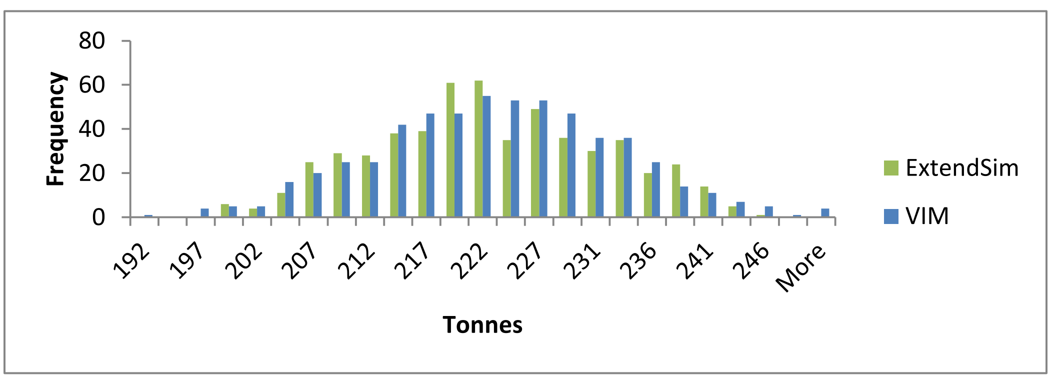


Figure 6. Production. in blue – Lucy data and in green – model data.

The cycle time in the model takes into consideration driver behaviour, vehicle interactions, road conditions, queuing times, loading times, and unloading times. In order to verify cycle time, the output of the model was plotted together with the Lucy mine data. Figure 7 compares the cycle times in the model with that from the VIMS© data. The average cycle time for VIMS© is 44 minutes and for the model is 46.91 (see Appendix 1). Changes in cycle time in the model are strongly dependent on the crew makeup. For this study, the model was set to a passive-normal-aggressive crew partition of 39%, 44%, and 17% respectively (See Chapter 4).

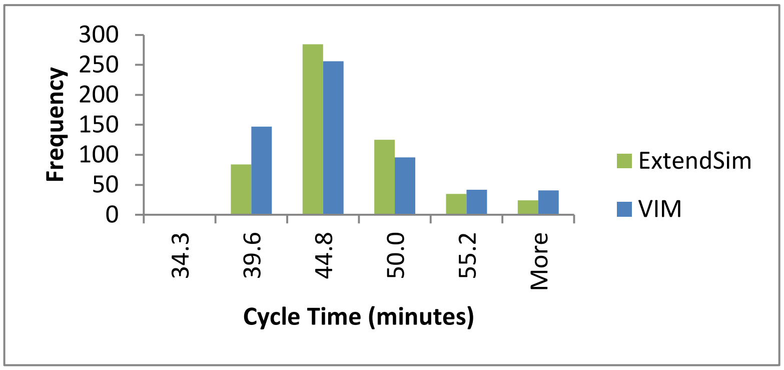


Figure 7..Cycle time comparison.

A hypothetical test was applied to verify whether the variables of Lucy mine such as cycle time, payload, unload and load time, speeds and fuel consumption are the same as the output of the model. Appendix 1 shows the details of the tests performed. 583 samples from the model were compared to 522 samples from Lucy mine. The results show that there is no evidence that the averages of each of the variables in the two groups (manual model and real mine data) are significantly different at a confidence level of 95%.

Appendix 21 provides some knowledge about the time it takes to run the model and the stability of the comparisons of manual and AHS to the test run length over periods of 7 days to 42 days. For all case studies reported, 7-day tests were used. Although this may have produced a small reduction in the benefits of AHS, the bias is small and skewed towards the manual fleet.

4 Driver Behaviour Model

All trucks in the fleet in the model are assumed to have the same mechanical efficiency with different operating performance depending on how the driver operates the machine. This chapter gives the purpose, methodology, and verification of the driver model.

4.1 General Information about Driving Behaviour

The objective of the driver sub-model is to generate controlled differences in driver behaviour to obtain valid output ranges for fuel consumption, tire wear, cycle times, production levels that mimic the Lucy mine fleet drivers. These ranges can be compared to that achieved by a simulated Autonomous System in which the variation from normal or accepted results is significantly reduced (Parreira et al., 2012). The driver model development first began by examining the literature on different parameters that affect drive behaviour in general and in the mining environment.

How a person drives will differ according to his or her skills, abilities, motivation, chemical influences, etc. These differences may account for a decrease in work performance, and/or an increase in operational costs and number of accidents (Clarke et al, 1999).

According to Maycock (1991), aging or maturity affects risk perception and social responsibility. Experience is essential to the driver learning process. Road safety corrective treatment can be linked to experience and learning. Stradling and Meadows (2000) relate attitude and personality as a predictor of accident risk with a driver's psychological characteristics determining how the automobile is driven.

Regarding emotional behaviour (anger, neutral, and excitation), Cai et al (2007) explain that a neutral emotion state is usually present while driving. Strong emotional states such as anger and excitement are likely to jeopardise driving safety due to prolonged reaction time. However, appropriate arousal level improves driving quality (Russell, 1980).

4.2 Driving in Open Pit Mines

From 1992 to 1999, employment in the trucking industry grew faster than the average employment rate in the United: 32% compared to 19%. Even though it grew faster, the trucking industry experienced high turnover rates of more than 100% annually resulting in greater hiring and training costs (Hunter et al, 2005, Dobmeier, 2009).

Min et al, (2003) state that such turnover might be associated with slow growth in the qualified labor force and poor human resource management. Bielock et al, (1990) showed that older and less educated drivers have a tendency to stay at their job. A stand-alone measure such as higher salary is ineffective at reducing turnover but is important in improving job-satisfaction (Min and Emman, 2003).

Drory (1985) did a study on heavy-haul truck drivers in a large open pit mine operating continuously for an eight-hour shift. According to the study, the drivers and supervisors characterized this task as boring and monotonous. High mental workloads lead to a psychological state of fatigue in which attention, accuracy and error responses, and brake reaction time deteriorates. Hashimoto et al (1971) describe three major factors regarding fatigue: body sensation associated with tiredness and drowsiness, motivation weakened sensation or concentration decrement, and psychosomatic disorders which are diseases that involve both mind and body. According to Modular Mining (2010), up to 65% of all haulage truck accidents are caused by operator fatigue.

Mabbott and Lloyd (2005) investigated operator fatigue for 14-nights. This study showed that 12-hour shift intervals do not trigger fatigue on the first night; however, the drivers studied had a lack of stimulus caused by the circadian cycle - a biological process that slows down human activities from 12 am to 6am and from 2pm to 4 pm. The study indicated that short breaks did not alleviate fatigue issues because short breaks only give a temporary relief from body fatigue such as drowsiness. The driver performance decreased only towards the end of the 14-day period. Knowing that they are close to the end of night work, drivers tend to become more careless. Driver individuality was another important factor demonstrated in this study. Each driver has a unique impact on skills; due to health and lifestyle habits such as obesity, poor diet, poor sleeping, and sleep disorders which showed a strong correlation between poor performance and high risk of fatigue (Mabbott and Lloyd, 2005).

According to Hanowski et al. (2003) identifying the worst drivers of a crew (up to 25%) can avoid about 85 % of all haul road accidents. Thompson (2010) argues that driver performance should be considered during mine road design. Badly designed roads cause human error and result in more accidents; the more that is known about driver performance, the better the haulage road can be designed. According to his study, 25% of accidents involving human error were associated with road design (See Table 7).

Table 7. General factors that affect truck haulage accidents (Thompson, 2010).

Factors	%
Road Design	**43**
Road design factors alone	14
Road design and human error	25
Other factors	4
Human error factor	**47**
Human error alone	19
Road design and human error	25
Human error and mechanical issues	3
Mechanical Factors	**4.5**
Mechanical Factors and other factors	1.5
Human error and mechanical issues	3
Other Factors	**5.5**

4.3 Driver Characterization in the Model

In order to compare the performance of a manually-operated system with an autonomous one, it was necessary to create a driver sub-model to simulate different types of drivers operating over a 12-hour shift for 14 work-day periods. Much has been written about factors that influence driving performance, however, little of this literature relates to mine haulage activities. Detailed information about open pit truck drivers is not widely available and the ability to validate driver behaviour against so many different factors was considered to be very poor, so instead, the driver model in this research has been based on a general profile that can be assembled and calibrated with relative ease.

The number of factors that may influence driver behaviors is extensive and may be difficult to assess directly. Some mines, for example Lucy mine, prefer female drivers, for example, claiming that gender issues affect the need for additional maintenance. The suggestion is that women are less aggressive and more respectful of their truck (Parreira et al., 2012). Whether such anecdotal concepts are accurate or uniform across the industry is speculative and without proper study; one would be remiss in accepting such ideas verbatim. Certain individual traits may also play a role such as energy level, age, health, family and personal issues, as well as tiredness (Parreira et al., 2011). These are likely candidate attributes to model driver behaviour, but the issues of provability diminish the approach. Initially, the model consisted of human attributes such as skill level, time since training, personality, gender, fatigue, time in shift, and time in work period in order to establish a “style" of driving. Although there may be a logical way to relate these inputs to speed, acceleration, and reaction time behaviours (Carsten, 2007), the method was set aside due to the difficulty in validation. Instead the model was changed to consider only two attributes – Aggressiveness and Stability.

It is evident that how a vehicle is driven with respect to desired speed and acceleration will affect the KPI elements within an overall haulage system. Some drivers are aggressive while some are passive (or timid). The majority operate the vehicle within a close tolerance to the desired levels. As such, a global parameter called Aggressiveness can be defined that ranges from -1.0 to +1.0 to characterize how a particular human drives a particular truck. The normal behaviour will be 0.0 while the two extremes represent undesired behaviours that exist within the crew. The best drivers are experienced (more than a year of driving background) and generally have recently completed a retraining program (within the past two months). On the other hand, the worst drivers are novices with less than several months of experience and only preliminary training. Such a driver exhibits either a degree of aggressiveness or a degree of passivity. Average drivers will be somewhere between these two extremes.

Each driver's Aggressiveness Factor is described by one of three sets: "Passive", "Normal", or "Aggressive" (see Figure 8). A second term called the Stability Factor (Table 8) characterizes the degree to which these terms change during a test run. Each time a truck enters a new road segment, the driver's behaviour is allowed to trend on a random basis between the limits established for each support range and at a rate related to the Stability Factor. The random trending algorithm is as follows:

$$AF(t) = AF(t-1) + \Delta af \qquad \text{Eq. 1.}$$

subject to: $AF(t) \leq AF_{max}$

and $AF(t) \geq AF_{min}$

where:

AF_{max} = Maximum Stability Factor of the driver in question

AF_{min} = Minimum Stability Factor of the driver in question

Δaf = Random number between ± 0.005 * AF_{max}

The Aggressiveness Factor determines how each driver chooses to select a steady state speed on any particular road segment as well as the actual acceleration to be used to achieve this speed. Each road segment is assigned a designed maximum speed and acceleration level. However drivers deviate from these levels depending on vehicular interactions and their assigned Aggressiveness Factor (see Figures 8 and 9). For example, an Aggressive (+1.0) and Very Stable (+0.80 to +1.00) driver in Figure 9 is driving at a steady-state speed and acceleration higher than that of a Normal driver. This will significantly impact both tire wear and fuel consumption and is characterized as such in the model.

A Passive and Variable (-1.00 to -0.20) driver will drive slower than the design speed and will accelerate lower than normal. The Aggressiveness Factor allows the impact of driver variations on the stochastic simulation to be studied.

Table 8. Aggressiveness and stability factors.

Aggressiveness Factor		Stability		
		Very Stable	Limited Change	Variable
Aggressiveness	Passive	-1.00 to -0.80	-1.00 to -0.50	-1.00 to -0.20
	Normal	-0.10 to +0.10	-0.25 to +0.25	-0.40 to +0.40
	Aggressive	+0.80 to +1.00	+0.50 to +1.00	+0.20 to +1.00

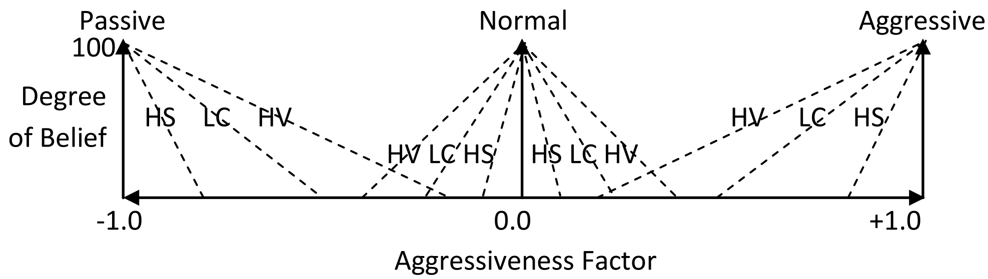


Figure 8. Aggressiveness factor and stability factor that characterizes driver behavior: passive, normal, or aggressive. the stability factor sets the support range. HS = Highly Stable; LC = Limited Change; HV = Highly Variable.

The benefits of Autonomous Haulage are clearly related to higher truck utilization from gains in having no lunches, breaks, and shift-changes - the sum of which can be as much as 5 hours or more per day of production. However, the simulation model allows the characterization of how more-consistent driving behaviour results in changes in KPIs such as production, productivity, maintenance schedules and costs, tire wear, and fuel consumption. The same Aggressiveness-Stability Factor analysis can be used to characterize an Autonomous System in which the Aggressiveness Factor is held close to 0.0 (Normal), with a very small variation reflecting changes in speed and acceleration due to tolerances of the on-board Obstacle Detection and Navigation systems. The set points for speed and acceleration in an Autonomous System can be chosen to be equal to that of the Manually-Controlled trucks or reduced to a level that is considered safer.

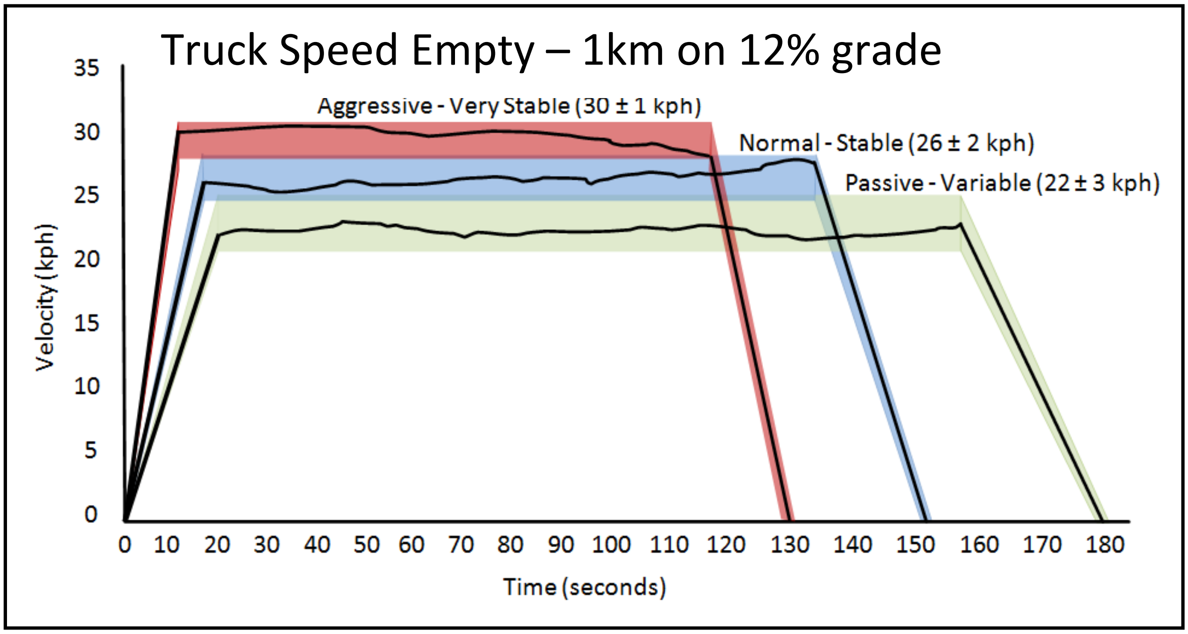


Figure 9. Acceleration and speed of different drivers over a 1,000 m haulage segment with a 12% effective grade with no load – from the extendSim model.

4.4 Calibration of the Driver Model

The baseline crew makeup of the model was assumed to be a passive-normal-aggressive crew partition of 39%, 44%, and 17% respectively with the stability factor set to Very Stable (Table 9) which gives a low variation over a shift period. This crew makeup was assumed this partition because Lucy mine has an average of 40% annual turnover. With such a high turnover, one would expect to find a crew with more normal and passive drivers since a passive driver is generally a novice who is reluctant to take risks. Although, new and old drivers can still be aggressive, the model was set to only a few aggressive drivers. The parameters of the driver model are open and can be changed at the beginning of a run. To this end, any crew makeup can be set depending on the simulation goal. This feature allows a mine engineer to set different crew makeup to see the impact on KPIs.

VIMS© data from 12-Feb-10 to 15-Feb-10 from Lucy mine were used to verify the model. The data contains 583 samples that were measured in every cycle. The data recorded 18 trucks for 96 hours. Lucy data gave a speed average for an empty truck of ~27 kph while a loaded truck drives at ~13 kph. Based on this information, the model was calibrated to give similar speeds. Table 9 shows the model average speed for 522 samples in a 4 days period.

Table 9. Comparison of VIMS© data to manual model output.

Data Source		V_{full} (kph)	V_{empty} (kph)
VIMS©	Ave.	13.76	27.53
	S.D.	0.88	2.25
ExtendSIM	Ave.	13.48	27.06
	S.D.	0.74	1.98

4.4.1 Assumption of Types of Drivers

The speed of trucks at Lucy mine was measured when the truck were driving full and empty (see appendix 16). This data does not specify who is driving the truck; therefore, the drive ranges are assumed in the model as it cannot be known from the data. The Lucy mine speed data of 582 samples was plotted and loaded speed is shown in Figure 10.

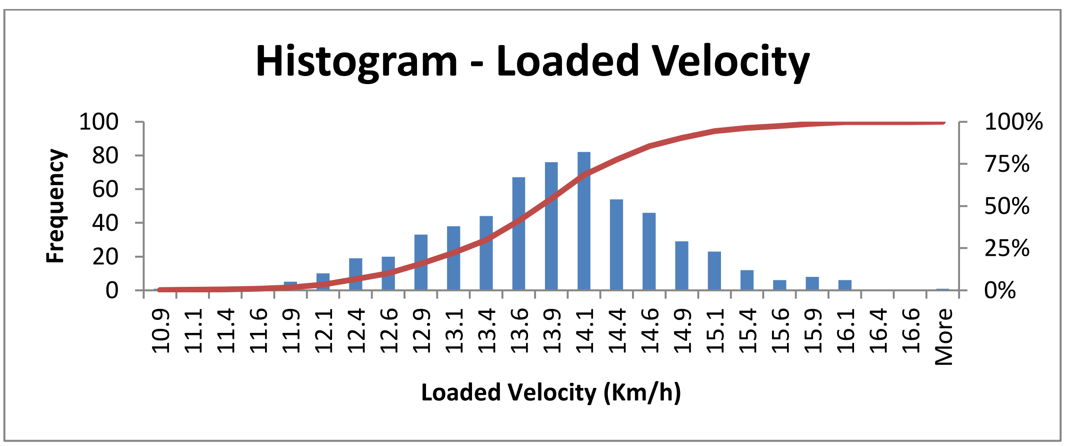


Figure 10. Lucy mine data – loaded truck velocity distribution.

The distribution shape of Lucy mine data is assumed as normal and from this information; the model reproduces a normal distribution for the all drivers speed. The distribution shape for passive is skewed to the left and the aggressive to the right.

Figure 11 shows the loaded speed of the model for 522 samples (green bar) for all drivers in 4 days of period. The model does not give exactly the same distribution as Lucy mine (blue bar). Calibrating the model is challenging, as one change made in speed will impact in many other variables, such as cycle time, fuel consumption, etc. The empty speed was also normally calibrated against the Lucy mine data. The Appendix 1 shows the details of the hypothesis test of the Model and Lucy mine data and Appendix 16 shows the data used for the verification.

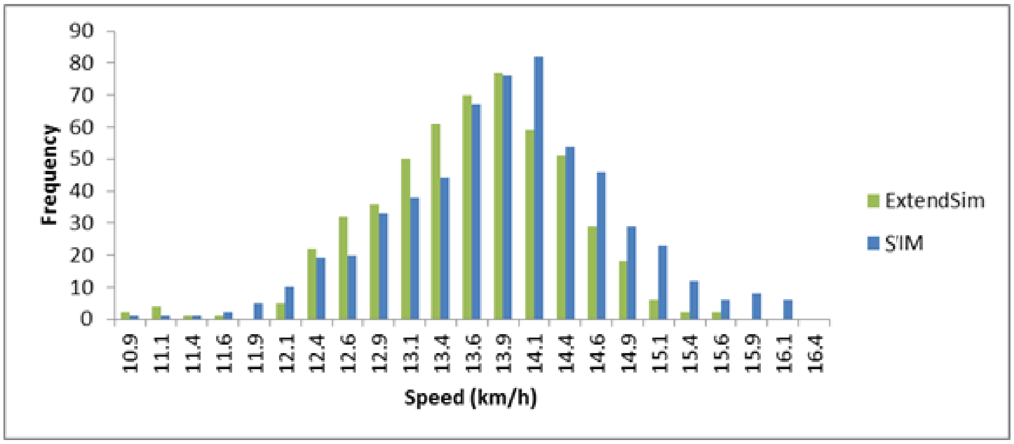


Figure 11. Empty truck velocities (VIMS data compared to extendSim data).

5 Vehicle Motion Model

This chapter explains the Vehicle Motion model. This model is a deterministic approach combined with a small increment of time used to calculate truck movement. The data required for vehicle motion include speed-rimpull characteristics of the CAT 793D haul truck together with haul road specifications such as section length, road bed quality, and maximum speed and acceleration.

5.1 Small Increment Approach

The main objective of this technique is to calculate the speed of haulage trucks by small increments of time. It is important to know the weight of the truck, its rolling resistance, grade resistance, traction coefficient, and drive axle weight distribution to calculate Rimpull forces in order to output acceleration and speed. The variable that accounts for the weight of a truck changes dynamically as it is loaded or as it dumps its load (Parreira et al., 2011). Haul road profiles such as section length, maximum speed, maximum acceleration, and grade resistance depend on the layout of the mine to be simulated as was specified in Chapter 2.

5.2 Forces Considered in the Model

In this research, it is assumed that forces acting on the truck at the road surface are as follows:

F_R = sum of all forces in the opposite direction to movement of the truck, such as:

- Rolling Resistance Forces;
- Aerodynamic Resistance Forces (wind acting in opposition to movement);
- Force of Gravity;

$$F_R = F_{RR} + F_D + F_G \qquad \text{Eq. 2.}$$

F_{assist} = sum of all forces acting on the truck in the direction of movement such as:

- Rimpull Force (Available or Required);
- Aerodynamic Forces (wind acting in favour of truck movement);
- Force of Gravity;

$$F_{assist} = F_{Rimpull} + F_D + F_G \qquad \text{Eq. 3.}$$

$$F_{resultant} = F_{assist} - F_R \qquad \text{Eq. 4.}$$

5.2.1 Available Rimpull

Available rimpull is the amount of mechanical force that the engine transfers to the transmission and drive train that is distributed to where the driven tires contact the ground (King Fahd University, 2004). Maximum speed attainable, gear range, and available rimpull can be determined from the rimpull-speed curves provided by the manufacturer (Caterpillar 3, 2007) when machine weight and total effective grade (resistance) are known.

The rimpull-speed curve of the manufacture was input to the model by approximating this curve into 12 straight lines (Appendix 5). By knowing the instantaneous speed of each time step, the model uses one of these equations to determine available Rimpull (Figure 12). For every segment, the model checks the weight of the truck (machine + payload) and total effective grade of the segment to find the maximum mechanical speed that a truck can reach (Appendix 5). Until the truck reaches this speed, the gears are changed instantaneously according to the linear equations. Note that Lucy mine is located is at an altitude of about 572m above sea level; as a result, the model does not consider derating effects (see Appendix 8).

In a case where there is an interaction with another vehicle, the truck will not achieve the maximum speed, but rather will set the truck speed to that of the front truck in order to keep speed constant and maintain a safety distance between vehicles. As well, if a road has a speed limit lower than the mechanical speed, the system will apply the road speed limit instead and set this to the maximum level.

Example: A truck is empty and on a zero grade segment, the truck could reach up to 52 kph, however the permitted speed for this road is 40 kph, so the truck will drive close to the road speed with all variations due to driver behaviour.

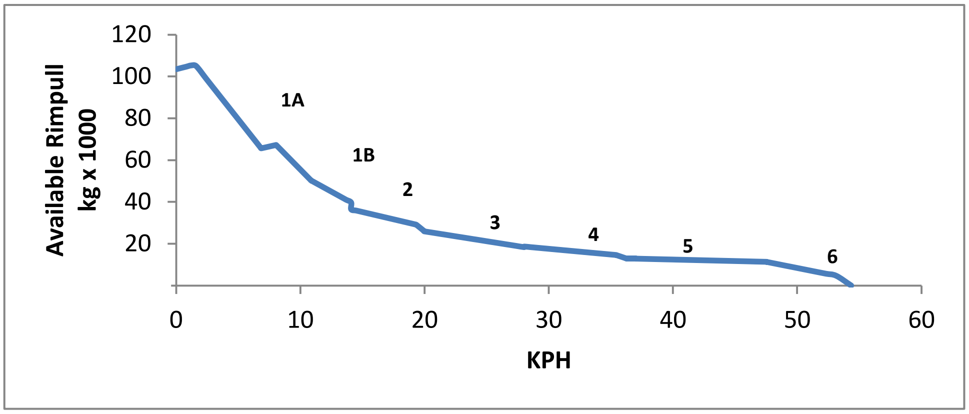


Figure 12.CAT 793D rimpull-speed curve used in the model – gears are used to engage each specific speed-rimpull range.

5.2.2 Braking Performance

When the truck is descending a grade, the maximum mechanical speed is determined from the retarder curve (Caterpillar 1, 2007) (see Appendix 5), if the machine weight and total effective grade is known. Applying the allowed mechanical speed, the brake can be used safely without exceeding the cooling capacity. The maximum allowed speeds from the retarder curve are stored in the ExtendSim internal database. When a truck is on a downhill slope, the model takes the maximum mechanical speed from this database according to the actual truck weight and actual effective grade of the road.

5.2.3 Traction Force

The total energy produced by the truck engine can be converted into movement only if there is sufficient traction between the driving wheels and the travelling surface. If traction is insufficient, the wheels will slip on the surface since the power produced by the engine is unavailable to do work (University of South Australia, 2009). The coefficient of traction between rubber tires and road surface varies according to the type of tire tread and the road surface. The traction coefficients for different road surfaces are listed in Appendix 6. The model uses a traction coefficient of 0.55 (Clay loam, dry) as baseline. This value was based on the Lucy mine weather database and road quality information. The traction coefficient changes in the model according to road conditions and weather and can drop to as low as 0.45 during a simulation run. The model uses fuzzy logic to determine this factor as described in Section 5.2.5.

When the wheels slip, there is another force to be considered, called useable Rimpull (*Ru*), which is defined as the amount of pull that the truck offers at the point where the drive tire contacts the ground (King Fahd University, 2004).

$$Ru = C_t W D \qquad \text{Eq. 5.}$$

where: Ru = useable rimpull

C_t = traction coefficient

W = truck weight

D = drive axle weight fraction (see Eq.6)

A loaded truck has 67% of its weight on the drive axle while an empty truck has 54%. The nominal payload capacity of a 793D is 218,000 kilograms and the gross machine operating weight is 383,789. Based on this information (Caterpillar 1, 2007), the formula below was developed in order to vary the weight distribution on the drive axle dynamically, according to the load of truck:

$$D = (0.13/218000)GVW + 0.442 \qquad \text{Eq. 6.}$$

where: *D* = drive axle weight fraction

GVW = Gross Vehicle Weight

After calculating the available rimpull and the useable rimpull, the smaller value between the two forces is chosen to establish the effective rimpull, i.e., the assisting force that it is actually propelling the truck (Fytas, 1983).

5.2.4 Resistive Forces

In order to determine the force responsible for truck movement, the total resistance must be subtracted from the effective rimpull. The total resistance force is defined as the required rimpull which accounts for resistance forces caused by rolling, grade and wind (air) resistances.

$$F_R = F_{RR} + F_G + F_D \qquad \text{Eq. 7.}$$

where: F_R = resistive force

F_{RR} = rolling resistance force

F_G = gravity force

F_D = drag force

5.2.5 Rolling Resistance

Rolling Resistance (F_{RR}) is the force that must be overcome to roll a wheel over the ground (King Fahd University, 2004). It is affected by road conditions and payload (Bonates, 1996); the deeper a wheel sinks into the ground, the higher the F_{RR} value. The rolling resistance for different haulage surfaces is given in Appendix 6 and can be calculated as follows (Kennedy, 1990):

$$F_{RR} = 10WCr \qquad \text{Eq. 8.}$$

where: F_{RR} = rolling resistance force

W = truck weight

C_r = rolling resistance coefficient

Truck speed depends on rolling resistance at the ground-wheel interface (Smith et al, 2004). If the road section currently has a rolling resistance higher than the mine average, thus the efficiency of a truck is decreased, and failure frequencies in equipment and tire wear increase. The categories of "cut" and "impact" tire failures are directly related to road conditions (Monroe, 1999). F_{RR} is difficult to estimate, and each mine sets its own rolling resistance value which considers the combination of road conditions and equipment (Karaftath, 1988).

The rolling resistance coefficient is set according to the factor used at the Lucy mine which represents a watered, well-maintained, hard, smooth, stabilized-surface roadway with no penetration under load. In order to keep this coefficient in the proximity of this number, water truck and grader schedules must be adjusted according to changes in road quality and the amount of water on the road. In the model, the water truck and grader are scheduled to drive through all the routes every 12 hours resetting the route rolling resistance coefficient to 2% and the traction coefficient to 0.55 (See Appendix 6). Fuzzy logic, a form of multi-valued logic based on principles of approximate reasoning (Von, 1995), has been used to calculate dynamic changes in rolling resistance and traction coefficient (see Figure 13) according to environmental conditions (precipitation).

The logic consists of a map of precipitation factors: intensity (mm) and duration (hours) of rain (or snow). These elements are passed through fuzzy sets that relate these discrete inputs to the degrees of belief (DoB) in the linguistic terms "none", "average", and "high". For each scenario, i.e., precipitation (none, average and high), a second fuzzy map is applied together with the times since watering and grading were done (none, low, medium and high). Once these DoBs are known, IF-THEN rules are applied to all combinations - precipitation low (grading x watering), precipitation average (grading x watering), precipitation high (grading x watering).

To determine rolling resistance and traction coefficient, all rules are processed and combined (defuzzified) using a MIN-MAX weighted average technique based on the input DoBs. Every time a truck enters a segment, the rules are fired and the rolling resistance and traction coefficient are applied. Note that watering and grading variables depend on the time since the water truck and grader last passed. A counter is used for this purpose in the model - when the water truck and grader pass a point on the road, the counter is reset to zero. Note that the traction coefficient calculation has the same fuzzy logic structure as rolling resistance (see Appendix 7).

Intensity (mm) and duration (hours) are reset every time a truck starts a new route. These random values are set very low as rainfall at the Lucy mine may occur, but is very rare. As well, snowfall does not occur at this location (See Appendix 15 for weather data).

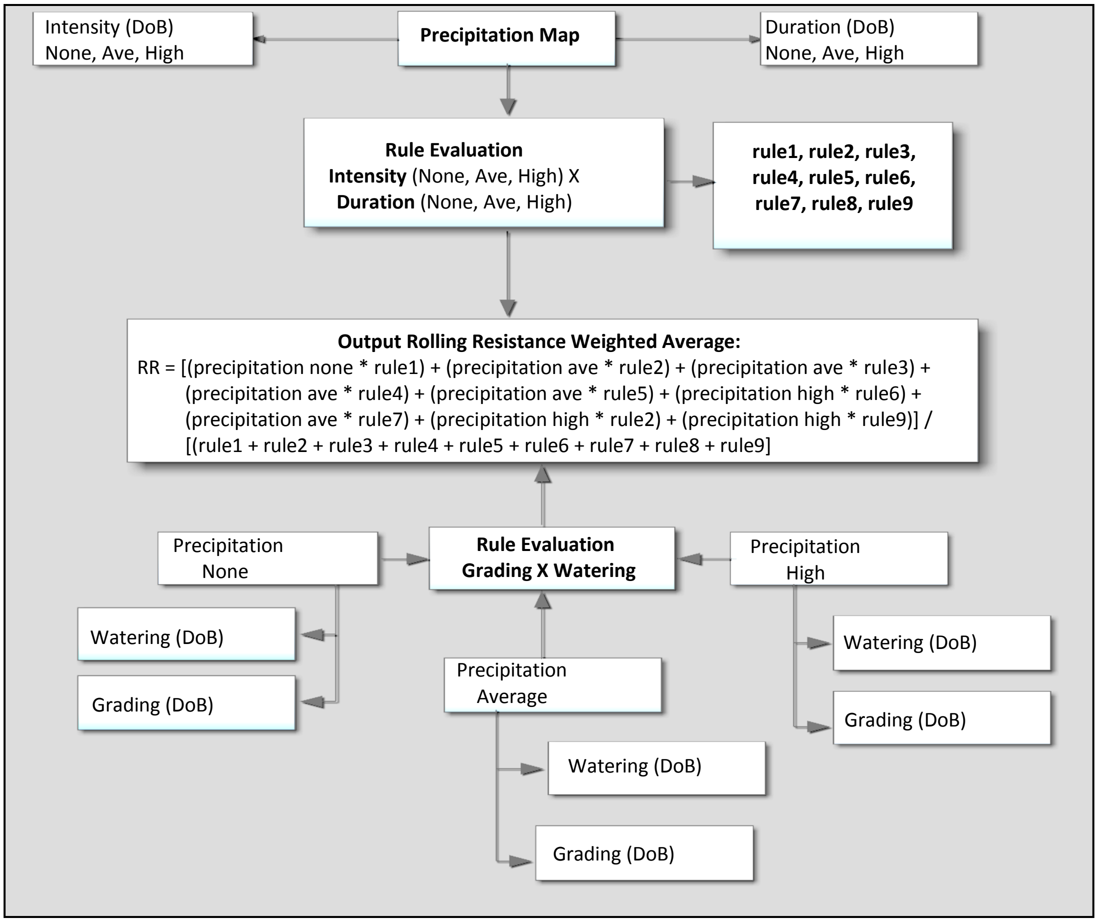


Figure 13. Rolling resistance – fuzzy logic chart (see Appendix 7).

(DoB = degree of belief; rule = net degree of truth of the rule)

5.2.6 Grade Resistance

Grade resistance is the contribution of the force of gravity - in an uphill run, this force is negative to movement while in a downhill run, gravity assists truck movement (Kennedy, 1990). Grade resistance is expressed as a function of percent grade or grade resistance factor. The grade resistance is calculated by (Kennedy, 1990):

$$F_G = 10\ WG \qquad \text{Eq. 9.}$$

where: F_G = grade force or gravity force

W = truck weight

G = grade of the road (%)

5.2.7 Drag Force (Wind Resistance)

Air tends to create resistance, although a following wind can act to assist with movement. In the case of air, the force by which wind interacts with an object is proportional to the contact surface area of the vehicle, the air density and the relative speed of the wind (Hilier, 2004). The following equation allows the model to calculate the opposing (or assisting) force to the movement of an object due to wind resistance.

$$F_D = 0.5\rho C_x A V_r^{\,2} \qquad \text{Eq. 10.}$$

where: ρ = air density (kg/m^3)

C_x = Drag Coefficient

A = frontal area of truck (m_2)

Vr = speed of the wind relative to the direction of the truck (m/s)

The greatest difficulty with this equation is to determine an accurate value for C_x. The drag coefficient may also be a function of wind direction as turbulent motion within the truck body may change drag forces acting on the truck. Since the vehicles used in surface mining are not driven at speeds above 50 kph, turbulent changes in drag forces are unlikely to affect the value of C_x. Similarly high winds (> 60 kph) generally result in suspension of mine operations, so a C_x change due to a wind speed change likely plays a minor role.

The drag coefficient for a CAT 793D is unknown, so the value was assumed according to a reference that drag coefficients of off-road truck generally lie between 0.8 and 1.0 (Engineering Tool box2). As mining trucks have a larger cross-sectional area compared to a regular haulage truck, it was assumed C_x equal to 1.0.

5.2.8 Wind Considerations

The relative speed of the wind changes according to its direction. To determine the role that wind might play in truck movement, a spreadsheet was created to calculate drag force according to different headwind speeds such as, 10, 20, 30, and 40 km/h. These numbers were chosen based on two years of data from the Lucy mine in which the average wind speed was 15.4 km/h with a standard deviation of 5.6 km/h (appendix 15). The drag force was calculated for each road segment from *Ore Shovel to Crusher* (route1); from *Waste Shovel* to *Dump* (route2); and for the reverse directions. The drag force in this exercise has considered the worst truck movement scenario. The assumptions are:

- Maximum truck speed allowed (lesser of mechanical limit and road speed limit)
- Wind blowing directly on the frontal area of the truck and parallel to the road

The results indicate that the maximum wind-produced energy occurs in the dump/crusher area where wind speed is 40 km/h blowing against the travel direction of an empty truck. In this scenario, for route shovel/crusher, the maximum wind-produced energy is 3 % of the total truck energy while for route shovel/dump, it is 2.8%. In examining a more normal situation where the headwind is 20 km/h (+1 σ), the maximum wind-produced energy for route shovel/crusher is 2.8 % while route shovel/dump shows 2 %. As such, wind energy represents a small percentage to total truck. Although these examples show a small impact on truck performance; wind variation changes have been included in the model. Every time a truck starts a new route, wind direction and wind speed is randomly set according to Lucy mine data (see Appendix 15 for weather data).

5.3 Acceleration

As described previously, in order to decompose the forces acting on a truck, the road grade must be known. The model calculates acceleration in a deterministic way for each time step. When a truck is moving on a flat road, the acceleration responsible for truck movement is:

$$Acc_{movement} = (Rimpull_{eff} - F_R \pm F_D) / M \qquad \text{Eq. 11.}$$

where:

$Acc_{movement}$ = acceleration responsible for truck movement

$Rimpull_{eff}$ = effective rimpull (smaller value of Available rimpull and Useable rimpull)

M = truck mass

F_R = resistive force

F_D = drag force (depending on wind direction)

Figure 14. Truck parallel forces when moving on a grade = 0%.

If the grade is above zero, $F_R = F_G + F_{RR} \pm F_D$. If grade is equal to zero, the equation becomes $F_R = F_{RR} \pm F_D$. The drag force depends on wind direction which either opposes or assists truck movement.

If $Acc_{movement}$ is higher than the set point, the acceleration responsible for truck movement is set as the driver maximum acceleration, which is the value set according to the design level recommended for all drivers multiplied by the driver behaviour factor.

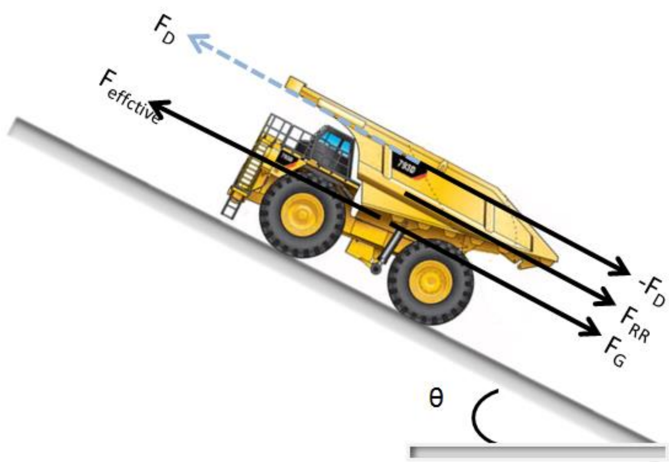


Figure 15.Truck parallel forces when moving on a grade > 0%.

After reaching the steady state speed, $Acc_{movement}$ is calculated based on the resistance force that tends to slow down the truck when on a flat or uphill drive, as shown below. For downhill, the driver applies the brake to maintain the maximum speed according to the resistive force

$$Acc_{movement} = -(F_R)/M \qquad \text{Eq. 12.}$$

Figure 16 shows the last segment of the route Waste Shovel to Parking. Segment length is 424 m with a grade of 5%. Trucks must make a full stop at an intersection before entering this segment. The driver is driving to the parking lot for his/her break and it takes about 1 minute to complete this segment. The maximum speed is 31 kph and the minimal value of the steady state condition is 29 kph. Note the graphic shows just 35 seconds of steady state motion.

The blue line in the acceleration graphic (Figure 17) represents $Acc_{movement}$. This acceleration is responsible for the slope inclination of the speed graph. Until steady state, the acceleration is 0.44 m/s^2 and at steady state, the resistance portion of the equation prevails. When drivers are in a steady state mode on an uphill or flat section, the brake pedal is used only in cases of an emergency; the small variation in speed is due to the resistance force that tends to slow down the truck. In this example, when the resistance slows the truck to 29 kph, the driver will press the acceleration pedal again to maintain the range. The resistance of this segment, which in this case is caused by grade, rolling resistance and a small amount of drag, produces a truck deceleration of 0.67 m/s^2. The total acceleration is used to calculate the fuel burned to produce movement as described in Chapter 6.

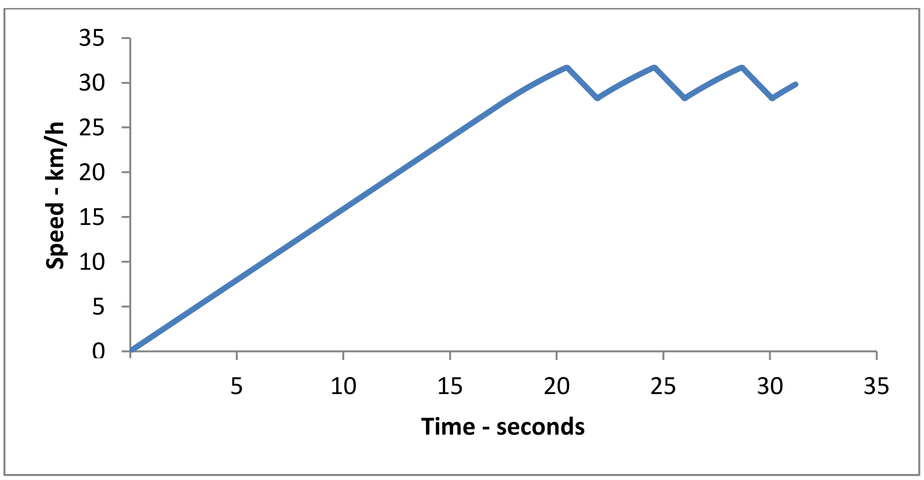


Figure 16. Speed of a truck following a full stop.

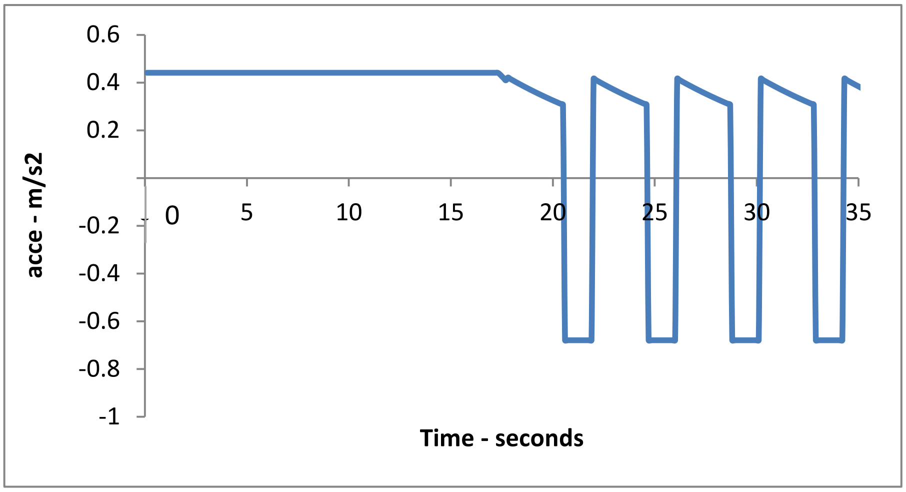


Figure 17. When in steady state, the truck decelerates according to road resistance forces.

Figure 18 shows that the engine must produce a force higher then 112kN (required rimpull) to propel the truck. This force (red line) comes about from resistance forces such as grade, ing resistance, and drag. The engine is producing about 200kN in this segment; the force takes the smaller value of the available and useable Rimpull (Fytas, 1983).

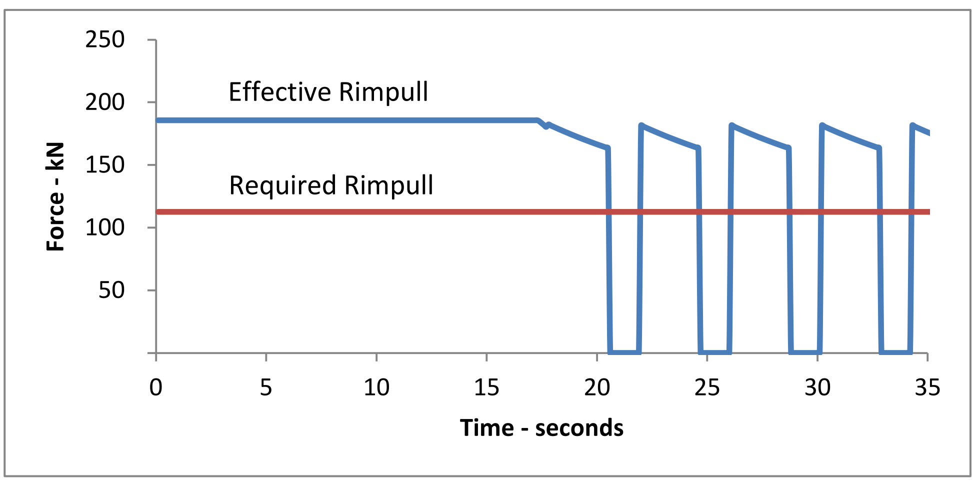


Figure 18. Blue line shows effective rimpull and red line shows the required rimpull.

Figure 19 shows an illustration of the acting forces when a truck is moving on a grade < 0. When a truck is downhill, acceleration can be calculated by the following equation:

$$Acc_{movement} = [F_{assist} - (F_{RR} \pm F_D)] / M \qquad \text{Eq. 13.}$$

where:

$Acc_{movement}$ = acceleration responsible for truck movement

F_{assist} = assisting force to propel the truck

F_{RR} = rolling resistance force

F_D = drag force (depending on wind direction)

M = truck mass

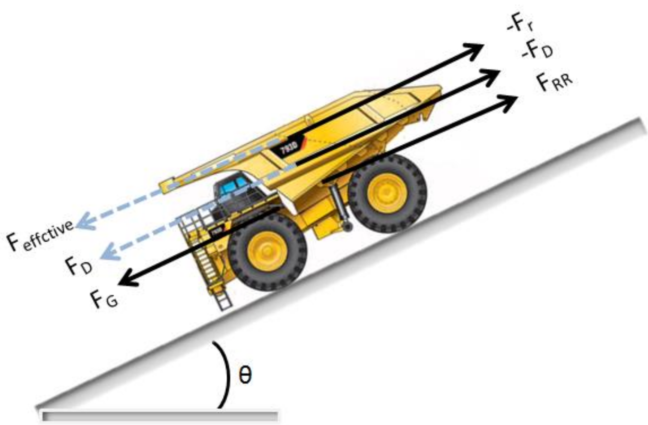


Figure 19. Truck forces when moving on a grade < 0%.

If the gravitational force (truck weight) triggers truck motion, then this force is used as the truck assisting force; however, if the weight is not enough, an extra force (rimpull) must be produced by the engine.

Figure 20 shows the first segment of the route Parking to Waste Shovel. This segment length is 424 with a grade of -5%. The driver is returning from a break and the truck starts the segment without motion. The total speed is 31 kph and the minimal of the steady state range is 28 kph. Note that the truck is in a downhill mode, so the engine is producing less power than in the previous example. Figure 21 shows that the $Acc_{movement}$ is 0.65 m/s^2 until the steady state condition is achieved. The driver then applies a minimal braking action to prevent further speed increases. In this example, the value is -0.30 m/s^2.

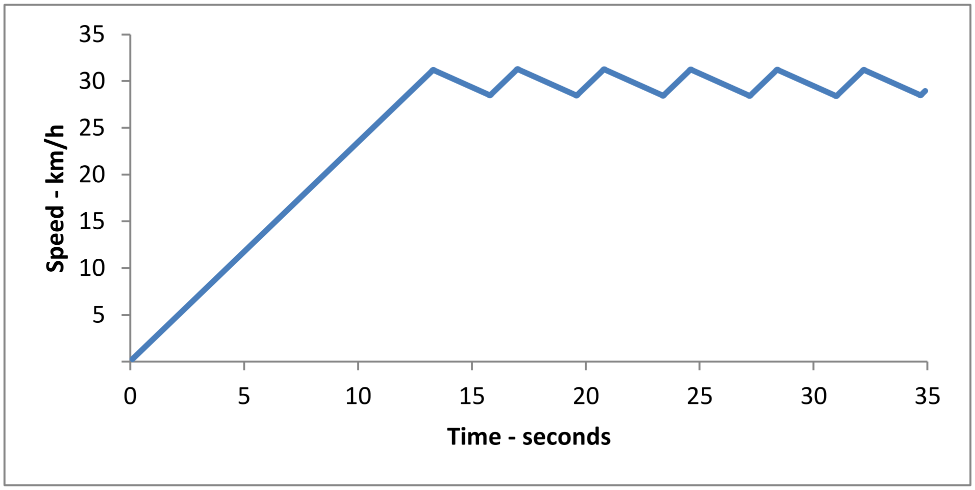


Figure 20. Speed of an empty truck after a full-stop - grade = -5%.

If the driver does not apply the brake, the resistance forces are not enough to slow down the truck since the gravitational force in this example is higher than the resistance force. The red line in Figure 22 is the required rimpull (resistances forces due to rolling resistance and a small amount of drag). In this example, the engine is producing an extra force to move the truck. When the driver presses the brake pedal, the engine only produces idling power. The blue line shows the effective rimpull, i.e., the total assisting forces used in this segment.

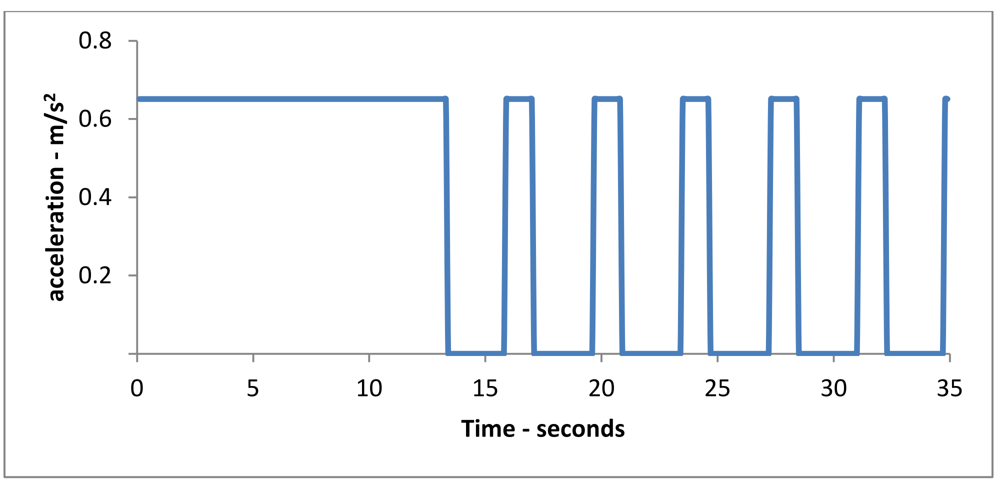


Figure 21. Acceleration of the truck on grade =-5%.

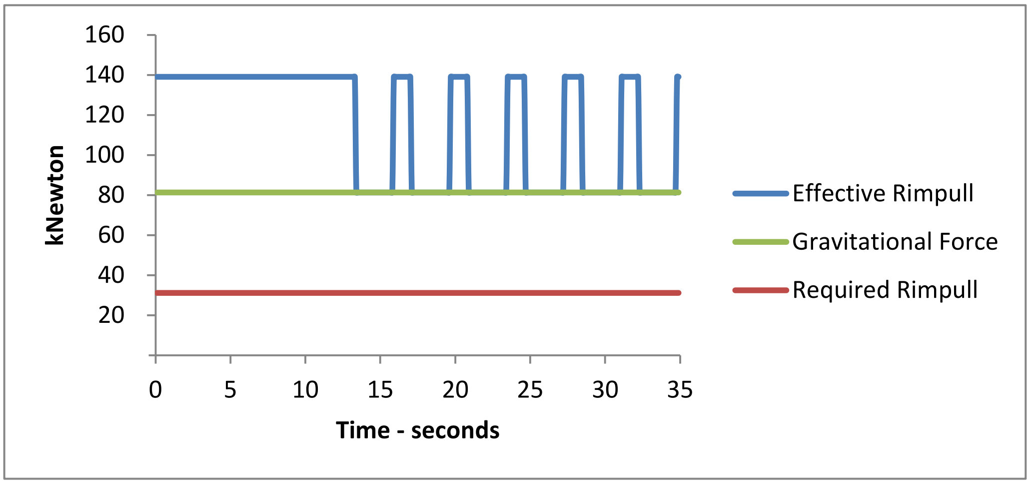


Figure 22. Forces acting on an empty truck - grade = -5%.

5.4 Kinematics

For each step change Δt, acceleration is known and so, the instantaneous speed and distance travelled can be also calculated as follows:

Speed variations over time step: $V_f = V_i \pm a \cdot \Delta t$ Eq. 14.

Position changes over time step: $S_f = V_i \cdot \Delta t \pm 0.5 \cdot a \cdot \Delta t^2$ Eq. 15.

Knowing the instantaneous speed, the acting forces can be determined and the gear, engine speed and power become known for each step change. These calculations loop until the truck reaches the end of the segment (See Appendix 9 for motion vehicle flowchart).

5.4.1 Critical Distance

Given the initial conditions of the segment such as: length, maximum acceleration and deceleration, initial and maximum speed, next segment speed, presence of a stop sign, the model applies one of the following cases to address how a truck will behave in a specific segment (see Appendix 10):

1) Given initial conditions, will a truck reach maximum speed within the segment length?

a. **Yes.** Once the maximum speed has been reached, can the truck execute a full-stop or slow down to the final required speed at the end of the road segment?

1. **Yes.** See Case 1A and 1B.
2. **No.** See Case 2.

b. **No.** Calculate a new reduced maximum speed. See Case 2.

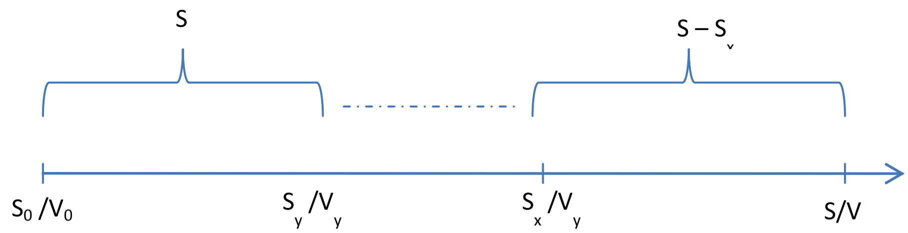


Figure 23. Case 1A: the segment is long enough for the truck to reach maximum speed.

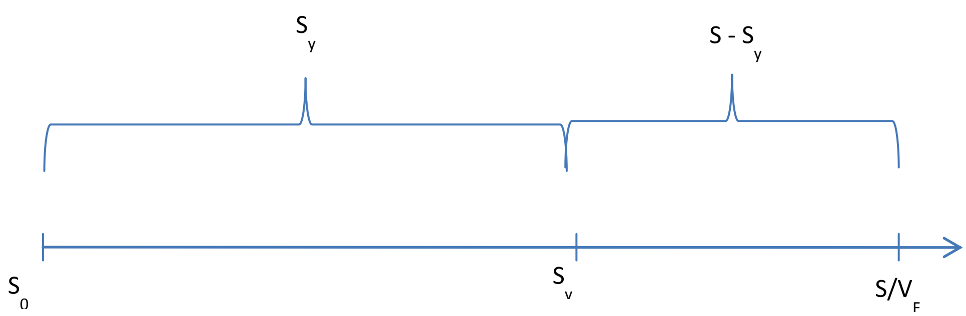


Figure 24. Case 1B: the truck reaches maximum speed but must decelerate immediately.

For case 1A and 1B, the model calculates the minimum distance (S_y) required to reach the maximum speed using the following formula:

$$(V_y)^2 = (V_o)^2 + 2\, a_1 S_y \qquad \text{Eq. 16.}$$

where:

V_y = Maximum speed of the segment. This speed is the initial speed when the truck starts decelerating.

V_o = Initial speed at the start of the segment

a_1 = Maximum acceleration allowed in the segment

S_y = Segment distance to the point where the truck reaches maximum speed

After determining S_y, the model calculates the Critical Distance ($S – S_y$): the shortest distance in which the truck can stop or reduce speed safely at the end of segment:

$$(V_F)^2 = (V_y)^2 - 2\, a_2\, (S – S_y) \qquad \text{Eq. 17.}$$

where:

a_2 = Deceleration

S = Segment length

$S – S_y$ = Critic Distance

V_F = Final segment speed

If S_y + (Critical Distance) is less than S, then the distance is sufficient for the truck to reach maximum speed and then brake or adjust speed before the end of the segment.

The model applies Case 2 (see Figure 25) when the segment length is not enough for the truck to reach maximum speed or once reached, does not allow the truck to safely reduce its speed by the end of the segment. In this case, it is necessary to calculate a maximum speed that the truck can develop so that when braking is required, the truck is able to stop or reach the speed set at the end of the segment.

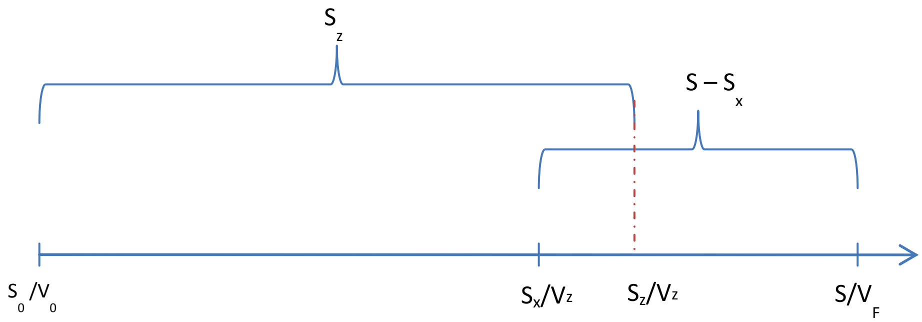


Figure 25. Case 2: length is insufficient to safely reduce or brake at the end of segment.

When this happens, the model transforms Case 2 into Case 1b. Looking at Case 1b, V_y is the final speed of the accelerating section and the initial speed from which the truck starts to decelerate. Substituting Eq. 16 for the accelerating section into Eq. 17 in the decelerating section, gives the following expression for V_F:

$$(V_F)^2 = [(V_o)^2 + 2a_1S_y] - 2a_2(S - S_y) \qquad \text{Eq. 18.}$$

With this speed, Sy can be calculated as follows:

$$Sy = [(V_F)^2 + 2\,|(a_2)|S - (V_o)^2] /[2(|(a_2)| + a_1)]. \qquad \text{Eq. 19.}$$

V_F, V_0, a_1, a_2 and S are given so once S_Y is known, the critical distance required to brake and the distance travelled before starting to brake ($S - S_y$) can be determined. To calculate the new maximum speed, the model reapplies Eq. 16. When the truck reaches the critical distance, the model checks to see if it needs to slow down due to a vehicle interaction. The Cases described above are based only on the initial conditions of the segment and do not consider vehicle interactions. However, by the time the truck reaches the critical point, it may have interacted with other vehicles on the road requiring a slowdown in order to respect the 50m following-distance requirement of Lucy mine. The model uses two routines to accommodate this situation: Option 1, (the model recalculates the deceleration rate when reaching the critical distance); and Option 2 (the maximum deceleration is maintained and the critical distance is recalculated). One of these two options is used to avoid the truck stopping before the end of the segment. Option 1 is safer while Option 2 is faster, but both reactions are present in a fleet.

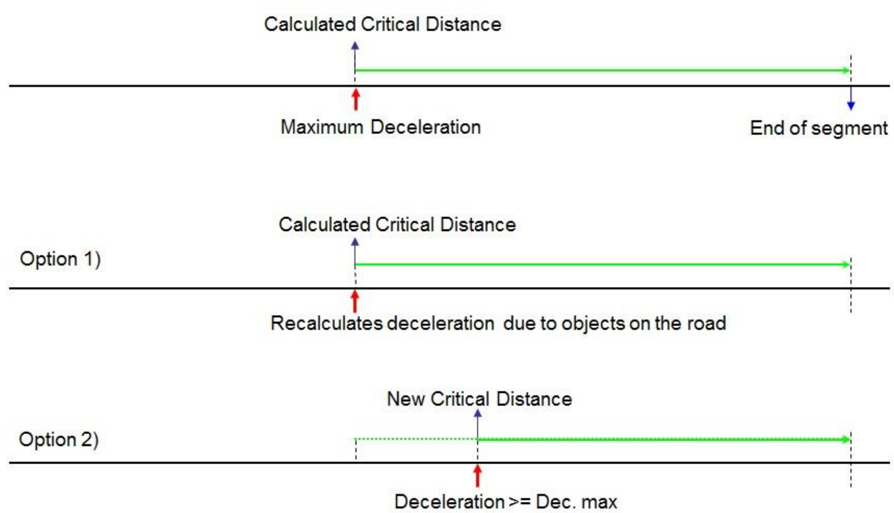


Figure 26. The model recalculates the deceleration rate or critical distance if the truck has to slow down during the segment.

5.5 Vehicle Interactions

For each time step, the safe following distance is checked for all vehicles on the road. Data such as direction, truck ID, position of the segment, actual speed, and distance travelled are stored in an internal database for all time steps. When the deterministic calculation is applied to Truck 1 for example, the model reads the data in the database, and checks for the following events:

- How many trucks are sharing the same segment?
- How many are travelling in the opposite and same directions?
- For trucks travelling in the same direction, which is the closest?

Data such as maximum and actual speed of the closest truck is then used to set parameters for Truck 1. If the safe distance is equal to or less than 50 m and Truck 1 is travelling faster, then the speed of Truck 1 is reset to that of the forward truck. Truck 1 will drive at the same speed parameters until the forward truck pulls over to the side or changes route. When this happens, the speed parameters of Truck 1 are reset. When Truck 1 reaches its critical distance, its deceleration is recalculated as described above.

This routine also checks vehicles at the start of a shift or after a break. If a truck at the parking lot is ready to move, the model checks to see if the road is clear or at least the distance to the last truck to move is 50m. If the truck at the parking lot has to wait, then this delay is added to its Cycle Time. This routine is also applied at the dump, the crusher and the shovel areas. In addition, the model counts and stores the number of interactions that each truck has encountered.

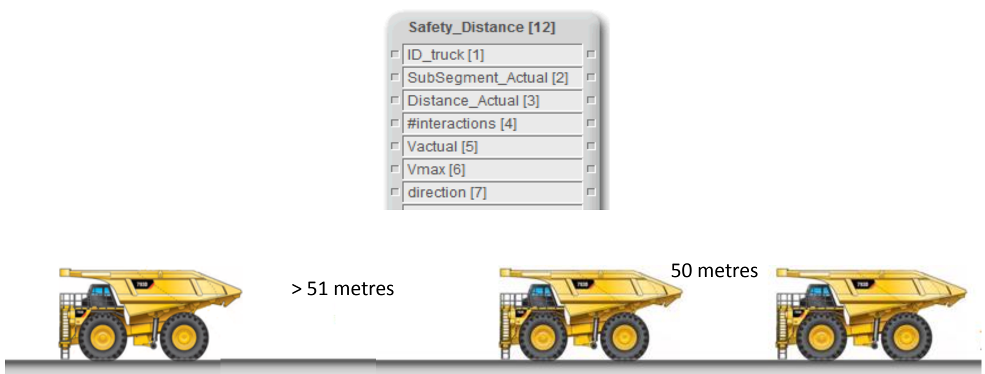


Figure 27. Safety distance between trucks.

For each time step, truck data are stored to check for safe following distance. Figure 27 shows an example of how the model works. The truck on the right sees the other two trucks, because the middle truck is 50 metres away, the right truck sets to the middle truck speed. The middle truck sees the left truck, but the distance is >50 m, so it continues using its parameters.

6 Fuel Consumption Model

This chapter describes the approach used to calculate fuel consumption based on truck manufacturer data combined with fundamental physics.

6.1 Fuel Consumption

There are a number of factors that contribute to fuel consumption such as truck load, speed, power, weight, acceleration, aerodynamics, tire conditions, road and fuel quality, idling time, wheel alignment, tire inflation, road grade, driver behaviour, outside temperature, weather, and maintenance (Kecojevic et al, 2010).

Fuel consumption can be calculated by many methods, for example, Runge (1998) and Filas (2002) used Equation 21 to find the rate of fuel consumption. Load Factors (L_F) differ: Runge states that L_F ranges from 0.18 to 0.50, while Filas claims the load factor ranges from 0.25 to 0.75 depending on driver and equipment performance.

$$F_C = P\ 0.3\ L_F \qquad \text{Eq. 20.}$$

where:

F_C = Rate of Fuel Consumption (L/h)

P (kW) = engine power (kW)

0.3 = unit conversion factor

L_F = engine factor

Hays (1990) suggested a similar equation, but he introduced Specific Fuel Consumption (SFC) and fuel density into the equation.

$$F_C = (S_{FC}\ P\ L_F) / F_D \qquad \text{Eq. 21.}$$

where:

F_C = rate of fuel consumption (L/h)

S_{FC} = specific fuel consumption

P = engine power (kW)

L_F = engine factor

F_D = fuel density

S_{FC} is the ratio of fuel flow rate per useful power output which is used in engine testing. If the useful power is measured as the net power from the crankshaft, S_{FC} is called the Brake Specific Fuel Consumption (BSFC). BSFC measures how efficiently fuel is used in the engine to produce work (Eshani et al, 2010).

As described in Chapter 5, the model uses a deterministic approach to calculate instantaneous speed, and then, it determines engine speed, power and BSFC in order to calculate fuel consumption. Fuel consumption is determined by how the driver operates the vehicle with terrain and grade playing major roles (Ghojel, 1992). At the end of a test run, the model gives the total fuel consumption for each driver and each driver behaviour type. Appendix 9 shows the flowchart of the model.

6.2 Gear Efficiency and Reduction

In order to find engine speed, the linear equations used to approximate the Caterpillar speed-rimpull Curve (Appendix 5) are used to estimate gear efficiency (Parreira et al, 2011). Efficiency is defined as the ratio of power at the axle to the power at the flywheel (Perdomo, 2001). The maximum power of a 793D standard engine is 1743 kW (Caterpillar 1, 2007). From the available rimpull and truck speed, the following equations are used to determine power (P) and efficiency (E):

$$P = 9.806 \times 10^{-3} V R \qquad \text{Eq. 22.}$$

$$E = 100P / Pmax \qquad \text{Eq. 23.}$$

Where: P = power (kW)

V = truck speed (m/s)

R = rimpull (kg)

Pmax = maximum power (kW)

E = engine efficiency (%)

An Excel spreadsheet was developed to apply the power and efficiency equations to all 14 linear equations of the Caterpillar speed-rimpull curve. For each speed/rimpull value, efficiency is given. Table 10 shows the efficiency for Gear 1B. When speed is 8.05 kph, the efficiency is

84.54%. This does not mean that gear efficiency is precisely this value since the engine may not be at peak torque. The higher efficiency of the gear range is chosen as the gear efficiency which in this case is 86.78% which occurs when available rimpull is 57,510 kg and speed is 9.66 km/h. (See Appendix 11 for the entire spreadsheet).

Table 10. Estimating gear efficiency.

Equation for Gear 1B*	km/h	Rimpull (x 1000)	Efficiency	Reduction Ratio	RPM	Power (kW)	BSFC
R(v) = 255,36 - 21,43*V	8.05	67.23	84.54%	121.4	1458	1698	201
	8.45	64.8	85.56%		1531	1718	202
	8.86	62.37	86.27%		1604	1733	203
	9.26	59.94	86.68%		1677	1741	206
	9.66	**57.51**	86.78%		1750	1743	212
	10.06	55.08	86.57%		1823	1698	219
	10.47	52.65	86.06%		1896	1718	227

**Linear equations of 1B gear taken from the Caterpillar speed-rimpull Curve. Appendix5.*

After estimating the gear efficiency, the reduction or gear ratio can be determined. Reduction ratio (R_r) is flywheel speed to axle speed and can be calculated by the following equation (Perdomo, 2001):

$$R_r = (RPM_{rated}\ 2\pi\ r) / 60\ V \qquad \text{Eq. 24.}$$

where 2π is used to convert angular into horizontal speed; r is the radius of the tire type 40.00R57 which is 1.778m (Caterpillar 3, 2007); the constant 60 is used to convert RPM into RPS; and RPM_{rated} for a 793D standard engine is 1750 RPM (Caterpillar 1, 2007).

In the example above, the R_r = (1750 x 2π x 1.778)/ (60 x 9.66/3.6) = 121.40. The gear reduction is based on the highest efficiency of the gear.

After estimating the reduction ratio and efficiency, the engine speed in RPM can be determined from: (Perdomo, 2001)

$$RPM = (R_r V) / 2\pi r \qquad \text{Eq. 25.}$$

For the above example, RPM = 121.40 x 8.05/(2π x 1.778) = 1458. To validate this approach, the instantaneous power according to the following formula was calculated and compared to the real Caterpillar data.

$$P = RV / E \qquad \text{Eq. 26.}$$

Where: P = power (kW)

V = truck speed (m/s)

R = rimpull (kg)

E = engine efficiency

The information of power and engine speed is available from the manufacture. From this data, linear equations were obtained to represent power-rpm variation. The model uses these series of linear equations to find instant power (Appendix 12).

BSFC and engine speed variation of the 793D is also known by the caterpillar data. This data was also input in the model by a series of liner equations. After determining RPM in the model, the BSFC is obtained. The model calculates BSCF and power for every step change. See Appendix 12 for the actual BSFC-RPM and Power-RPM linear equations.

After calculating the BSFC and engine power, the model applies the following formula to calculate the fuel consumption rate (L/hour) on each time step. Fuel consumption in the model is directly proportional to delivered net power.

$$F_C = (BSFC_{instant}\ \ P_{instant}) / F_D \qquad \text{Eq. 27.}$$

where F_D is fuel density. According to Hays (1990), diesel fuel density can range from 0.84 to 0.96 kg/L. A constant value of 0.85 kg/L was assumed based on diesel type used in Lucy mine diesel.

6.3 Fuel Consumption due to Movement

Uphill driving is responsible for the highest fuel consumption in a mine, as the engine must produce enough power to overcome both rolling resistance and gravitational forces and the trucks are fully-loaded. Downhill runs have a significantly lower consumption rate especially if the grade is steep enough such that gravity does all the work and no engine power is necessary to move the truck (Terex, 1970). Figures 28 and 29 show a segment length of 424 and grade of 5%. Figure 28 shows driver speed variations while Figure 29 shows the instantaneous net power for this segment. Note that when the driver decelerates, power drops to ~111 kW which represents idling conditions.

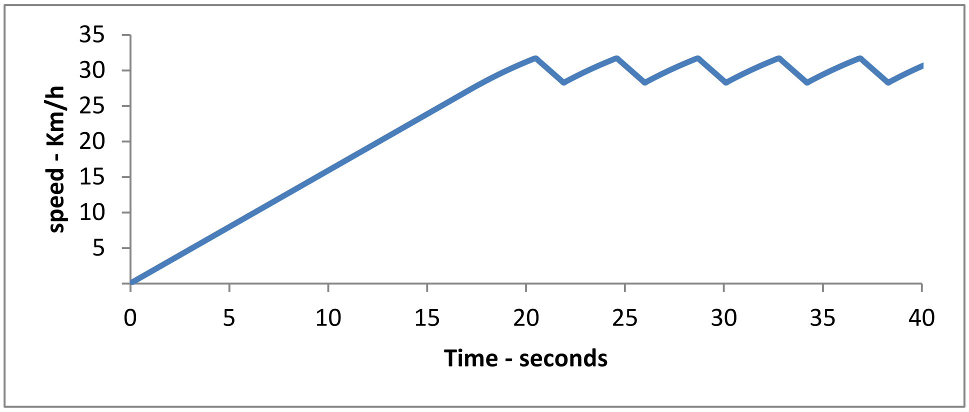


Figure 28. Speed variations for a segment of 424m, a 5% grade, and an empty truck.

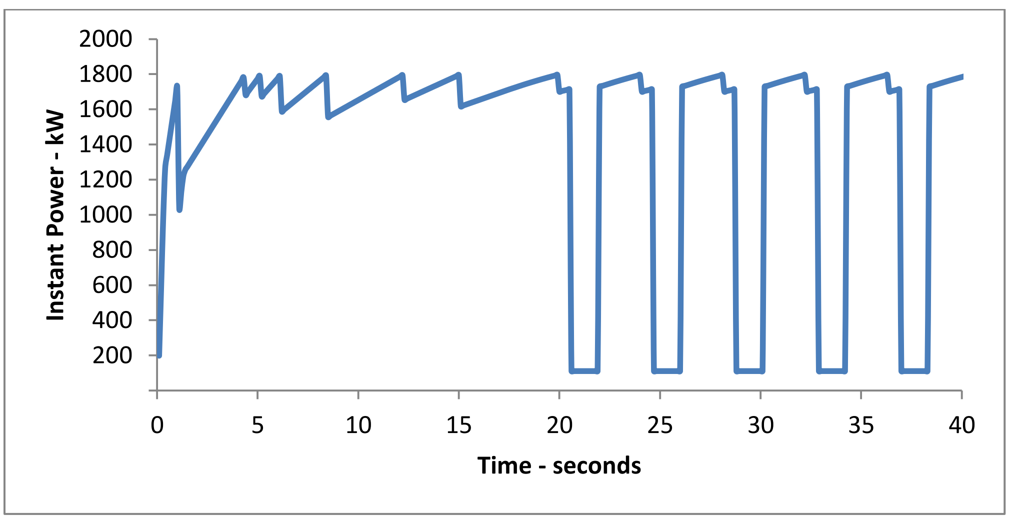


Figure 29. Instantaneous power for a segment of 424 m, 5% grade, and an empty truck.

For this example, the average fuel consumption rate is 307 L/h and when idling, this drops to 27 L/h in accordance with the mine prediction. In total, the truck consumed 5.57 L of diesel and took 62 seconds to complete the segment.

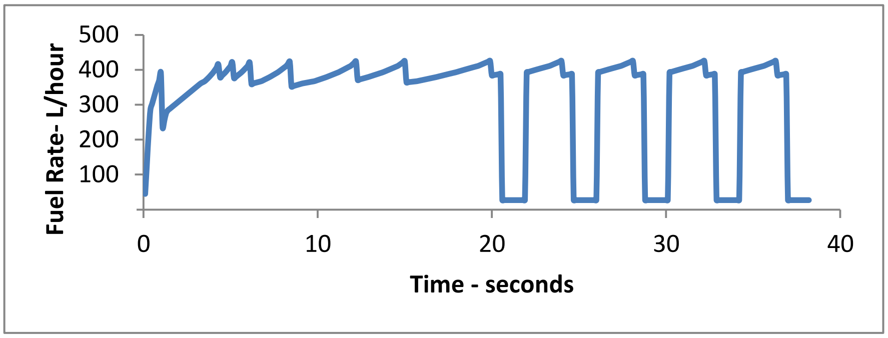


Figure 30. Instantaneous fuel consumption for empty truck on a 424 m segment at 5% grade.

Driving in the opposite direction on this same segment, the grade becomes -5%. Note that the engine produces only the extra power that the truck needs to move. The gravitational force is doing much of the work and the engine only produces an average of 400 kW to propel the truck. The fuel consumption rate is about 54 L/h and total fuel consumed for this segment is 1.5 L. The driver took 60 seconds to complete the segment.

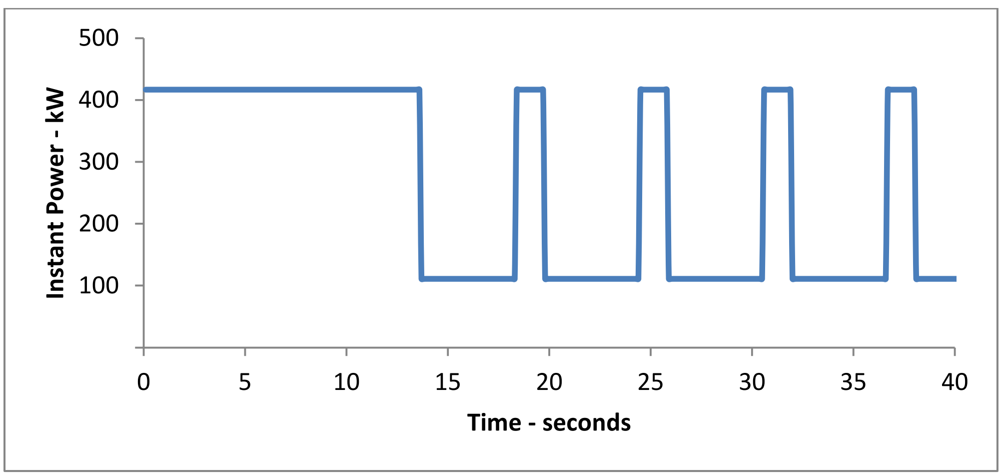


Figure 31. Instantaneous power for an empty truck on a 424m segment at -5% grade.

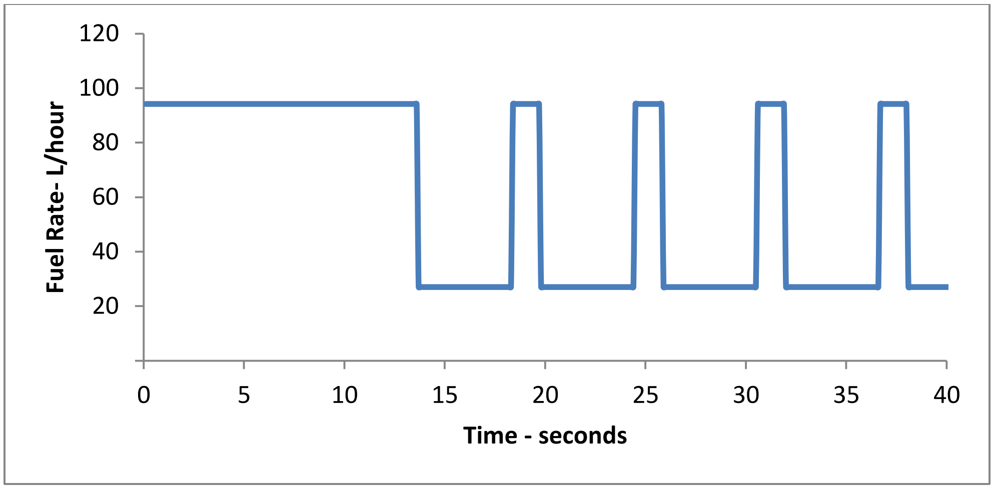


Figure 32. Fuel consumption for a 424 m segment at a grade of - 5% and empty truck.

In another example, the grade is -10%, the segment length is 130 meters and the truck is empty. The gravitational force is enough to move the truck and so, the engine only produces idling power of 111 kW. Average fuel consumption rate is 27 L/h and total fuel use is 0.18 L. The driver took 24 seconds to complete the segment. Note that idling is about 10% of the instantaneous power (Hays, 1990). The model also assumes idling fuel consumption when the truck is queuing, dumping, loading and refuelling.

6.4 Fuel Tank Decrement

The fuel tank level is set to full at the beginning of each simulation test. During each time increment, Δt, the consumed fuel is known from the fuel consumption algorithm and is decremented from the fuel tank volume. When the level reaches 10% of capacity, the truck must dump its load and advance to the refuelling area. This check is made at the dump or crusher location. According to the Caterpillar manual, the 793D tank has a capacity of 4,354 L (Caterpillar 1, 2007).

6.5 Verification of the Fuel Model

VIMS© data from 12-Feb-10 to 15-Feb-10 from Lucy mine were used to verify the model. Figure 33 shows in blue the fuel consumption rate average of the Lucy mine is 229 L/h with standard deviation of 27.23 L/h. The green line shows the fuel consumption rate of the model.

The model was run under similar topography and the output shows 234 L/h, with standard deviation of 23.55 L/h. Fuel consumption in the model varies with behaviour and, the makeup of the crew which is set at the beginning of each run determines the average output. For this reason, the model fuel consumption is slightly higher (2.2%). Although the averages are slightly different, the distribution is very similar to the VIMS© data range.

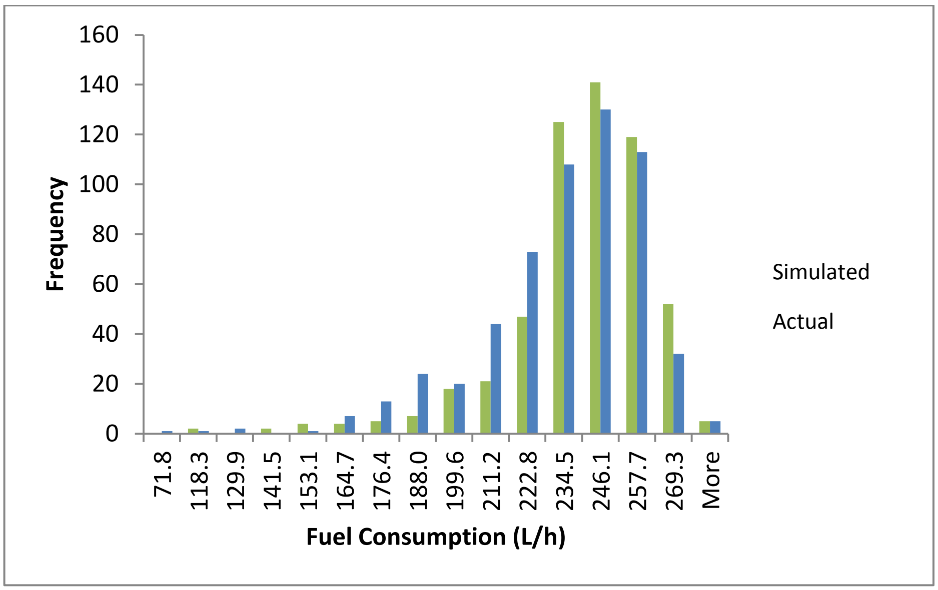


Figure 33. Fuel consumption comparison.

7 Tire Wear Model

7.1 Background

Tires significantly impact mine haulage economics and can represent as much as 20% of operating costs and more than the initial capital purchase of the truck over the life of a machine (Bauer, 2012). Wear depends on a variety of factors such as driver skill, climate conditions, maintenance, etc. Proper tire selection: tire size, tread design, tire material, carcass design, as well as good maintenance are all important attributes. The model developed in this research assumes use of typical CAT 793D tires – 40 R57 (see Appendix 23 for tire construction).

Grosch (1992) states that tire wear is largely caused by fatigue. Tire wear occurs in three major ways in which the intrinsic factors of load, speed, and tire temperature interact across all of the following mechanisms: abrasion (erosion); cutting and impact; and ablation (Veith, 1992). Abrasion occurs by attrition of rubber as the tire surface rubs against the road surface. The roughness of the road surface affects this mechanism substantially, but is reduced significantly in wet weather. Erosion is greatest with rocky surfaces and least with smooth or sandy surfaces. Cutting and impact failures occur when a tire runs over a large jagged rock at speed. This type of failure can be catastrophic if a high tire temperature exists at the time and may result in a blown tire or an explosion. Higher tire wear of an uneven nature occurs during cornering; the more corners and the longer their length, the greater the tire wear due to side slip as the truck navigates through each corner. Super-elevation of the road can eliminate or minimize this effect and allow vehicles to maintain speed while cornering (Kennedy, 1990).

As a truck moves, heat is generated from contact with the road surface and from flexing of the tire sidewalls. This heat is generated faster than it dissipates into the atmosphere from the rubber surfaces and will concentrates in the ply or belt. If the tire does not cool down, excess heat can cause tire failure. As tire temperature increases, rubber loses strength and tires may experience failure during cornering or braking; from impact or cutting from rocks on the road; from fatigue of the steel belts; and from separation of the belts from the rubber.

Tire wear can be characterized in a number of ways (Meech et al., 2013):

- Tread depth in mm;
- Tire wear rate in mm/10,000 km;
- Tire wear rate in mm/10,000 tonnes;
- Tire wear rate in mm/tonne/10,000 km;
- Tire life in months or days or hours;
- Tire life in terms of total service hours or kilometers driven

The most useful term for modelling is mm/10,000km while tire life in hours or kilometres driven is generally used in practice. With a mine haulage truck, typical tire life averages about 5,500 hours of operation at an average speed of 20 kph (15 kph loaded and 25 kph empty). This means with proper care (tire inspection, tire rotation, proper inflation and monitoring) 100,000 km or more service driving can be achieved (Meech et al., 2013). Regarding tire rotation, Zhou applied statistics to determine optimum tire rotation at two different mines. The results of this research showed that tire life increases and age-specific tire wear decreases in two different mines when tire rotation is used. He also identified that the sequence of the rotation influences tire life, tire rotation sequence acronyms were developed to assist in analyzing and determining tire rotation sequence (Zhou, 2007). With a utilization of 60% of which about 90% involves actual vehicle movement, tires need to be replaced in about 13 months. This can range from 8 to 15 months depending on road conditions, individual truck utilization and maintenance.

Tire temperature increases due to friction of the tread with the road surface as well as the cyclic flexing of the sidewalls as the tire rotates. The higher the speed, the faster that heat enters the tire through the surface. Temperature is affected by both load and speed while the ambient temperature is important in affecting the rate of cool-down (heat transfer from the tire to atmosphere). The rate of cool-down increases with temperature difference between the tire and the atmosphere so, as the atmosphere cools at night, the rate of heat transfer from a hot tire increases which can cause tire temperature to decline rapidly. Tire temperature affects normal wear in a very negative way, typically on an exponential basis. Cycle times with a significant idling component (10-15%) can give some control allowing tires to cool down from points of danger (Meech et al., 2013).

With an AHS system, the number of cycles per day should increase. Currently at the Lucy mine, each truck averages about 21 cycles per day (equivalent to a production rate of about 4,520 tonnes). An AHS truck should deliver about 26 loads per day - an increase of about 1,100 tonnes (~24%) of added production. The question is whether this added intense activity will lead to a higher overall tire temperature that would impact negatively on tire wear. Evidence from model testing suggests that the lower speeds (14 kph loaded/23 kph empty) of an AHS relative to a manual system (15 kph loaded/25 kph empty) will compensate for the increased activity (more operating time and less idling).

7.1.1 Manufacturer and User Method for Temperature Control

All manufacturers recommend that haul truck operators maintain driving conditions below a TMPH (or TKPH) rating assigned to each tire type. TMPH = Tons-Mile-Per-Hour while TKPH is Tonnes-Kilometer-Per-Hour.

TKPH is a rating of the amount of work done under given conditions but it is really a measure of momentum or force. It can predict tire temperature build-up. The formula is:

$$\text{TKPH} = \text{Mean tire load} \times \text{Average work day speed} \qquad \text{Eq. 28.}$$

where:

Mean tire load = (load empty + load full)/ 2 (in metric tons (tonnes))

Average work day speed = Cycle distance (in km) x cycles/day / operating hours (in kph)

Table 11 shows TKPH ratings for type E4 by Goodyear, Michelin and Bridgestone. The conventional TKPH calculations tell the user very little and serve merely as an alarm (Joseph, 2012). If drivers appear to exceed this rating on a regular basis, their truck will usually have the 5^{th} gear disabled to prevent excessive speed (Meech et al., 2013). The calculation can be done automatically by a Vehicle Monitoring System, but relies on data that may not be of high quality (time duration issues) and it is rarely applied accurately in a dynamic way (Meech et al., 2013). The use of tire temperature sensors is now becoming more prevalent and will likely preclude this approach in the future.

7.2 Effect of Speed and Temperature on Tire Wear Rate

The heat transfer coefficient (H) between a tire and air at a speed of 48 kph is generally accepted to be 57.12 W/mm^2·K (Yeow et al, 1977), (Schallamach, 1967). Some research claims that H is dependent on speed. In this work, it was decided to ignore speed effects on H since the cool-down period during idling (i.e., zero speed) is, perhaps, one of the most important elements in this analysis (Meech et al., 2013). Other work has considered different heat transfer coefficients for the circumferential heat loss and for transfer of heat between the wheel and the air inside the tire. These details have also been ignored in this analysis.

Table 11. TKPH for an E4-40.00R57 tire from different manufacturers.

Manufacturer:	Tire type: E4 – 40.00R57		
Goodyear	**2S**	**4S**	**6S**
RL-4H or RL-4H II	792	599	365
Bridgestone	**E2A**	**E1A**	**E3A**
VELS	533	648	770
VELSL	-	723	916
VZTS	533	648	770
Michelin	**A**	**B4**	**B**
XDR	529	661	794

The analysis begins with the "best" available data published in the literature on the impact of speed and temperature on tire wear (tread wear) – a 1928 report from the Miller Rubber Company published in Popular Mechanics. Over the years, tire manufacturers have been rather secretive about these relationships. Undoubtedly, considerable improvement in tire construction and rubber compounds have affected these relationships, but little sharing of the data in a useful form has been forth-coming. Table 12 lists the Miller tire data as reported. The units of wear were reported per 1,000 miles but the depth measurement unit was not given. It has been assumed the data are in mils/1,000 miles.

Table 12. Data extracted from Miller Rubber Company – 1928.

Original Data - Miller Rubber Company mil/1,000 miles**				
Speed - mph	Temperature °F			
	40	60	80	100
0	0.00	0.00	0.00	0.00
5	0.14	0.21	0.32	0.46
10	0.40	0.62	0.94	1.38
20	1.01	1.61	2.47	3.67
30	1.72	2.77	4.29	6.44
40	2.58	4.19	6.53	9.85
50	3.62	5.89	9.22	13.96
55	4.21	6.87	10.74	16.28
60	4.87	7.94	12.44	18.88

**Load (weight of vehicle) not given. Assumed to be 2268 kg (5,000 lb), i.e., 567 kg per tire.*

*** Mil represents a thousandth of an inch (English system)*

Figure 34 presents a graph of this data and the correlation as reported. Figure 35 shows the same data converted into SI units and re-plotted to show the equations for each temperature in a form that can be used to gain a better understanding of how a tire wears.

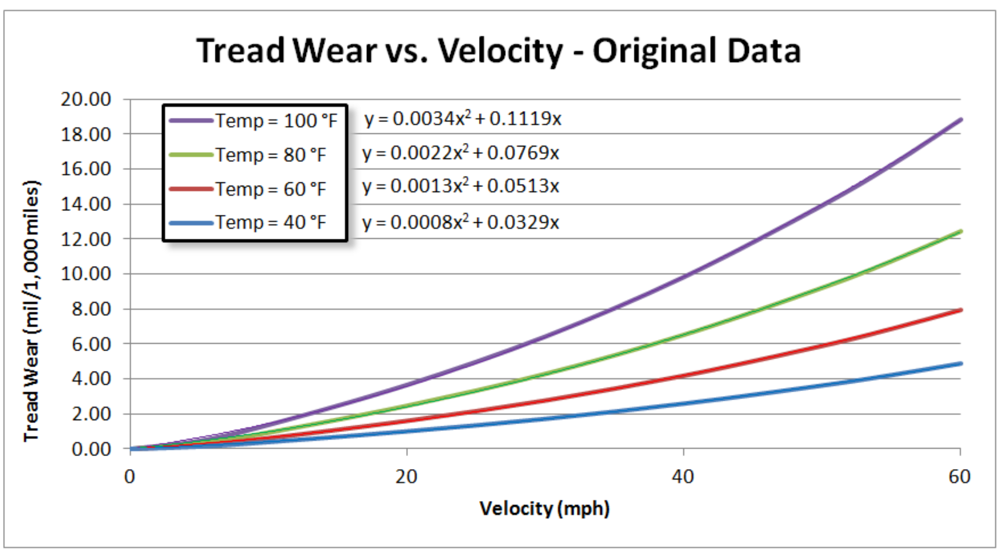


Figure 34. Original tread wear data as a function of temperature and speed as reported by the Miller Rubber Company (Popular Mechanics, 1928).

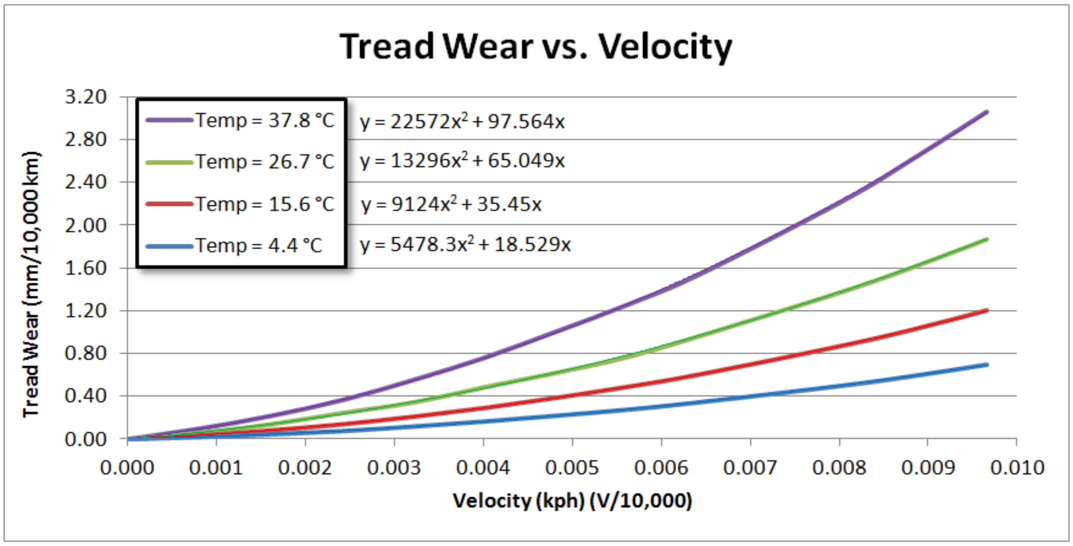


Figure 35. Tread wear data converted to SI units as a function of temperature and speed as reported by the Miller Rubber Company (Popular Mechanics, 1928).

The coefficients in the equations shown in Figure 35 have been analyzed with respect to temperature using a thermodynamic-kinetic approach. An Arrhenius equation has been applied to each coefficient to represent the "activation energy" required to wear rubber from a tire. These relationships are shown in Figure 36.

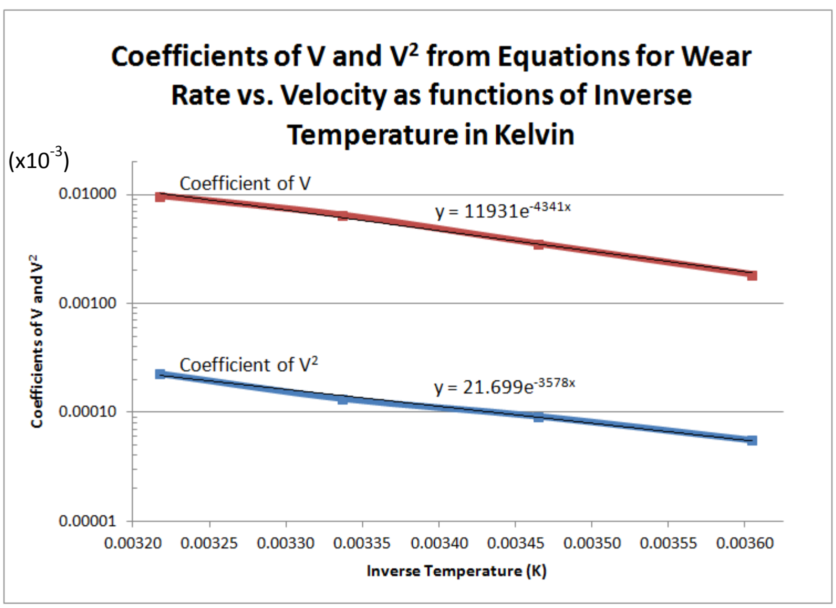


Figure 36. Coefficients of V^2 and V in the equations for wear rate vs. speed as functions of inverse temperature measured in Kelvin.

As can be seen, correlation of these two equations is extremely high with R^2 values of 0.995 in both cases. The final derived equation for the Miller Rubber Company data (after including the gas constant R (1.9859 cal/K·mol) is given in Equation 29:

$$\text{Wear Rate} = 21.699V^2e^{-7,106/RT} + 11,931Ve^{-8,621/RT} \qquad \text{Eq. 29.}$$

The exponent values in the two parts of Eq. 29 represent the activation energies necessary to wear rubber from a tire in two different modes – from energy that flows through the tire and from the force exerted on the rubber-road interface. The coefficients in the equation are measures of how the energy used to drive a truck results in increased wear rate (V^2 is representative of energy) and how the force (or load) affects wear rate (V is representative of momentum). What is interesting about this equation is that it represents two temperature effects on the tread wear rate: one term that depends on energy (represented by speed^2); and a second term that depends on momentum or force (represented by speed). This suggests two different mechanisms of wear are inherently embedded within the data. The part due to momentum is likely an ablation mechanism in which rubber volatilizes as temperature increases with load (tire pressure and weight), while the other part is due to energy flow through the tires, part of which abrades particles off the surface. The strength of rubber declines as temperature increases, hence tire wear rate by abrasion also increases with increasing temperatures. Saibel et al (1969) stated that if temperature changes from 30^o C to 60^o C, the wear rate may change by up to 50 times. This is explained by molecular-kinetic theory in which abrasion occurs due to failure of chemical bonds because of fluctuations in thermal movement of molecules.

Table 13 shows the predicted wear rate as a function of temperature and speed over the range of interest in open pit mining (from 0 to 30 kph and from 5 to 95 °C). The upper temperature represents tire conditions that most mines try to keep well away from. Table 14 shows the percentage of tire wear that takes place according to the momentum term in Eq. 29. The model shows that tires wear mainly because of the momentum term. As temperature increases at a constant speed, the load on the tire leads to an increased contribution to tire wear. The effect of load will be discussed in Section 7.3.

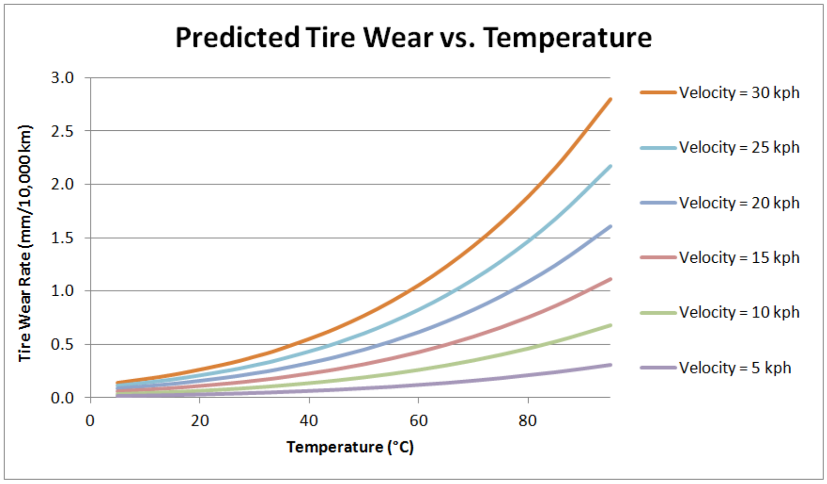
Table 13. Wear rate predicted by Equation 29 (see Figure 37).

mm/10,000 km										
Speed Kph	**Temperature °C**									
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.011	0.019	0.031	0.050	0.077	0.117	0.171	0.247	0.348	0.482
10	0.025	0.043	0.070	0.110	0.169	0.253	0.370	0.531	0.746	1.029
15	0.042	0.071	0.114	0.144	0.274	0.409	0.597	0.852	1.193	1.641
20	0.062	0.103	0.166	0.208	0.394	0.585	0.850	1.210	1.689	2.318
25	0.084	0.139	0.223	0.280	0.528	0.781	1.131	1.605	2.235	3.059
30	0.109	0.180	0.288	0.360	0.676	0.997	1.440	2.038	2.831	3.866

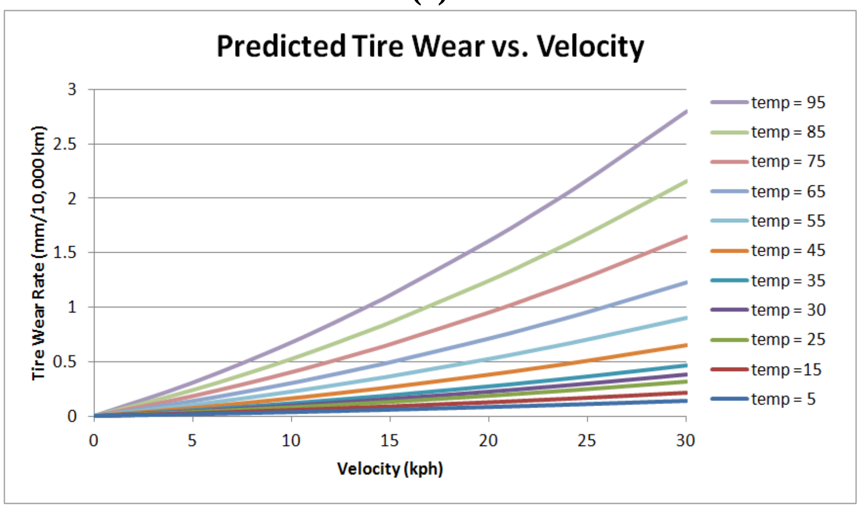
Table 14. Percentage of total wear rate due to the momentum term in Equation 29.

Percentage										
Speed kph	**Temperature °C**									
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**
0	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	87.6	88.6	89.5	90.2	90.9	91.5	92.0	92.5	92.9	93.3
10	77.9	79.5	80.9	82.2	83.3	84.3	85.2	86.0	86.7	87.4
15	70.2	72.2	73.9	75.5	76.9	78.2	79.3	80.4	81.3	82.2
20	63.9	66.0	68.0	69.8	71.4	72.9	74.2	75.4	76.5	77.6
25	58.6	60.9	63.0	64.9	66.6	68.2	69.7	71.1	72.3	73.4
30	54.1	56.4	58.6	60.6	62.5	64.2	65.7	67.2	68.5	69.7

On the other hand as speed increases at a constant temperature, the contribution of momentum on total wear declines. This means the impact of ablation increases more with a temperature increase than with a speed increase while the impact of abrasion increases less with a temperature increase than with a speed increase. It must be remembered however, that tire temperature is linked to speed and load such that as a truck speeds up, the temperature will also rise. Thus, the rate of tire wear will increase across this data set in a diagonal direction from left-top to right-bottom (see shaded cells in the table). This explains part of the reason that trucks should not drive up-hill loaded with material at speeds greater than 15-16 kph.



(a)



(b)

Figure 37. Model prediction of tire wear as a function of (a) temperature and (b) speed.

7.3 Effect of Load on Tire Wear Rate

The literature contains very limited data on the influence of load on tread wear rate. Much of the data deals with the importance of tire pressure to balance-off the load. Both under- and over-inflation leads to increased wear likely due to higher operating temperatures in the case of over-inflation and reduced tire circumference in the case of under-inflation. The relationship is reported as linear, but dependent on temperature and speed according to many reports. The weight of a 1928 vehicle is estimated at 2,268 kg on 4 tires. So the load on each tire is estimated at 567 kg. The road surface contact area of a Miller Rubber Company tire is estimated to be 232 cm^2 (~6" x ~6"), so tire load (pressure) on this surface is 2.44 kg/cm^2.

The weight of an empty and full CAT793 truck varies from 180 t to 400 t respectively distributed on 6 tires. So the load on each tire varies between 30 and 67 t. Taking into account the reported weight distribution of 40:60 (front:back) when full and 45:55 (front:back) when empty, the load can be as high as 80 t on the front tires. The surface contact area of a CAT793D truck is 15,000 cm^2 (~100 cm x ~150 cm), so the load (pressure) varies from 2.00 to 5.00 kg/cm^2. Note that this range overlaps that calculated for the Miller Rubber Company analysis. So the ratio of tire wear rate between a regular automobile tire and a CAT793D tire due to changing load (pressure) characteristics will vary from 0.82 to 2.05.

A second factor to be considered is the influence of tire diameter. The difference in the number of times per kilometer that an element of the tire surface meets the road is significant. For the Miller data, the tire diameter is estimated at 0.67 m, so the circumference is approximately 2 m. A CAT793D tire has a diameter of 3.7 m, so its circumference is 11.6 m. For a travelled distance of 1 km, a regular tire revolves 500 times while a CAT793 tire revolves 86 times. So for each kilometer travelled, a tire element on a regular vehicle meets the road surface 5.8 times more than that of a tire element on a CAT793 truck. Countering this lower contact frequency is the fact that the element is in contact for a greater distance with a CAT793 tire than for a regular tire. This contact percentage is 7.27% of the circumference for a regular tire and 12.89% for a CAT793 truck tire, i.e., about 1.77 times more contact per revolution. This yields a ratio of 0.305 (1.77/5.8) for the CAT tire compared to a regular tire. However, the CAT tire is much wider than a regular tire so that must be accounted for as well. A CAT tire is 1 m in width compared to a width of ~0.25 m on a regular tire. So the ratio of tire element contact is 1.22 (0.305/0.25) for the CAT tire compared to a regular tire.

Road surface conditions must also be taken into account. The measurements reported by the Miller Rubber company were for an asphalt road surface which is smooth and with no significant discontinuities. A mine haulage road consists of rocks of varying sizes that presents a much rougher surface that impacts negatively on tire wear rate. Maintenance of the road through grading and watering can help maintain a more consistent surface (and perhaps a slightly reduced wearing surface) but tread wear on a mine haulage road compared to an asphalt surface is estimated at 10-15 times higher (see Table 15) (Meech et al., 2013).

Table 15. Tire wear impact factors (mine haulage compared to regular asphalt).

Factor	**Ratio**
Load Ratio	0.82 – 2.05
Contact Interface	1.22*
Road Surface Condition	10 – 15**
Combined Ratio	10.0 – 37.5

** assumed not to vary by load condition which should be studied. ** assumed to be 12.5 in this analysis*

In analyzing the Miller Company data, the load is assumed to be 567 kg per tire. Using speed as a surrogate for energy, Eq. 29 can be used to determine the wear rate and the ratio of the impact factors can be used to attempt to scale-up the data to a CAT793D. Speed represents Energy and Momentum as in the following equations:

$$\text{Energy} = (WV^2)/2 \qquad \text{Eq. 30.}$$

$$\text{Momentum} = (WV) \qquad \text{Eq. 31.}$$

where: V = Truck Speed

W = Truck Weight

Wear at 15 kph and 45 °C = 0.274 mm/10,000 km, 0.063/0.211 between energy and force

Wear at 25 kph and 45 °C = 0.528 mm/10,000 km, 0.176/0.352 between energy and force

Load (Miller) = 567 / 232 = 2.44 kg/cm^2

Load (CAT793) - full = 400,000 / (6 x 15,000) = 4.44 kg/cm^2, so the load ratio is 1.82

Load (CAT793) - empty = 180,000 / (6 x 15,000) = 2.00 kg/cm^2, so the load ratio is 0.82

For a CAT793, the tire wear rate will be increased as follows:

Travelling fully-loaded at 15 kph and 45 °C = 0.274 x 1.82 x 1.22 x 12.5 = 7.61 mm/10,000 km

Travelling empty at 25 kph and 45 °C = 0.528 x 0.82 x 1.22 x 12.5 = 6.69 mm/10,000 km

The average travel speed is 20 kph and the typical tire life to scrap is 5,500 hours. This is equivalent to a service travel distance of 110,000 km. So for this service distance, the tire wear at 15 kph and fully loaded is 83.7 mm while at 25 kph and empty, it equals 73.6 mm. This gives an overall average of 78.7 mm. Current final depth of wear of scrapped tires at the Lucy mine is reported to be an average of 72 mm (97 mm (new) – 25 mm (scraped)). The prediction is remarkably close to the actual mine data.

Other factors that must be taken into account are the road and tire rolling resistance. Since the analysis is dealing with a gravel road, the frequency of trucks passing, together with maintenance practices (grading and watering), will affect the rolling resistance of the road surface on a daily basis. Rolling resistance variation at the Lucy mine falls between 2.5 to 3.5 %, which affects the energy required to drive the truck and indirectly, may lead to changes in tire wear rates.

7.4 Effect of Load and Speed on Tire Temperature

Tire temperature will increase as a tire moves along a road surface. Heat enters the tire through the contact surface with the road and from the flexing of the tire sidewalls as the tire rotates. The heat generated is a function of the energy that flows through each tire which is a function of the vehicle weight and its speed as follows:

$$\text{Total Energy}_{in} = (\text{Mass x Speed}^2)/2 \qquad \text{Eq. 32.}$$

Heat is lost from the tire through its sidewalls and circumferential surface to the surrounding air. This heat transfer occurs regardless of whether the truck is moving. The drop in temperature due to heat loss to the atmosphere is calculated as follows:

$$\Delta T_d = (T_{atm} - T_{tire}) \cdot e^{-k_d t} \qquad \text{Eq. 33.}$$

where ΔT_d = temperature decline during the time step (°C)

T_{atm} = temperature of the atmosphere – current (°C)

T_{tire} = temperature of the tire – current (°C)

k_d = heat transfer coefficient (1.6×10^{-4})

t = time (seconds)

The equation to calculate the increase in temperature due to load and speed is:

$$\Delta T_i = K_T(1 - e^{-k_i t}) - \Delta T_d \qquad \text{Eq. 34.}$$

where ΔT_d = temperature increase during the time step (°C)

K_T = $8.344 \times 10^{-3}(P+GVW)V$

k_i = $6.836 \times 10^{-7}(P+GVW)V^2$

t = time (seconds)

ΔT_d = temperature decline during the time step (°C)

P = payload (tonnes)

GVW = gross vehicle weight including fuel (tonnes)

Saibel and Tsai (1973) state that heat generation on automobile tires have significant effect on both temperature distibution and wear. According to their study, the tire temperature of a trailer travelling at 30 mph was measured at stopping points about 8 miles apart. Surface temperatures were measured within a minute after stopping the trailer. The results shows that tire surface temperature rises exponentially during travelling and achieves a steady state temperature at the end of eight miles of travelling. One minute after stopping, the tire surface temperature began to decrease exponentially from the maximum value.

Figure 38 depicts the dynamic temperature increase of a CAT793 truck moving at a speed of 16 kph with a full payload of 220 tonnes (+ GVW of 180 tonnes) and the temperature decline when the truck is idling (motionless) for an atmospheric temperature of 35 °C. As can be seen the temperature while travelling increases to a steady-state value of 75 °C after a time interval of about one hour. The time to decline from this value back down to ambient conditions is a bit longer at about 90 minutes.

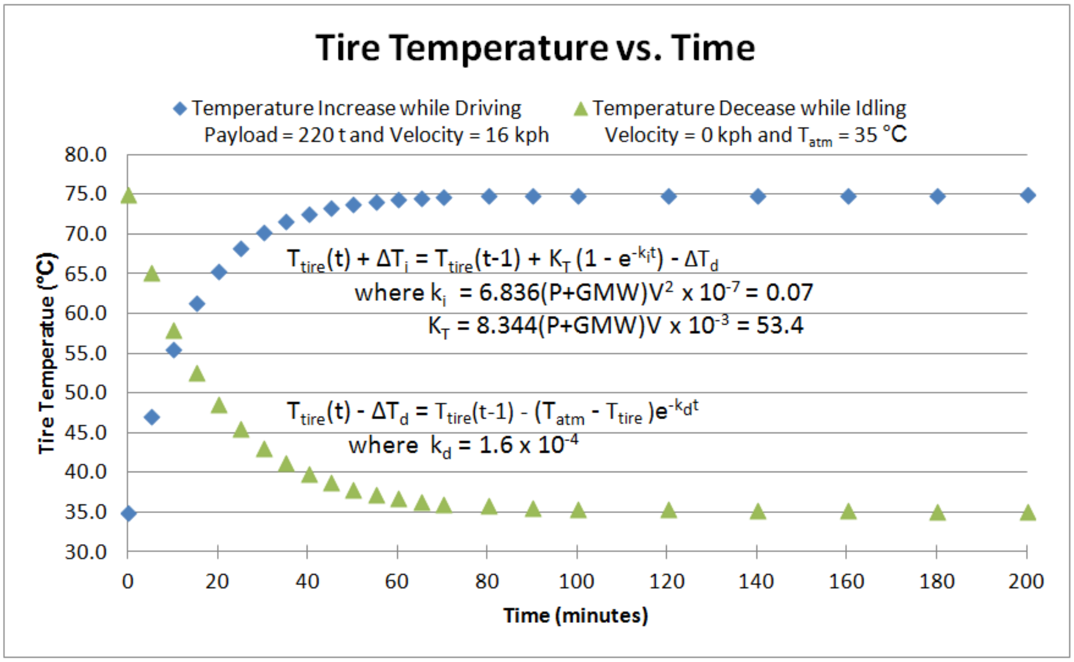
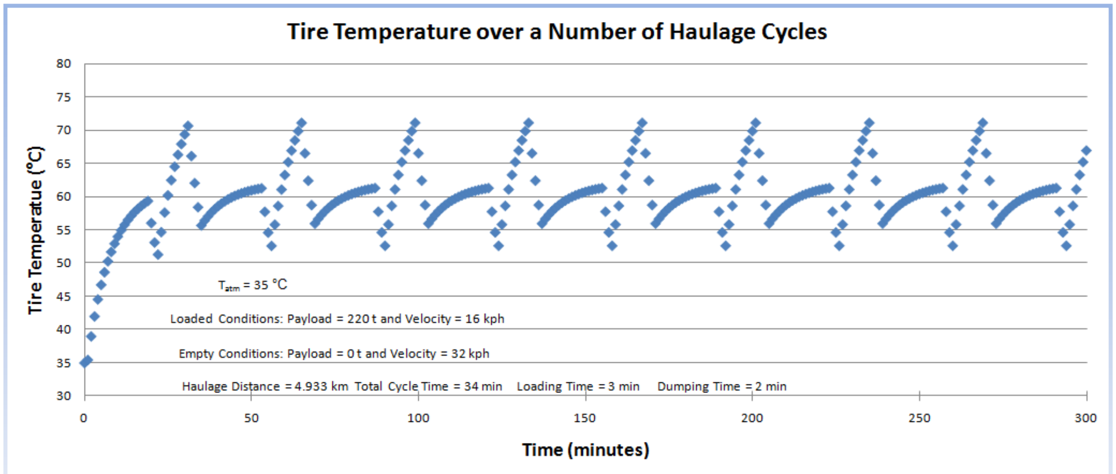


Figure 38. The effect of speed and load on tire temperature change.

In Figure 38, for tire cool-down, the change in temperature is determined by the difference between atmospheric and tire temperature. Two parameters affect heat gain – load and speed. One term (k_i) relates to energy (Load x Speed^2) used to drive the truck while the other term (K_T) relates to the force acting on the tire expressed as a momentum term (Load x Speed). The blue data points refer to tire temperature while driving under full load conditions. The green data shows the cool-down occurring when a "hot" tire is in an idling condition. The cool-down parameter (k_d) is equivalent to the heat transfer coefficient between the tire surface and the air.

Figure 39 is an example of a situation that is cyclic, the tire temperature is able to cool down during the idling period. Figure 40 is an example of a situation that is unstable, i.e., the tire temperature does not reach steady state and continues to increase over a number of cycles leading to very excessive tire wear and potential failure conditions.



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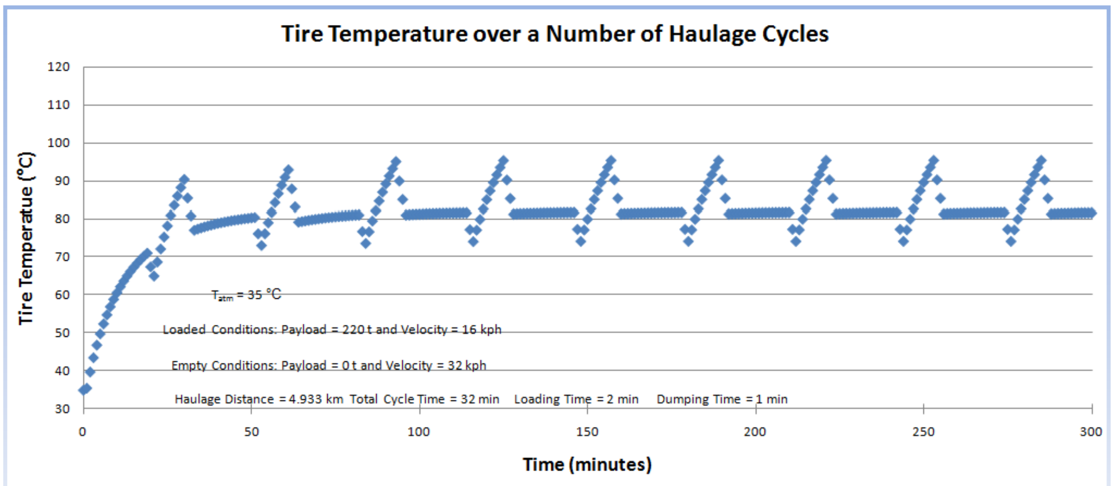

b)

Figure 39. Effect of idling time on tire temperature change during the haulage cycle (a) total idling time = 5 min. (14.7%) (b) total idling time = 3 min. (9.3%)

7.5 Tire Wear Model

To apply this model, three inputs are required to calibrate for any specific mine site – maximum speed; maximum load, and maximum tread wear rate (mm/10,000 km) at these maximum values (Parreira2 et al. 2012). This last element can be determined from an examination of tire life data at a mine site. For example, at the Lucy mine the average tire life is about 5,500 operating hours. With an average cycle traveling speed of 20 kph [(13 kph + 27 kph)/2] which also includes idling time, this is equivalent to a traveling distance of 110,000 km. The average tread wear depth is 72 mm (97mm – 25mm), so this gives a theoretical tread wear rate of 6.82 mm/10,000 km.

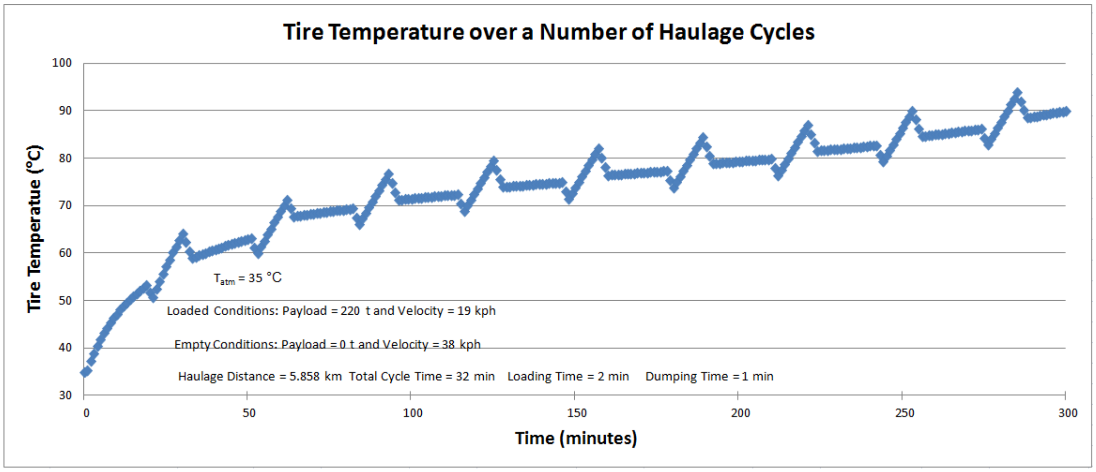

Figure 40. Example of an unstable situation in which the idle time is not long enough for the current driving conditions to allow tires to reach a stable level.

However, in examining the data in more depth, it was discovered that about 12% of all tires at the Lucy mine are scraped after significantly lower operating times because of blow-outs or failed sidewalls. Discounting these tires from the analysis is important since the model is aimed at estimating normal wear, not unplanned failures. Assuming an average service life of about 3,000 hours for these tires, the true average operating time is 5,841 hours. Actual driving time is about 88% of this value, so 5,100 hours of actual driving takes place. This translates to an average distance travelled of just over 100,000 hours. So the true average tread wear rate at the Lucy mine is 7.5 mm/10,000 km.

The range in wear rates for CAT793 tires is about 2.5 from lowest to highest. The range in wear rates in Equation 30 based on speed variations from 15 to 30 kph for the same load gives a value of 2.64. For this range of variation and an average condition of 7.5 mm/10,000 km, the maximum tire wear rate at the Lucy mine is estimated to be 10.88 mm/10,000 km. The assumption used in this research was 10 mm/10,000 km. The calibration data is input to a Fuzzy Logic-based model of tire wear as a function of payload and speed. The output graph for this model is shown in Figure 41. The model uses a rule base approach that defines fuzzy sets for wear rate: zero, low, moderately-low, moderate, moderately-high, high, and very high together with fuzzy sets that describe payload as zero, low, design, high, and excessive as well as fuzzy sets that describe speed as zero, slow, moderate, fast, and very-fast (see Table 16).

Table 16. Fuzzy rule base used to predict wear rate from speed and payload.

Payload	Speed				
	Zero	Slow	Moderate	Fast	Very-Fast
Zero	Zero	Zero	Low	Mod-Low	Moderate
Low	Zero	Low	Mod-Low	Moderate	Mod-High
Design	Zero	Mod-Low	Moderate	Mod-High	High
High	Zero	Moderate	Mod-High	High	Very-High
Excessive	Zero	Mod-High	High	Very-High	Very-High

The system output using the Accumulation method of Defuzzification is shown in Figure 41. This 2-D plot shows wear rate as a function of Payload (as a % of maximum) for different speeds running from zero to maximum. The two areas shown in the diagram represent the types of wear conditions for the travel empty situation and the travel loaded situation. Note that the travel empty region shows a slightly higher wear rate than the travel loaded region since speed has a greater impact on tire wear than does payload.

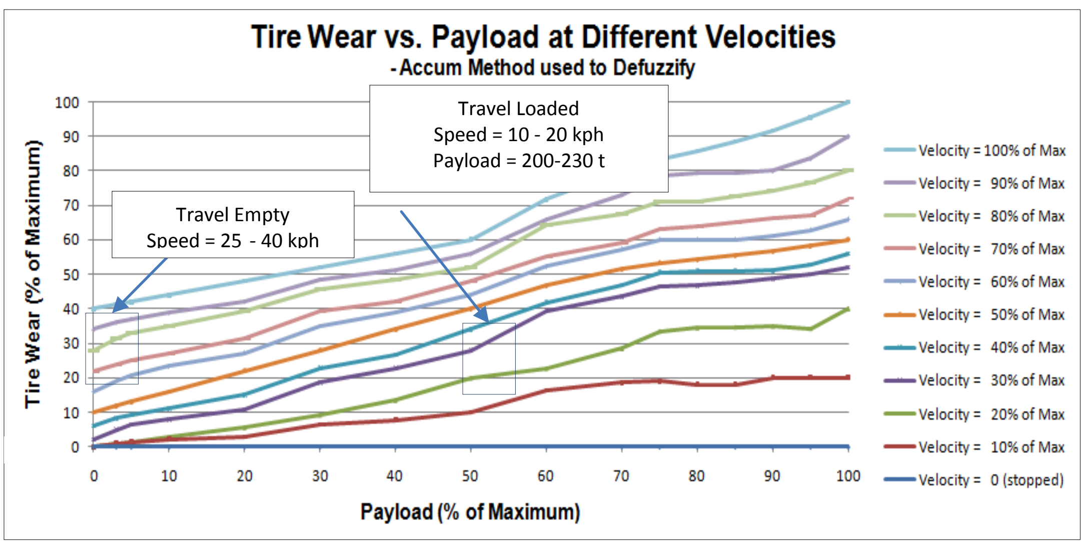

Figure 41. Tire wear vs. payload at different speeds: defuzzification = accumulation. Calibration factors: maximum speed = 40 kph; maximum payload = 400 t; maximum tire wear = 10 mm / 10,000 km.

8 Case Studies

This chapter shows the results from the various test runs of the model. A base case was set-up, and then different model configurations were tested to look at fleet size, gear efficiency, tire temperature, stops signs, higher speeds, and safe following-distance between trucks.

8.1 Model Output: Base Case

The model output in each of the tables that follow is based on the simulation of 28-day work periods. The model was run 3 times for each test conditions to establish a measure of the variance for each test condition. The same baseline parameters were set for all tests. The crew make-up consist of 39% passive, 44% normal, and 17% aggressive drivers. In the autonomous model, all trucks were set to 100% normal, i.e., the best driver type, but with a significantly reduced variation from that of normal human drivers. Table 17 shows the average speed of the different driver types when trucks are loaded and empty. The speed of an autonomous truck was set to ~5% below that of a normal human driver when the truck is loaded and ~10% when the truck is empty.

Table 17. Average road speed for different driver types when a truck is at steady state driving.

Driver Type	Steady State Speed (km/hr)			
	Ave Empty	S.D**	Ave Full	S.D
Aggressive	29.1	0.95	18.1	1.65
Normal	27.4	0.89	17.4	1.49
Passive	24.6	1.04	16.7	1.27
Autonomous	24.8	0.26	16.6	1.05

** these speeds do not reflect periods when trucks are accelerating and braking.*
***Ave. is the average and S.D is the standard deviation of the3 samples*

The Aggressiveness-Stability Factor described in Chapter 4 allows variations in the range of design speeds and accelerations. With these tests, a "very stable" driving condition was used for all driver types so variations over a shift period were reduced.

Table 18 shows the average and standard deviation of fuel consumption and tire wear when a truck is loaded and empty for the three runs. The average of fuel consumption is 384 L/hr when a truck is loaded. Uphill driving is responsible for the highest fuel consumption since the engine must produce more power to overcome both rolling resistance and gravitational forces. When the truck is empty and returning to be loaded, the average fuel consumption drops to 80 L/hr.

Table 18. Model results - fuel consumption and tire wear - loaded and empty. 28-days.

Element	Passive		Normal		Aggressive		Autonomous	
	Ave.*	**S.D.****	**Ave.**	**S.D.**	**Ave.**	**S.D.**	**Ave.**	**S.D.**
Fuel Consumption (idling) - L/h	26.62	0.01	27	0	26.77	0.02	27	0
Fuel Consumption (full) - L/h	384.31	0.05	384.19	0.05	384.44	0.24	381.48	0.04
Fuel Consumption (empty) - L/h	80.82	0.3	79.31	0.18	77.79	0.09	69.53	0.07
Total Litres/cycle	184.81	1.35	180.11	0.08	183.1	0.32	173.17	0.06
% difference	2.61	0.79	0	0	1.66	0.4	-3.85	0.07
Tire Wear Rate (idling) - mm/h	0.0032	0	0.0032	0	0.0032	0	0.0032	0
Tire Wear Rate (full) - mm/h	0.0303	0	0.0306	0	0.0304	0.03	0.0298	0
Tire Wear Rate (Empty) - mm/h	0.0066	0	0.0073	0	0.0067	0.01	0.0063	0
Tire Wear (mm/cycle)	0.0151	0	0.01	0	0.01	0.01	0.01	0
% difference	0.72	0.04	0	0	0.07	0.01	-7.45	0.06
Total Fuel (L/Cycle)	<-------------------- 182.43 ----------------->						173.17	
% difference	-						-5.3	
Total Fuel (L/t)	<-------------------- 0.83 ----------------->						0.78	
% difference	-						-6.1	
Tire Wear (mm/cycle)	<-------------------- 0.0150 ----------------->						0.014	
% difference	-						-7.6	

**Ave. is the average of the model outputs of three runs of 28 days each.*

*** S.D is the standard deviation of the three runs. The model simulated the Lucy production for 28 days.*

Note that the Autonomous mode shows an improvement in the fuel consumption KPI of 5.3% for L/cycle and 6.1% for L/t. The main cause of this improvement is due to the small speed variation after the AHS reaches the steady state speed together with reduced braking and acceleration variations and lateral displacement. The AHS is under a cruise mode of control after achieving the steady state speed in cases where no truck interactions exist.

Tire wear (mm/cycle) also shows an improvement of 7.6% which is a conservative scenario in improvement since the model is only considering driver characteristics. A much higher tire wear improvement is expected by looking at road maintenance infrastructure changes with an AHS project.

Table 19 shows an AHS improvement in production of about 21.3% based on average. Process delays decrease because of the elimination of shift changes and human breaks. The AHS trucks are set in the model to work for 24 hours a day and will stop only if failures or road delays occur.

Although the AHS trucks drive slower, the cycle time decreased by 28.7% because of elimination of human breaks and decrement in queuing time. AHS are set up to drive in a consistent speed; therefore, the queuing time is decreased compared to driver fluctuation speeds. A cycle time in this research considers the necessary time for the truck to complete an operational cycle which includes time to spot, load, dump, haul and road delays. Every time a driver goes to a break, the time that takes to drive from parking to shovel is included in the cycle time. The model uses the Lucy mine data to simulate the maintenance delays based on planned, and unplanned (major and minor) failures. The delays for the manual and autonomous model are assumed relatively close. The impact of an AHS system on scheduled maintenance is not a focus of this research.

Table 19. Cycle times, delays, and production output – 28-day work-period simulation.

Element	Manual	AHS	%Change
Ave. Number of Cycle/day	18.9	23.1	22.3
Ave. Total Cycle Time: min/ day/truck	51	45.7	-10.3
Ave. Queuing: min/cycle/truck	1.8	1.3	-27.8
Ave. Total Haulage: hours/day/truck	15.6	17.6	12.8
Ave. Shift Change: hours/day/truck	0.4	0	-100
Ave. Coffee/Lunch Breaks: hours/day/truck	1.9	0	-100
Ave. Process Delay: hours/day/truck	2.2	2.1	-2.3
Ave. Unplanned Maintenance: hours/day/truck	1.3	1.4	7.7
Ave. Planned Maintenance: hours/day/truck	2.6	2.8	7.6
Ave. Percent Utilization (%)	65.0	73.4	12.9
Ave. Total Production: tonnes/day/truck	4,231	5,130	21.2
Ave. Payload: tonnes	223.9	222.1	

The manual fleet cycle time output is 51 minutes indicating that the crew shifts to a more passive behavior – slower operation. On the other hand, with the AHS fleet set to normal with a low variation, the cycle time actually declines by about 4 minutes. This is due to a significant reduction in queuing as well as truck interactions along the haulage routes.

8.2 Sensitivity Analysis – Varying Production

Several case studies have been run to consider fleet size optimization, gear change efficiency, as well as safety constraints. Each case study was run three times in which each run simulated Lucy mine for 7 days, representing 168 hours of the mine production. The first case compare 7, 8, 9 and 10 trucks maintaining the same speed parameter of the base case for both manual and AHS, the Table 20 shows the results. The 7-truck scenario showed a difference in production between manual and AHS of -5% with, 8 trucks yielding about +7.7%, 9 trucks showing 20.8% and 10 trucks giving about +34% increased production respectively. Regarding cycle time, the more trucks added to the fleet, the longer the queuing time which leads to an increase in cycle time.

Table 20. Difference between AHS and manual fleets for 7-day work-period.

Elements	Manual	7 T.	8 T.	9 T.	10 T.	%change*			
						7 T.	8 T.	9 T.	10 T.
Ave. Number of Cycle/day /truck	20.23	25.14	24.9	24.81	24.82	24.3	23.1	22.6	22.72
Ave. Total Cycle Time (min)/truck	50.53	45.21	45.67	45.77	45.76	-10.5	-9.6	-9.4	-9.4
Ave.Queuing (min)/truck	1.95	0.98	1.26	1.45	1.48	-49.7	-35.4	-25.6	-23.77
Ave. Total Haulage Time/day/truck	16.68	18.96	18.99	18.94	18.96	13.7	13.9	13.6	13.7
Total Production (tonnes)/day	41,171	39,101	44,344	49,744	55,152	-5.0	7.7	20.8	34.0

**% change is comparing 7, 8, 9 and 10 trucks to 9 manual trucks stopping at intersections*

A second study examined removal of stop signs at intersections. Trucks are set to slow down at an intersection, but not stop unless another truck is closer than 50m. Table 21 shows with this configuration, 7 AHS trucks match the production of a 9-truck manual fleet. Queuing time decreased slightly, and production increased 14.93% for the 8-truck fleets due to a 15.61% decrease in cycle time.

Table 22 shows that when simulating 8 trucks without the need to stop at intersections, average of fuel consumption L/cycle decrease by 5.47% and the average of L/tonnes decrease by 5.27%; however, tire wear mm/cycle increases by 2.97 % compared to stop sign configuration.

Table 21. KPIs for no stopping at intersections - comparison with a 9-truck manual fleet.

Elements	Manual baseline	non Stopping		%change from manual	
		7 T.	8 T.	7 T.	8 T.
Ave. Number of Cycle/day /truck	20.23	26.61	26.63	31.53	31.66
Ave. Total Cycle Time (min)/truck	50.53	42.29	42.65	-16.32	-15.61
Ave. Queuing (min)/truck	1.95	1.04	1.37	-46.41	-29.77
Ave. Total Haulage Time/day/truck	16.68	18.77	18.96	12.53	13.65
Total Production (tonnes)/day	41,171	41,433	47,319	0.64	14.93

Table 22. Fuel consumption and tire wear KPIs for a 9 AHS fleet – 7-day work-period.

	Units	Stopping at intersections	No Stopping at intersections	% change
Average Fuel Consumption	L/cycle	172.91	163.46	-5.47
	L/tonnes	0.78	0.74	-5.27
Average Tire Wear	mm/cycle	0.0139	0.0143	2.97

8.3 Higher Speed

The autonomous base case is set to have lower speed than the manual because of possible issues related to bandwidth and latency in operating the AHS safely. In this study, we are interested in knowing the level of improvement if the autonomous mode is set to an Aggressive behavior with a small variation. Table 23 shows when a truck is empty, speed is set to 18.5% higher than the base case. When a truck loaded, speed is set 13.8% higher. This assumption is made in order to simulate AHS speeds close to the speed range of the aggressive behaviour of the manual base case.

Table 23. Autonomous truck set to a higher speed over a 7-day work period.

AHS	Speed(km/h)	
	Ave. Empty*	Ave. Full
Higher Speed	29.4	18.9
Base Case	24.8	16.6

** Averages of speed output of AHS fleet over 7 days of Lucy mine operating.*

The results of the run on Table 24 shows productivity per truck and queuing time increased by 1.89%, and 15%, respectively. Although queuing time is increased, total cycle time declined by 5.58%. Table 25 shows that fuel consumption per tonne increased by 1.49% and tire wear per cycle increased by 8.54%.

Table 24. Cycle outputs for a high speed AHS operation – 7-day work-period.

Element	Default Speed	Higher Speed	%Change
Ave. Number of Cycle/day	24.81	25.34	2.13
Ave. Total Cycle Time (min)/truck	45.77	43.21	-5.58
Ave. Queuing (min)/cycle	1.45	1.67	15.00
Total Haulage Material (tonnes)/day/truck	5,527	5,631	1.89

Table 25. Fuel consumption & tire wear KPIs for high speed operation: 7-day work period.

	Units	Base Case	Higher Speed	% change
Average Fuel Consumption	L/cycle	172.89	175.06	1.25
	L/t	0.78	0.79	1.49
Average Tire Wear	mm/cycle	0.014	0.0152	8.54
	mm/10,000t	0.63	0.67	6.77

8.4 Gear Efficiency

The fuel consumption model takes gear efficiency into consideration (see Chapter 7). It is generally accepted that most drivers do not necessary change gears exactly at the point that gear efficiency peaks. However, an AHS fleet can be optimized to maintain high gear efficiency. With the base case conditions for both AHS and manual mode of operation, gear changes were configured to change at the exact point that power peaks. The model checks if the engine speed is at 1750 rpm and will change gear right after this point. In reality, human drivers will not change gears exactly at this point and so, a maximum 2-second random delay, (average of 1-second and S.D of 0.3 second) was added to the manual fleet test runs.

The results show that with a 2-second maximum delay, fuel consumption increased by only 0.5% per cycle. In some cases, this delay may be higher – particularly with novice drivers. A conservative level was chosen simply to show that the model has the ability to execute studies of fuel efficiency.

8.5 Relaxation of Safety Constraints

When a truck is within 50 m of another vehicle, the truck must slow down and drive at the speed of the front truck. When this distance is greater and when the truck in front has left the road segment, the following truck can then accelerate according to its set point to achieve a higher speed.

This safe following-distance was reset to 40 and 30 m for an AHS fleet to see if this change would impact production, fuel use, and tire wear. Each configuration was run 3 times with little difference observed. Queuing time was the only variable that showed a change above 1%. For 40 m, queuing time increased by 6.4% while for 30 m, it increased by 5.4% compared to 50 m. The results show that decreasing the safe-following distance has no advantage in improving KPIs.

8.6 Tire Temperature and Wear – Influence of Tire Temperature

In the base case model runs, tire wear is affected by payload and speed. The impact of tire temperature on tire wear was added as a later feature. The results show that the effect of temperature on tires increased tire wear by 15% per cycle (Table 26). In these test runs, the ambient temperature was set according to to Lucy mine temperature (Appendix 15). This variable is very important when autonomous trucks are being operated on a 24/7 basis.

Table 26. Tire wear with influence of tire temperature – 7-day runs of AHS fleet.

Element	Tire Wear with T	Tire Wear without T	% change
Tire Wear Rate (Idling) - mm/h *	0.00300	0.00300	0.0
Tire Wear Rate (Loaded) - mm/h	0.03265	0.02900	12.6
Tire Wear Rate (Empty) - mm/h	0.00828	0.00600	38.0
Tire Wear (mm/cycle)	0.01613	0.01400	15.2

* *Idling includes spotting while at the loader and dump positions, hence some minimal tire wear has been assumed.*

9 Economic Analysis

This chapter presents a detailed incremental economic analysis comparison of three case studies:

- 9-truck manual fleet and 7-truck AHS fleet (AHS set to same production as manual);
- 9-truck manual fleet and 9-truck AHS fleet (different production for both cases);
- 11-truck manual fleet and 9-truck AHS fleet (manual set to same production as AHS).

9.1 Economic Criteria

An incremental analysis has been done in order to establish if the additional costs of purchasing more expensive AHS trucks can be justified through reduced operating and maintenance costs. The incremental analysis focuses on changes or differences among a number of alternatives. The analysis is based on examining the impact of alternative managerial decisions on revenue, costs, and profit (Hischey, 2009). The economic criteria for this analysis uses a Net Present Value (NPV) calculation to bring future net Cash Flows (CF) into the present discounting the values in terms of the cost of capital (Brigham et al, 2009). Incremental Revenue has been held constant across all comparisons to avoid difficulties in dealing with ore value and stripping ratio changes. The equations below are used in this analysis (Meech and Paterson, 1980):

$$\Delta CF = (1 - t)\,(\Delta Opex) + t\Delta D \qquad \text{Eq. 35.}$$

where ΔCF = cash flow difference between the two projects.

t = Tax Rate of 50% (assumed for conservative analysis reasons)

$\Delta Opex$ = operating cost difference between the two projects.

ΔD = depreciation difference between the two projects (straight-line)

Net Present Value is given by:

$$NPV = \sum_{y=1}^{d} [\Delta CF/(1+i)^{y}] - \Delta Capex + \Delta S/(1+i)^{d} \qquad \text{Eq. 36.}$$

where i = interest rate of 10%;

y = year and d = Project life (years);

$\Delta Capex$ = capital cost difference between the two projects,

ΔS = salvage value difference between the two projects.

Appendices 13 and 14 contain the detailed operating and capital costs used to do the calculation. This data was based on information obtained from the Lucy mine. Variables that could not be obtained were assumed based on other sources.

9.2 Economic Analysis: AHS to Maintain the Same Production as the Manual Fleet

The AHS model was run to maintain the same production as the manual fleet. To achieve this result, the number of autonomous trucks was progressively reduced with speeds adjusted to provide identical production to a 9-truck manual fleet. Table 27 shows that 7 AHS trucks are able to produce the same production as the 9-truck manual fleet with a slight increase in the speeds over that used in the baseline run (Chapter 8, pp.97). With 8 AHS trucks, their speeds were reduced to the baseline case to -23.1% and -13.6% for empty and loaded trucks respectively. Having these new set of speed, the AHS fleet achieved the manual production target. With 9 AHS trucks, speeds were reduced to -26.8% and -36.4% of the baseline case for loaded and empty trucks respectively. Running the AHS model at these speeds shows that although the AHS fleet consumed slightly more fuel, tire wear was reduced. For the 7-truck AHS fleet, both fuel consumption and tire wear were improved.

Table 28 shows a summary of the incremental economics of these comparisons while Appendix 17 gives the details of the analysis. The incremental rate of return on a 7-truck AHS fleet is high at 48.67%. Although the incremental rate of return drops-off considerably when 1 or 2 trucks are added to the fleet, it must be remembered that unused productivity is available in these cases (17% for 8 trucks and 31% for 9 trucks) depending on speed. This added flexibility has significant value that has not been assessed economically.

Table. 27. AHS truck to match a manual production of 37,867 tpd.

Element	Manual	7 AHS	8 AHS	9 AHS	% Change (AHS-Man)		
					7 AHS	8 AHS	9 AHS
V full - km/h	17.4	18.5	13.4	12.7	6.2	-23.1	-26.8
V empty - km/h	27.1	28.6	23.4	17.2	5.7	-13.6	-36.4
Ave Fuel Use - L/t	0.83	0.76	0.83	0.78	-8.1	-0.1	-5.1
Ave Fuel Use - L/cycle	185.3	168.4	209.3	223.9	-9.1	12.9	20.9
Ave Fuel Use - L/hour	218	235.5	252	239.4	8.1	15.6	9.9
Ave tire wear - mm/cycle	0.015	0.014	0.014	0.013	-5.0	-7.8	-13.8
Ave tire time to scrap - hrs	5504	4876	5834	7029	-11.4	6.0	27.7
Ave. Number of Cycle/day	18.9	24.5	21.1	19	29.4	11.9	0.4
Ave. Total Cycle Time (min)	51	42.9	49.8	56.1	-15.9	-2.3	10.0
Ave. Queuing (min)/cycle	1.8	0.9	0.9	1.0	-49.4	-50.8	-47.8
Percent Utilization (%)	65	78	73	74	19.43	12.65	14.06

Table 28. Incremental economic analysis of AHS fleet to match production of 37,867 tpd.

Element	Manual 9 trucks	7 AHS	8 AHS	9 AHS	7 AHS vs. Manual	8 AHS vs. Manual	9 AHS vs. Manual
CAPEX (M$)*	$36.00	$42.19	$47.19	$52.19	-	-	-
OPEX (M$/year)	$50.17	$44.63	$46.08	$47.11	-	-	-
ΔCC (M$)	-	-	-	-	$6.19	$11.19	$16.19
ΔOC (M$/year)	-	-	-	-	-$5.54	-$4.09	-$3.06
ΔD - Depreciation (M$/year) **	-	-	-	-	$0.88	$0.76	$0.66
ΔCF (M$/year)	-	-	-	-	$3.21	$2.42	$1.86
ΔSV (M$) - Salvage Value @ DCFROR	-	-	-	-	$0.00	$0.65	$5.23
After Tax NPV@10%	-	-	-	-	$9.45	$1.26	-$1.92
After Tax DCFROR	-	-	-	-	48.67%	11.65%	-5.21%

** includes an AHS infrastructure cost of M$6.690 and a start-up cost of 0.M$500 regardless of the number of AHS trucks (see Appendix 13, 14). ** Straight line depreciation.*

9.3 Economic Analysis: AHS Running at Default Speeds

In this example, a 9-truck manual system is compared to 9-, 8- and 7-truck AHS fleets without changing the autonomous default speed to achieve a total production over the life of the trucks as that produced by the manual system (Table 29).

The outputs of these simulations show that 9 autonomous trucks improve the production rate by 20% reducing the life of the project from 7.0 to 5.3 years. Appendix 18 contains the details of this analysis. Note that the mine life decreases when more AHS trucks are added into the system. For the 9-truck AHS fleet, despite a 44% higher capital cost and a 14% higher annual operating costs, the reduced life produces a 9.45% DCFROR. For an 8-truck fleet, the return is 14.8%, and for a 7-truck fleet, the return is 48.7% (see Table 30). This trend is due to the advancement of revenue from later years into early years which yield a significant economic credit.

Table 29. AHS trucks running at default speed.

Element	Manual*	7AHS	8 AHS	9AHS
Ave Fuel - L/tonnes	0.83	0.78	0.78	0.78
Ave Fuel - L/cycle	185.27	172.53	172.91	172.89
Ave tire - mm/cycle	0.015	0.014	0.014	0.014
Fuel burn rate (L/h)	218	236	252	239
Tire life (hours)	5504	4876	5834	7029
% Utilization	65%	78%	73%	74%
Maintenance (%)	4.0%	3.4%	4.3%	4.9%
Annual Material Moved (t)	13,821,605	13,821,605	16,185,560	18,156,560
Years of Mining	7	7	5.98	5.33

**Fuel burn rate of AHS is higher due to the crew makeup of the manual model*

Table 30. Incremental economic analysis of different production targets.

Element	Manual 9 trucks	7 AHS	8 AHS	9 AHS	7 AHS vs. Manual	8 AHS vs. Manual	9 AHS vs. Manual
CAPEX (M$)*	$36.00	$42.19	$47.19	$52.19	-	-	-
OPEX (M$/year)	$50.17	$44.63	$51.51	$57.08	-	-	-
ΔCC (M$)	-	-	-	-	$6.19	$11.19	$16.19
ΔOC (M$/year)	-	-	-	-	-$5.54	$1.34	$6.91
ΔD =Depreciation (M$/yr)	-	-	-	-	$0.88	$2.72	$4.65
ΔCF (M$/year)	-	-	-	-	$3.21	$0.69	-$1.13
ΔSV (M$) = Salvage Value	-	-	-	-	$0.00	$0.00	$0.00
After Tax NPV@10%	-	-	-	-	$9.45	$3.36	$15.59
After Tax DCFROR	-	-	-	-	48.67%	14.80%	9.45%

9.4 Economic Analysis: 10 Manual Trucks Matching the Production of 9 AHS Trucks

In this example, 10 manual trucks with a crew make-up of 88% aggressive and 22% normal were compared to a 9-truck AHS fleet. Note that crew make-up had to be changed since a higher overall speed was necessary to match the AHS production. Table 31 shows that the AHS fleet consumed about 4.4% less fuel per cycle than did the manual fleet. Tire wear was down by 9.8% in terms of the mm/cycle KPI. Output from this configuration gave a manual production almost identical to the 9-truck AHS production. Appendix 19 contains the details of this analysis.

Table 32 shows that a 9-truck AHS fleet will give an improved tire life of 7,029 hours versus 5,630 hours for the manual fleet. The mine life for both cases is 5.33 years. The fuel rate for the manual crew is increased since the crew make-up was changed to a more aggressive behaviour.

Table 31. Same production: 10-truck manual fleet vs. 9-truck AHS fleet.

Element	10 Manual trucks	9 AHS trucks	Units	%Change
Fuel Consumption (Average)	180.9	172.9	L/Cycle	-4.4
	0.79	0.78	L/tonnes	-1.3
Tire Wear (Average)	0.0153	0.014	mm/cycle	-9.8

Table 32. Same production: 10-truck manual fleet vs. 9-truck AHS fleet.

Element	10 Manual	9 AHS
Fuel burn rate (L/h)	226	239
Tire life (hours)	5,630	7,029
% Utilization	69%	74%
Maintenance (%)	4.0%	4.9%
Annual Material Moved (tonnes)	17,775,500	18,156,560
Years of Mining	5.33	5.33

The CAPEX for the AHS fleet in this configuration is 30% higher than manual while the AHS OPEX is 9% lower. The NPV for this comparison is M$4.6 with a DCFROR of 119.8% as shown in Table 33.

Table 33. Incremental economic analysis of 10 manual trucks vs. 9 AHS trucks.

CAPEX (M$)*	Manual 10 trucks	9 AHS	9 AHS vs. 10 Manual
CAPEX (M$)*	$40.0	$52.2	-
OPEX (M$/year)	$62.5	$57.1	-
ΔCC (M$)	-	-	$12.2
ΔOC (M$/year)	-	-	-$5.4
ΔD - Depreciation (M$/year)	-	-	$2.3
ΔCF (M$/year)	-	-	$3.9
ΔSV (M$) - Salvage Value @ DCFROR	-	-	$0.0
After Tax NPV@10%	-	-	$4.6
After Tax DCFROR	-	-	119.8%

10 Concluding Chapter

10.1 Discussion

This thesis has presented a simulation model that compares an autonomous haulage truck system to a manual fleet by estimating benchmarked Key Performance Indicators (KPIs) such as productivity, safety, maintenance and labour costs, cycle time, fuel consumption, and tire wear. The model extends conventional shovel/truck simulation into a variety of truck sub-systems such as truck movement, driver behaviour, fuel consumption, and tire wear to capture the mechanical complexities and physical interactions of these sub-systems with the mine environment on a 24/7 time basis. Running the model in identical scenarios for the two cases allowed comparison of benchmarked KPIs that demonstrate the improved utilization and adaptability of an AHS.

What is the level of improvement of this new technology?

The main improvement of the AHS is the elimination of manual incidents and accidents that comes from distraction, fatigue and micro-sleep. AHS avoid fatal accidents due to human error and poor-driving habits. Other aspects to consider are the AHS operation and production. AHS operates more consistently – tires, brakes, and other components subject to wear failures that are properly used and maintained, will have longer operational lifetimes. The economic value of the system is also improved due to reduced truck maintenance costs since the equipment is more consistently used and better managed under computer control.

Fuel consumption is reduced when a truck is driven in a stable, consistent manner. Human-operated trucks have significantly fluctuating fuel efficiency as drivers have a large degree of influence over fuel economy. Looking at the AHS production, if the equipment operates without stoppages for breaks or shift-changes, overall production is also improved. As a result, AHS leads to improvements in workplace efficiency, production, and cost effectiveness.

Are robot trucks more efficient?

The model was run under different scenarios and the results shown that an AHS is more efficient then a manual fleet. The base case of the model for example, was run with 9 manual trucks in order to compare with 9 AHS trucks. The manual crew make-up was set to 39% passive, 44% normal, and 17% aggressive while in the autonomous model, all trucks were set to 100% normal. The autonomous mode showed an improvement in fuel consumption KPIs of 6.5% for L/cycle and 5.7% for L/t. Tire wear (mm/cycle) also showed an improvement of 7.6%. AHS production increased by 21.3% over manual. Although the AHS trucks drive slower, the cycle time is shorter than manual because queuing times decreases by 28.7% and distance travelled is reduced.

Are Lucy Mine KPIs an efficient and effective way to measure the performance of this new technology?

The KPIs used in the model are able to measure performance of the current mine operation as well as the AHS system. Certain KPIs of the AHS deteriorated with respect to a manual system, but this does not mean that improvement did not occur. An AHS truck does not stop for breaks. The AHS consumes more fuel and tire wear increases, but more tonnes are produced because of the added cycles per shift. As result, Litres per hour of an AHS are higher than the manual system, but Litres per cycle are lower. The same analysis applies to tire wear; mm/hour for the AHS is higher but mm/cycle is lower. The model only looked at existing Lucy mine KPIs. When an AHS is actually in use, new KIPs may be needed to measure the efficiency of the technology itself such as measuring efficiency of data transmission, computer and sensor speeds and reliabilities. New KPIs will be required to measure the technology interacting within the mine environment.

Are all mines ready for autonomous haulage technology? What are important aspects to consider before using AHS?

Not all mines are ready for AHS. Automation should not be viewed as a solution in itself and failures have occurred in the past, INCO’s Sudbury LHD and Drilling Automation program is an example (Mottola and Holmes, 2009). To be successful, an automation project must identify and analyze levels of interest, expectation, priorities and influence of stakeholders in the early stages, as well as developing a management plan that incorporates quality control, risk management, communication plans, and exit strategies.

An important issue of automation is the replacement of employees. In a new mine, the implementation is potentially easier while with an existing mine, there are more challenges related to addressing people's perception and providing proper training. However, if an AHS is implemented in an existing mine, employee replacement can be done in a way that manages labour attrition and turnover issues to avoid negative impacts on affected personnel.

Each mine has unique variables such as weather, road material type, etc., and as a result, different set points are needed for each AHS project. Trials must take place in the mine and when the technology is adjusted, replacement takes place. Implementing the AHS by isolating the AHS from MHS would be a good option for this new technology. Mining will evolve with the project, workers are able to understand gradually new safety procedures, and the technology grows and improves step by step. The improvements take place slowly according to knowledge gained and the experience of acceptance by stakeholders.

Safety concerns require careful design and planning, a back-up or fall-back system may be necessary. It must be expected that the need for new safety/traffic rules, more maintenance, less manual operation activities in the pit, and practices such as drilling and blasting may change. Another important issue is to focus on integrating massive data collection. Data are just numbers unless they are well-structured and analysed. Without analysis, implementation will be slow.

Is integration the future of mining?

Mine operations often have expensive software that are not being used to their full extent as they are not linked together. Much can be gained through the integration of operational technology, production control systems, and information technology which can bring much value to the mine rather than having independent software for each process. Integration will allow management to intelligently view and analyse a "big picture" of critical assets to plan, operate and schedule the logistics of the mine. This thesis has provided an insight into the benefits of initiating this integration in which considerable sub-models had to be developed and combined from different areas such as truck mechanicals, driver behaviours, mine topography, maintenance scheduling, economic analysis, mining planning, mine design and scheduling. A "business case" for implementing AHS at the Lucy mine was created to understand the benefits of an AHS system and its integration into the overall mine operations. The software could be used in the future to run in parallel with the actual operation to provide model feedback control of the overall mine haulage system. Integration of AHS with other automation systems can assist in driving mining towards a more highly-collaborative enterprise, allowing managers to quickly respond to changes more efficiently than at present.

The software company Mincom, the ABB software group, and a company called Ventyx, are in the final stages of creating software solutions that will integrate mine planning, logistics sales and marketing, asset management, and business analytical software to cover the entire mining lifecycle (Jessop et al., 2012). As mentioned in Chapter 1, technology by itself does not necessarily improve a process, but by using information technologies, data can be transformed into valuable information that can be accessed in the form of reports that allow the study of new innovations that will lead to further improvements.

Integration in real-time, will create opportunities to control and monitor mining operations at new levels of supervision. Integration is key for the mine of the future, as connecting hardware, operational technology, and information technology will allow improvement in the mining operation.

10.2 Research Contributions

This stochastic-deterministic model can be integrated into the management decision-making process to predict key performance indicators of autonomous haulage technology at a potential application site. By comparing manual to autonomous haulage, improvements can be made to improve the utility of an AHS fleet and guide production management.

Manual processes have high variations, because driver skills and other factors affect performance. In contrast, autonomous trucks can be programmed to operate at best braking and acceleration rates throughout the haul such that variations are predictable and controllable. As well, AHS can maintain speed at the highest gear efficiency to give significant savings in tire wear and fuel consumption. The model can be used to study fuel efficiency of AHS systems by finding the best target for each gear, i.e., finding the range of highest gear efficiency.

The model uses fuzzy logic to correlate tire wear to truck speed and payload. Using the model in this work provides also a dynamic estimation of temperature beyond which a truck must stop to allow cool-down or to re-assign the truck to less intense use instead of using TKPH models.

Vehicle Monitoring System provides a TKPH calculation automatically using data that may not be of high quality (time duration issues) and is not applied accurately a dynamic way. As a result, TKPH calculation gives an average value of temperature that it serves merely as an alarm (Joseph, 2012). The use of tire temperature sensors that is now becoming more prevalent can be used to validate the model. The model can be calibrated to reflect known operating conditions at a specific mine site and can be adjusted throughout the life of a set of tires to reflect current tire conditions. When validated, the model could predict tire temperature and tire wear of a specific mine. Tire temperature changes and tire wear are predicted in the model when hauling or idling.

10.3 Recommendations for Future Work

- Tire temperature model needs to be verified and validated against real data. If data is available regarding tire wear and tire temperature, the parameters in the model formulae can be adjusted. This model was developed with the intention to open future studies when data become unavailable. Despite this short-coming, the formulae in the model are empirical in nature and can be verified to fit real data from any specific mine site.

- Data for AHS maintenance is needed to derive the nature of the impact of an AHS system on scheduled maintenance.

- The data (583 samples) in this research was taken from the VIMS© software at the Lucy mine which allowed verification to be done. The model should be extended to simulate the entire mine to establish the running time for a more complex mine model. There are potential improvements likely in how the model operates in order to conduct different study goals.

- The model can be used to study fuel efficiency of AHS or manual systems by finding the range of highest efficiency for each gear. Setting truck speed within the range of the highest gear efficiency will decrease fuel consumption and maintenance.

- It would be interesting to bring this tool into an online environment such that KPIs could be automatically monitored and analysed in real time (it can be run in 3D for graphical output visualization). Automated real-time KPI measurement could be incorporated as a basic control system to be used as reference points when making real time decisions for either a manual fleet or an AHS.

- A module to simulate how an AHS communication system operates would be a useful feature to add to this system. Simulation studies of COM network issues would allow an estimation of scale-up with respect to network latency and bandwidth constraints. Appendix 20 provides an overview and discussion of this potential sub-model.

10.3 Conclusion

1. The base case run showed that AHS improves the fuel consumption KPI by 5.3% for L/cycle and 6.1% for L/t. Tire wear KPI (mm/cycle) improved by 7.6% and production increased about 21.3% based on manual fleet averages. Process delays decrease because of the elimination of shift changes and human breaks.

2. The case studies considering fleet size optimization, gear change efficiency, as well as safety constraints. Case 1 compared 7, 8, 9 and 10 trucks maintaining the same speed as the base case for both manual and AHS. The 7-truck scenario showed a difference in production between manual and AHS of -5%, with 8 trucks yielding +7.7%, 9 trucks

showing +20.8% and 10 trucks giving +34% increased production. Adding more trucks to the fleet increased queuing which led to an increase in cycle time.

3. Case Study 2 focused on removing stop signs at intersections. Trucks are set to slow down at an intersection, but not stop unless another truck is closer than 50m. The results showed that 7 AHS trucks could match the production of a 9-truck manual fleet under this condition. Queuing time increased slightly. Production from the 8-truck AHS improved 14.9% due to a 15.6% decrease in cycle time when stop signs were not used.

4. Case Study 3 considered the AHS running as an Aggressive manual driver with a small variation. The speed was set to 18.5% above the base case when a truck is empty and 13.8% above the base case when a truck is loaded. The results showed some improvement in productivity, but queuing time increased compared to the AHS base case.

5. The study on safety constraints showed that decreasing the safe-following distance has no advantage in improving KPIs. Gear efficiency results showed a small change as well, but this case study took a conservative approach to simply show that the model can be used in the future to attempt to increase fuel efficiency.

6. An economic assessment of an AHS compared to a manual system shows an after-tax incremental DCFROR of 48.7% when comparing a 7-truck AHS fleet to a 9-truck manual system both of which were designed to achieve equivalent production.

11 Claims to Original Research

I claim the following as original research developed during the conduct of this project:

1. An integrated framework for business decision analysis for mine planning using computer based simulation. Designed to look at an Autonomous Haulage System, the model can be used to study costs and production effects of changes in manual operations as well. Integration of data is the key to the success of this modeling approach.

2. A hybrid simulation model employing deterministic simulation for moving trucks on haul roads, and stochastic simulation for generating load and dump times, production and operational delays for haulage truck systems has been developed. The system contains several novel sub-models on vehicle movement, fuel consumption, tire wear, dynamic rolling resistance prediction, and driver behaviour.

3. The fuel consumption model allows future study of the impact of gear changes on the efficiency of power use.

4. The tire wear model incorporates payload, speed, and tire temperature as key factors that affect tire wear. The model can be calibrated with ease at any mine site and could be a replacement for the TKPH alarm system in current use.

5. The rolling resistance model allows a mine to estimate dynamic changes in rolling resistance and traction coefficient which can assist in scheduling auxiliary equipment (graders and water trucks).

6. A unique approach to modeling human driver behaviours has been developed based on characterizing drivers as passive, normal, or aggressive.

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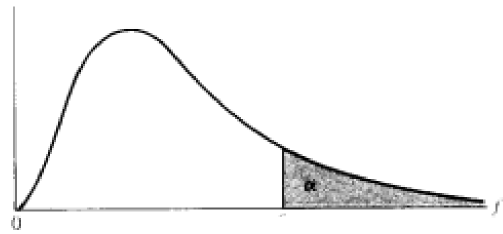
Appendix 1: Equivalency Testing

Hypothesis:

H_0: $F_{calculated} \leq F_{critic}$

H_1: $F_{calculated} > F_{critic}$

Criteria: P(95) = F_{critic} = 3.80



F_{critic}

Where F_{critic} is based on N1 and N2 degree of freedom:

$$N1 = total_{group} - 1 \quad \text{and} \quad N2 = Total_{sample} - total_{group}$$

Table 34. Fisher-Snedecor distribution test

VIMS©							
	Payload	V_{full}	V_{empty}	Loading	Unloading	Cycle	L/hour
Ave	221.52	13.76	27.53	2.88	4.61	44.02	229.81
S.D.	10.41	0.88	2.25	0.88	6.06	8.63	27.23
variance	108.37	0.77	5.06	0.77	36.72	74.48	741.47
Number of Samples (VIMS©)							583
Model							
	Payload	V_{full}	V_{empty}	Loading	Unloading	Cycle	L/hour
Average/Total	222.92	13.41	26.95	2.46	5.27	46.91	229.12
S.D.	9.14	0.73	2.18	0.89	6.93	7.36	27.36
Variance	83.54	0.53	4.75	0.79	48.02	54.17	748.57
Number of Samples (model)							522
$F_{calculated}$	1.30	1.45	1.07	0.98	0.76	1.37	0.99
Average/Total	222.18	13.59	27.26	2.68	4.92	45.39	229.48
SQE	539.80	33.74	92.65	48.58	119.97	2300.24	131.12
SQD	106,594	728	5,422	863	46,394	71,568	821,542
$F_{calculated}$	0.01	0.05	0.02	0.06	0.00	0.03	0.00
F_{critic}							3.8
Total Group							2
Criteria							95%

where:

$Ave_{total} = Ave_{group1}*Sample_{group1} + Ave_{group2}*Sample_{group2}/ Sample_{group1}+ Sample_{group2}$

$SQE = (Ave_{total} - Ave_{group1})^2 * Sample_{group1} + (Ave_{total} - Ave_{group2})^2 * Sample_{group2}$

$SQD = Ave_{group1} – (Sample_{group1} -1) + Ave_{group1} – (Sample_{group1} -1)$

$F_{calculate} = SQE / SQD$

For all outputs where $F_{calculate} < F_{critic}$ at a confidence level of 95%; H_0 is true, i.e., there is no statistical difference between the means of the two groups.

Equivalence Testing

In order to compare the performance of the modelling approach to a real system, statistical equivalence between them must be considered (Deo, 2004). The key to equivalence testing is the subjective choice of a region within which differences between model and real system data is considered negligible (Robinson et al., 2004). Stabilising the indifference region allows the determination if the confidence level of the mean of the differences, is totally contained within that region. If the region of indifference does not encompass the confidence interval, then the null hypothesis of difference is not rejected; however, if indifference region encompasses the confidence level, the two populations are "suggestively" similar (Robinson et al., 2004).

The two groups: model data and Lucy mine data were compared using different tests to verify equivalency. In order to choose a test that better suits the testing, it is important to understand the samples. The groups are independent; each group has more than 500 samples (Appendix 16), and the data has absolute values. With data that are normally distributed, the two-sample t-test and p-value was used to test for equivalence and for those in which normality is not present, the Mann-Whitney procedure was used (Wellek, 2003).

SSPS© gives the data statistics to verify if a data set has a normal distribution. The construction of a 95% confidence interval about a skewness score enables the evaluation of the variability of the estimate (Thode, 2002). The key value is whether the value of 'zero' is within the 95% confidence interval. If the statistic range is within -1 to +1, then one can say that the data set is not different from a normally-distributed population (Hildebrand, 1986). Table 35 shows that the variables, Payload, Travel Empty Distance, Loaded Velocity, Empty Velocity, Travel Loaded, and Travel Empty are normally distributed.

Table 35. Data statistics

Descriptive					
	Flag		Statistic	Std. Error	Equivalent Test
Payload (tonnes)	1	Skewness	.000295	.1012742	t-test
	2		.042355	.1039754	
Loaded Travel Distance(Km)	1		.022091	.1012742	Mann-Whitney
	2		***-2.574820***	.1039754	
Travel Empty Distance(Km)	1		-.213634	.1012742	t-test
	2		-.093769	.1039754	
Loaded Velocity (Km/h)	1		-.034402	.1012742	t-test
	2		-.516581	.1039754	
Empty Velocity (Km/h)	1		-.334561	.1012742	t-test
	2		-.358649	.1039754	
Travel loaded (min)	1		.376927	.1012742	t-test
	2		.862846	.1039754	
Travel Empty (min)	1		.573316	.1012742	t-test
	2		.233134	.1039754	
Unloading(minutes)	1		***3.620077***	.1012742	Mann-Whitney
	2		***4.853354***	.1039754	
Loading Time (min)	1		***1.513072***	.1012742	Mann-Whitney
	2		***2.610031***	.1039754	
Cycle Time (min)	1		***2.721955***	.1012742	Mann-Whitney
	2		***3.410051***	.1039754	
Fuel Consumption(L)	1		***3.170994***	.1012742	Mann-Whitney
	2		***1.199156***	.1039754	
Fuel Rate (L/Hr)	1		-.613333	.1012742	Mann-Whitney
	2		***-1.838231***	.1039754	
Fuel Consumption(L/t)	1		***2.911260***	.1012742	Mann-Whitney
	2		.762885	.1039754	

** Flag =1 (VIMS©) and Flag =2 (Model)*

SSPS Statistical Software

The equivalence test was done using IBM SSPS© software Version 18 and was performed using Levene's Test, "two-sample t-test", and Mann-Whitney. The Mann-Whitney test is a nonparametric test of the null hypothesis that is used to verify if two groups are the same against an alternative hypothesis when the distribution does not follow normality (Gravetter, 2009).

Table 37 shows that when performing the two-sample t-test, the loaded velocity and empty velocity variables do not show equivalency in their means. However, using the inference of equivalence based on probability p-values, only payload did not show equivalency in means. Table 38 shows that the means are equivalent for data sets that do not have a normal distribution.

Table 36. "t-test" statistics

t Table

cum. prob	$t_{.50}$	$t_{.75}$	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.99}$	$t_{.995}$	$t_{.999}$	$t_{.9995}$
one-tail	**0.50**	**0.25**	**0.20**	**0.15**	**0.10**	**0.05**	**0.025**	**0.01**	**0.005**	**0.001**	**0.0005**
two-tails	**1.00**	**0.50**	**0.40**	**0.30**	**0.20**	**0.10**	**0.05**	**0.02**	**0.01**	**0.002**	**0.001**
df											
1	0.000	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.000	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.000	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.000	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.000	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.000	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.000	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.000	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.000	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.000	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.000	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.000	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.000	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.000	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.000	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										

Table 37. Equivalence test for normal distributed data

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Payload (tonnes)	**1**	.534	.465	.619	1132	.536	.3743890	.6050274	-.8127122	1.5614902
	2			.620	1131.974	.536	.3743890	.6042574	-.8112015	1.5599795
Travel Empty Distance(Km)	**1**	185.585	.000	-13.228	1132	.000	-.3993737	.03019097	-.45861028	-.34013714
	2			-13.060	883.969	.000	-.3993737	.03057959	-.45939078	-.33935664
Loaded Velocity (Km/h)	**1**	12.723	.000	5.760	1132	.000	.2788669	.0484105	.1838825	.3738513
	2			5.788	1114.678	.000	.2788669	.0481843	.1843247	.3734091
Empty Velocity (Km/h)	**1**	3.613	.058	3.705	1132	.000	.4673028	.1261390	.2198103	.7147953
	2			3.717	1125.620	.000	.4673028	.1257126	.2206454	.7139602
Travel loaded (min)	**1**	55.859	.000	-14.427	1132	.000	-1.2798585	.0887144	-1.4539218	-1.1057953
	2			-14.550	1054.650	.000	-1.2798585	.0879632	-1.4524614	-1.1072557
Travel Empty (min)	**1**	31.545	.000	-11.715	1132	.000	-1.0678535	.0911519	-1.2466992	-.8890079
	2			-11.645	1051.406	.000	-1.0678535	.0916973	-1.2477841	-.8879230

** Flag =1 (VIMS©) and Flag =2 (Model)*

Table 38. Equivalence test for non-normal distributed data

Variable	Loaded Travel Distance (km)	Loaded Velocity	Empty Velocity	Unloading Time	Loading Time	Cycle Time	Fuel Consumption (L/h)	Fuel Rate	Fuel Consumption (L/t)
Mann-Whitney U	115811	129577	140150	155724	118881	144779	102875	141344	93996
Z	-8.147	-5.634	-3.716	-.890	-7.574	-2.876	-10.478	-3.499	-12.088

Table 39. Fisher-Snedecor table

		GL_1									
GL_2	$P(F>)$	1	2	3	4	5	6	7	8	9	10
29	0,100	2,89	2,50	2,28	2,15	2,06	1,99	1,93	1,89	1,86	1,83
	0,050	4,18	3,33	2,93	2,70	2,55	2,43	2,35	2,28	2,22	2,18
	0,025	5,59	4,20	3,61	3,27	3,04	2,88	2,76	2,67	2,59	2,53
	0,010	7,60	5,42	4,54	4,04	3,73	3,50	3,33	3,20	3,09	3,00
	0,005	9,23	6,40	5,28	4,66	4,26	3,98	3,77	3,61	3,48	3,38
	0,001	13,39	8,85	7,12	6,19	5,59	5,18	4,87	4,64	4,45	4,29
30	0,100	2,88	2,49	2,28	2,14	2,05	1,98	1,93	1,88	1,85	1,82
	0,050	4,17	3,32	2,92	2,69	2,53	2,42	2,33	2,27	2,21	2,16
	0,025	5,57	4,18	3,59	3,25	3,03	2,87	2,75	2,65	2,57	2,51
	0,010	7,56	5,39	4,51	4,02	3,70	3,47	3,30	3,17	3,07	2,98
	0,005	9,18	6,35	5,24	4,62	4,23	3,95	3,74	3,58	3,45	3,34
	0,001	13,29	8,77	7,05	6,12	5,53	5,12	4,82	4,58	4,39	4,24
40	0,100	2,84	2,44	2,23	2,09	2,00	1,93	1,87	1,83	1,79	1,76
	0,050	4,08	3,23	2,84	2,61	2,45	2,34	2,25	2,18	2,12	2,08
	0,025	5,42	4,05	3,46	3,13	2,90	2,74	2,62	2,53	2,45	2,39
	0,010	7,31	5,18	4,31	3,83	3,51	3,29	3,12	2,99	2,89	2,80
	0,005	8,83	6,07	4,98	4,37	3,99	3,71	3,51	3,35	3,22	3,12
	0,001	12,61	8,25	6,59	5,70	5,13	4,73	4,44	4,21	4,02	3,87
60	0,100	2,79	2,39	2,18	2,04	1,95	1,87	1,82	1,77	1,74	1,71
	0,050	4,00	3,15	2,76	2,53	2,37	2,25	2,17	2,10	2,04	1,99
	0,025	5,29	3,93	3,34	3,01	2,79	2,63	2,51	2,41	2,33	2,27
	0,010	7,08	4,98	4,13	3,65	3,34	3,12	2,95	2,82	2,72	2,63
	0,005	8,49	5,79	4,73	4,14	3,76	3,49	3,29	3,13	3,01	2,90
	0,001	11,97	7,77	6,17	5,31	4,76	4,37	4,09	3,86	3,69	3,54
120	0,100	2,75	2,35	2,13	1,99	1,90	1,82	1,77	1,72	1,68	1,65
	0,050	3,92	3,07	2,68	2,45	2,29	2,18	2,09	2,02	1,96	1,91
	0,025	5,15	3,80	3,23	2,89	2,67	2,52	2,39	2,30	2,22	2,16
	0,010	6,85	4,79	3,95	3,48	3,17	2,96	2,79	2,66	2,56	2,47
	0,005	8,18	5,54	4,50	3,92	3,55	3,28	3,09	2,93	2,81	2,71
	0,001	11,38	7,32	5,78	4,95	4,42	4,04	3,77	3,55	3,38	3,24
infinito	0,100	2,71	2,30	2,08	1,94	1,85	1,77	1,72	1,67	1,63	1,60
	0,050	3,84	3,00	2,60	2,37	2,21	2,10	2,01	1,94	1,88	1,83
	0,025	5,02	3,69	3,12	2,79	2,57	2,41	2,29	2,19	2,11	2,05
	0,010	6,63	4,61	3,78	3,32	3,02	2,80	2,64	2,51	2,41	2,32
	0,005	7,88	5,30	4,28	3,72	3,35	3,09	2,90	2,74	2,62	2,52
	0,001	10,83	6,91	5,42	4,62	4,10	3,74	3,47	3,27	3,10	2,96

Appendix 2: Basic Steps to Create an ExtendSim Model (ExtendSim, 2007)

The basic steps to create a model are:

1) Formulate the problem. Define the problem and state the model objectives.

2) Describe the flow of information. Determine where information flows from one part of the model to the next and which parts need information simultaneously.

3) Build and test the model. Build the system with ExtendSim blocks. Start small, test as you build, and enhance as needed.

4) Acquire data. Identify, specify, and collect the data needed for the model. This is usually the most time-consuming step. It includes finding not only numerical data values, but also mathematical formulas such as distributions for random events.

5) Run the model. Determine how long you want to simulate and the granularity of the results, then run your model.

6) Verify simulation results. Compare model results to what was intended or expected.

7) Validate the model. Compare the model to the real system, if available. Or have system experts evaluate the model and its results.

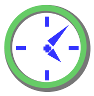
8) Analyze your results. Draw inferences from the model results and make recommendations on how the system can change.

9) Conduct experiments. Implement and test recommended changes in the model.

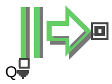
10) Document. State the model's purpose, assumptions, techniques, modeling approaches, data requirements, and results.

11) Implement decisions. Use the results in the real world.

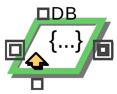
Appendix 3: Blocks Used in the Model



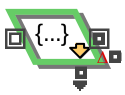
Executive Block - Does event scheduling and provides simulation control, item allocation, attribute management, and other discrete-event settings.



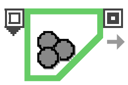
Create Block - Provides items or values for a discrete event simulation at specified inter-arrival times.



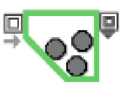
Set Block - Attaches user-assigned properties (attributes, priorities, and quantities) to items passing through the model.



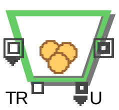
Get Block - Displays and outputs properties from items that are passing through the model.



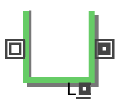
Batch Block- Joins multiple items into a single item for use in the model.



Unbatch Block - Outputs multiple items for each input item.

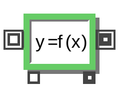


Resource Item Block - The block stores resources as items for use in the model.

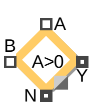


Queue Block - Stores items until there is downstream capacity. As a sorted queue, holds items in FIFO or LIFO order, or sorted by their priority or attribute value.

Select Item Out Block - Selects which output gets which items from which input based on a decision.



Equation Block - Calculates equations when an item passes through.



Decision Block - Makes a decision and outputs TRUE or FALSE values based on the inputs and defined logic.

Appendix 4: Important Processes in the Model

1) Resources Allocation Process

The model flows from left to right. The first item on the left (the clock), is the Executive Block that allocates items and manages attributes. The model has three types of item resources: drivers, trucks, and spares. Each resource carries many attributes, such as Driver Behavior, Truck MTBF, Production, Cycle Time, etc. As the shift starts, the drivers and trucks are batched together. The model separates these two item resources when there is a coffee break, lunch, preventive maintenance, refuelling, or in the case of a run-to-failure situation.

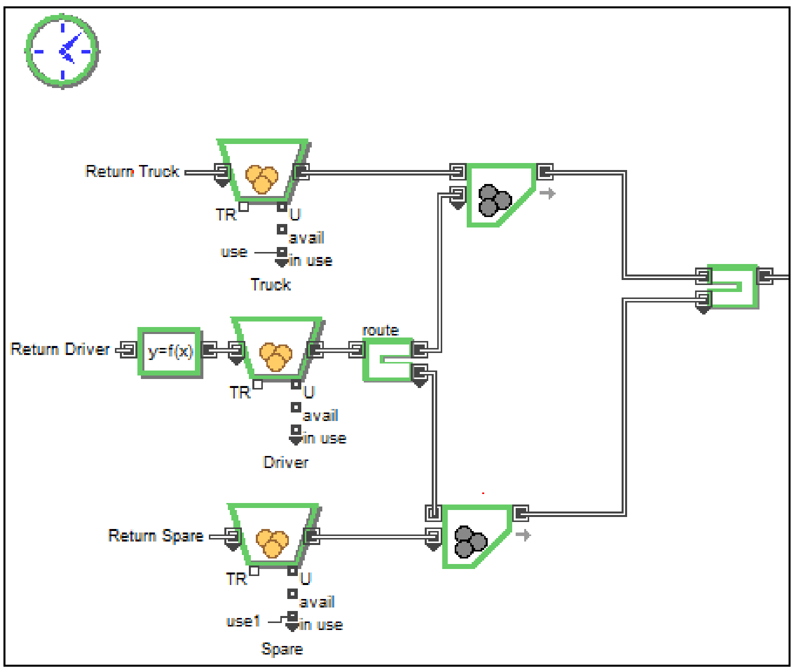


Figure 42. Drivers and trucks resource item are batched at the beginning of shift.

2) Digging and Loading Process

A Create Block generates scheduled items (materials) to simulate a daily mining schedule. The schedule feature in Create Block defines when the item arrives; the time between arrivals follows a relatively fixed distribution causing items to be generated by a specific arrival rate. After an item is created, it must be submitted to one batch process that uses Batch Blocks to simulate the transformation of items. The batch process put together a shovel, a truck and material. A Queue Block is placed before this batch process to calculate truck waiting time. After the loading process, the resource *Shovel* is released to be used in the next loading process and the item (material + truck + driver) moves through the model.

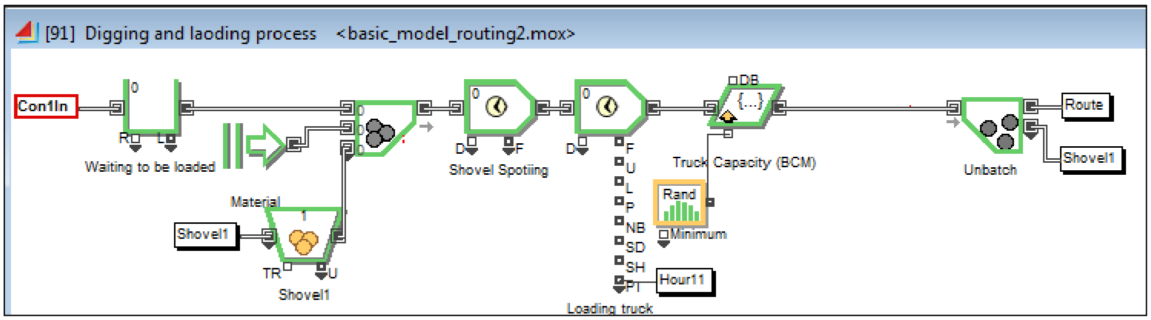


Figure 43. Loading process used in the model.

A Queue Block is also placed before the unload activity to calculate truck unloading wait time. The repeated action load/unload process will take place until a shift change, lunch, coffee break, maintenance or refuelling. According to the Lucy mine data, there are two kinds of maintenance: minor - where the problem can be solved quickly and major - where maintenance can take days. In the latter case, spares may be available.

Attributes allow items to be distinguished from one to another. An item will leave the Set Block with general characteristics such as: bucket/truck capacity (quantity), route factors, delays, etc. These attributes are established according to the mine data. In addition to attributes, road conditions, truck weight, fuel consumption, and tire wear are also considered.

Regarding truck and shovel maintenance, certain attributes of the item *Trucks* are used to track information such as accumulated travel time (MBTF). If a truck accumulates a specific travel time, it is sent for maintenance and the accumulated hours are reset to 0. The Resource Item block attaches an *AcumHours* attribute for each piece of equipment. During equipment operation, the *AcumHours* is increased by an Equation Block which obtains the

Shovel/Truck working time and adds it to the Truck's or Shovel's *AcumHours* attribute. After the equipment is unbatched from the material, and before the equipment returns to the Resource Item block for reuse, a Get block reads the value of the equipment's *AcumHours* attribute and the Decision block determines if the accumulated time is greater than the specific time set. If that is the case, the equipment is routed to the maintenance group for processing. After maintenance, the Set block re-initializes the *AcumHours* attribute to zero. If *AcumHours* is not greater than the specific time set, the equipment is returned to the Resource Item block where it will be available for new activity.

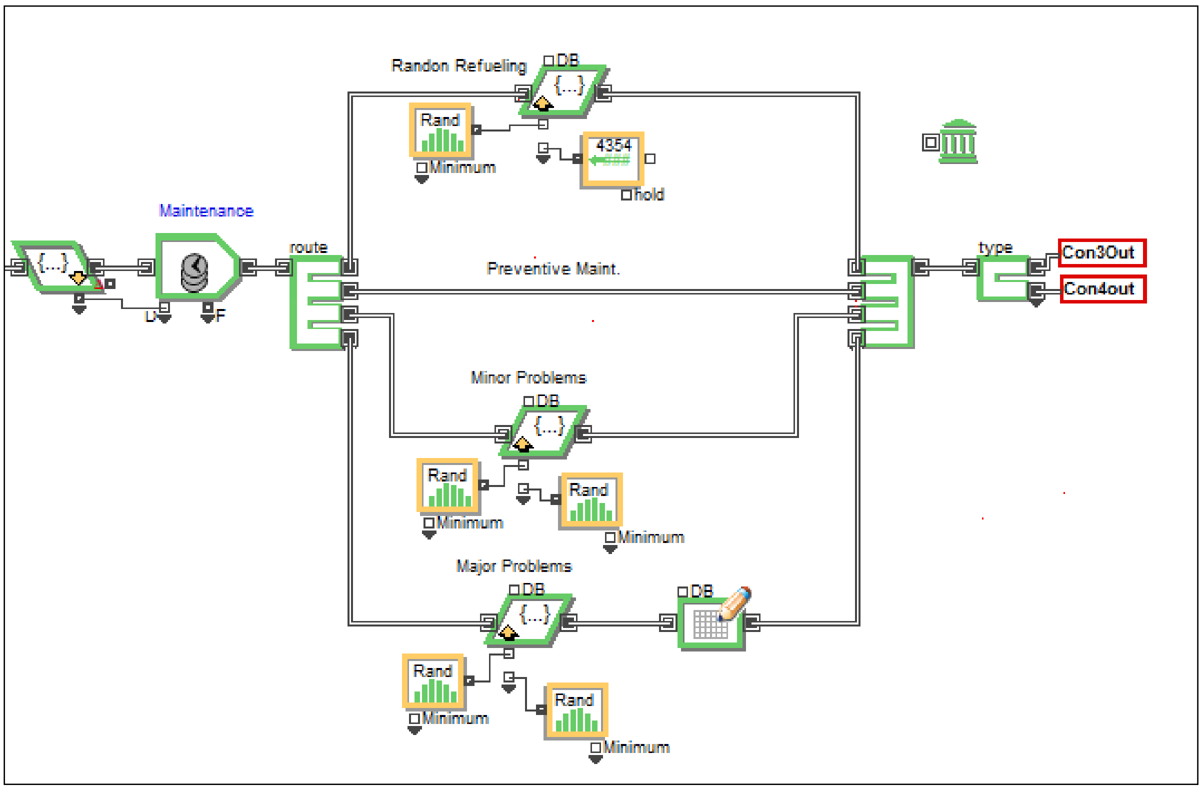


Figure 44. Routes for maintenance and other breaks.

Appendix 5: Rimpull Curve and Retarder Curve – CAT 793D

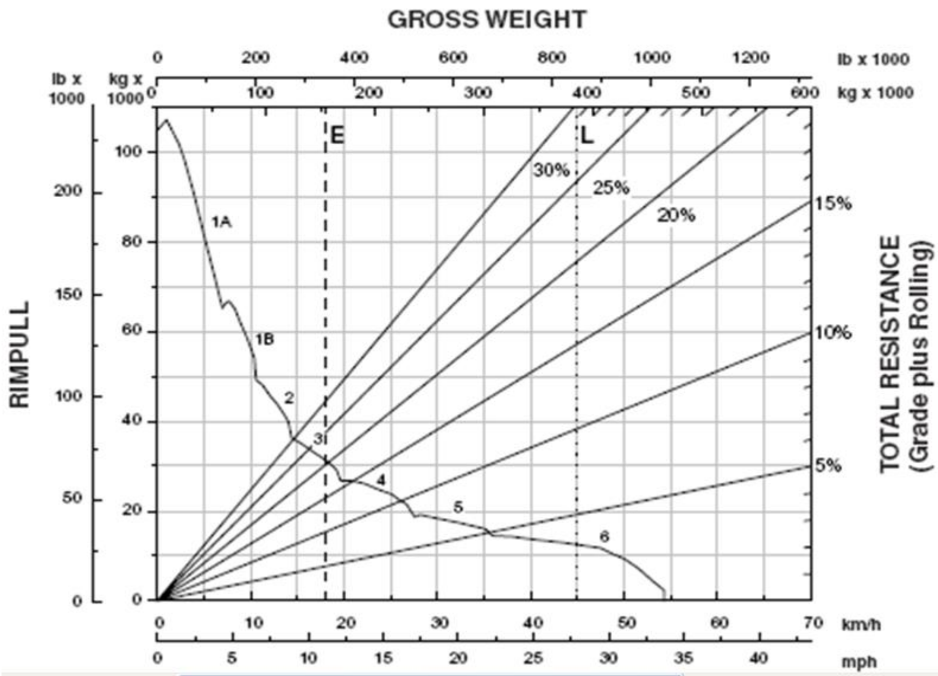


Figure 45. Rimpull curve – 793D, (Caterpillar 1, 2007).

Table 40. Linear equations of the above graph.

#	Linear Equation	Gear	Speed (mph)
1	R(v) = 228,04 +5,36*V	1A	0 - 1
2	R(v) = 258,15-26,70*V	1A'	1 - 4.25
3	R(v) = 124,41+4,76*V	1A'/1B	4.5 - 5
4	R(v) = 255,36 - 21,43*V	1B	5 - 6.5
5	R(v) = 189,04 - 11,6*V	2	6.5 - 8.75
6	R(v) = 123,62 - 4,95*V	3	8.75 - 12
7	R(v) = 267,99 - 16,98*V	3 / 4	12 - 12.4
8	R(v) = 98,57 - 3,34*V	4	12.4 - 17.40
9	R(V) = 74,86 - 1,94*V	5	17.40 - 22
10	R(V) = 189,23 - 7,14*V		22 - 22.5
11	R(V) = 40,09 - 0,511* V	6	22.5 - 29.5
12	R(V) = 148,9 - 4,2*V		29.5 - 33.75

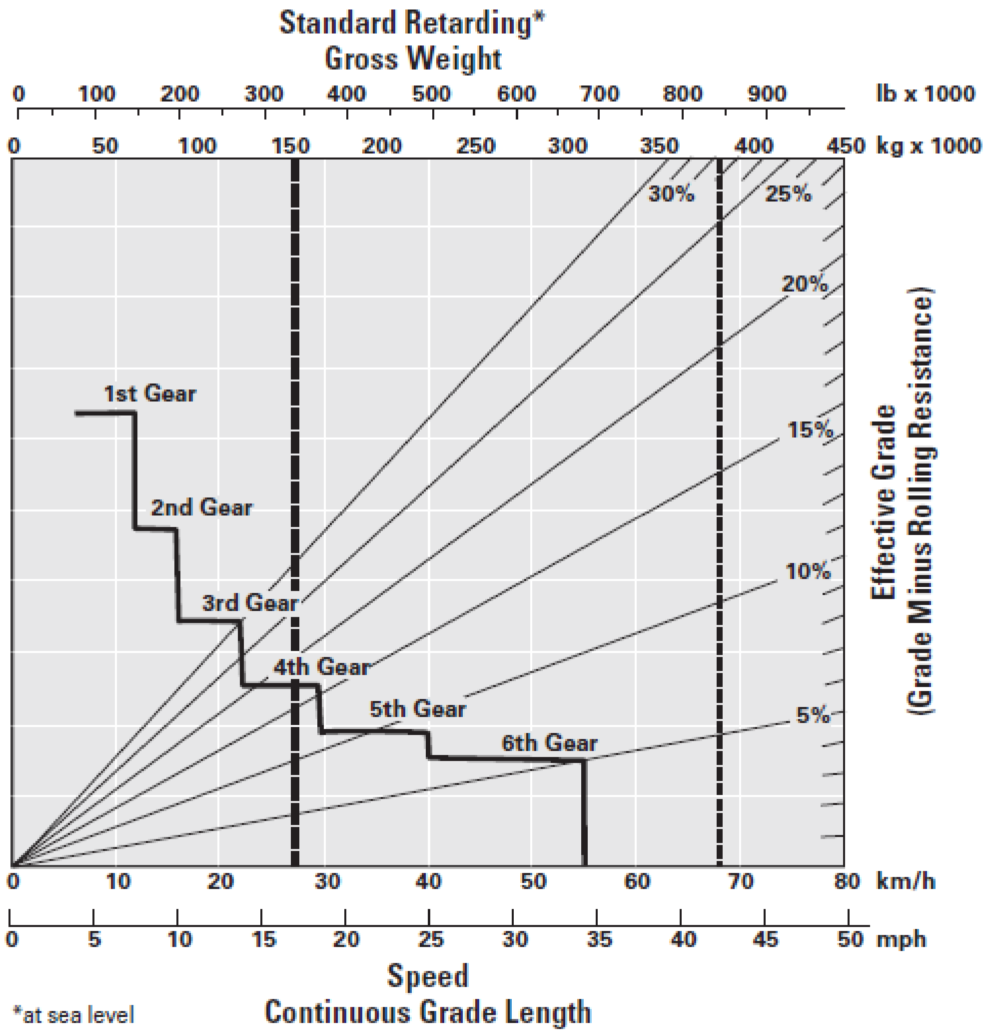


Figure 46. CAT 793D retarder curve, (Caterpillar 1, 2007).

Appendix 6: Traction and Rolling Resistance Coefficient

Table 41. Traction coefficient for different road surfaces, (Terex, 1970).

MATERIAL	TRACTION FACTORS	
	Rubber Tyres	***Tracks***
Concrete	0.9	0.45
Clay loam, dry	0.55	0.9
Clay loam, wet	0.45	0.7
Rutted dry loam	0.40	0.7
Dry sand	0.20	0.3
Wet sand	0.40	0.5
Quarry pit	0.65	0.55
Gravel road (loose not hard)	0.36	0.5
Packed snow	0.20	0.27
Ice Semi-skeleton shoes	0.12	0.12
Firm earth	0.55	0.9
Loose earth / stockpiled coal	0.45	0.6

Table 42. Rolling resistance factor for different road surfaces, (Terex, 1970).

Under-footing	Rolling Resistance	
	F_{RR} (kg/t)	(%)
Hard, smooth surface with no tire penetration (well maintained).	20	2
Firm, smooth surface, flexing slightly under load (well maintained).	33	3.3
Flexible, dirt roadway (irregular surface with about 2.5 cm of tire penetration)	50	5
Flexible, dirt roadway (irregular surface with up to 10 cm of tire penetration)	75	7.5

Appendix 7: Fuzzy Logic

Fuzzy Logic is a form of probabilistic (or possible) logic that deals with reasoning that approximates an answer rather than calculating a fixed and exact value. Fuzzy Logic has a truth value that ranges from 0 to 1 (or 100%) (Novák, 1999). Fuzzy set terminology is shown in Figure 47 (Meech, 2010).

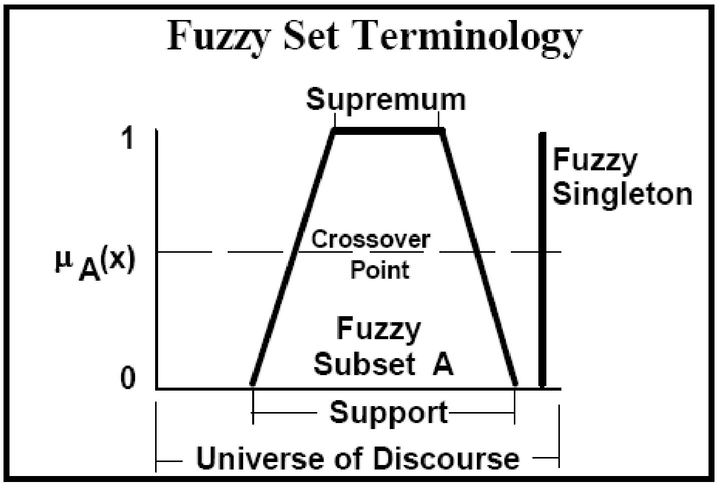


Figure 47. Fuzzy set terminology.

1) Universe of discourse **X** is defined as those elements which can be grouped as identifiable, labeled units from some minimum value to some maximum value.
2) A fuzzy subset **A** of a universe of discourse **X** is characterized by a membership function $\mu_{\mathbf{A}}\mathbf{(x)}$.
3) Cross-over point (or saddle point) of **A** is any element of **X** whose rank in **A** is 0.5 (or 50 %).
4) A singleton is a fuzzy set whose support is a single element of **X**. An integer is a fuzzy singleton. Linguistic terms may also be singletons.
5) The supremum (or height) of a fuzzy set **A** are values of **X** whose rank is 1.0 (or 100 %).
6) The support of a fuzzy set **A** are those values of **X** with a rank greater than 0 (or 0 %).
7) The ratio of the supremum range to the support range is a measure of the uniqueness of a fuzzy set. As this ratio approaches 1.0, the set becomes non-fuzzy or "crisp". As this ratio approaches 0, the set assumes a unique supremum point.

Accumulation Method of Defuzzification

A fuzzy rule base consists of a set of rules that generally relate two fuzzy input variables to a single output. Each variable is characterized by a series of fuzzy terms such as low, medium or high. Three to five terms are generally used. Discrete inputs are mapped into the two sets of fuzzy terms to arrive at a Degree of Belief (DoB) in each term for each variable. The rules combine each fuzzy term of variable 1 with each fuzzy term of variable 2 to conclude about one of the fuzzy terms of the output variable. The relationships are determined by an expert. The Net Degree of Truth (NdT) of each rule is determined by taking the Minimum DoB value of the two fuzzy terms in each rule. That Ndt value is then assigned as the DoB in the particular output fuzzy term. If more than one rule successfully assigns a DoB to the same output term, the Maximum Defuzzification method takes the maximum DoB as the result for that term. The Accumulation Method adds the two DoBs together. Here is an example:

Table 43. The Accumulation method with two DoBs together

(a)

Output Variable		Variable 1		
		Low	Medium	High
Variable 2	Low	Negative-Big	Negative-Small	No Change
	Medium	Negative-Small	No Change	Positive-Small
	High	No Change	Positive-Small	Positive-Big

(b)

Output Variable		Variable 1		
		Low (DoB = 20)	Medium (DoB=80)	High (DoB = 0)
Variable 2	Low (DoB = 0)	Negative-Big	Negative-Small	No Change
	Medium (DoB = 40)	Negative-Small DoB = 20	No Change DoB = 40	Positive-Small
	High (DoB = 60)	No Change DoB = 20	Positive-Small DoB = 60	Positive-Big

To obtain a discrete output value for the Output Variable, the Supremum values of each set is weighted by its DoB level as follows for the Accumulation Method:

$$\text{Output Variable} = \frac{\text{SupremumNS} * 20 + \text{SupremumNC} * 20 + \text{SupremumNC} * 40 + \text{SupremumPS} * 60}{20 + 20 + 40 + 60}$$

Fuzzy Logic Rules to Characterize the Rolling Resistance Factor

Table 44. When precipitation is none.

Precipitation is "none"		Trucks since Grading			
		None	Low	Medium	High
Trucks since Watering	None	2.7	2.8	2.9	3.1
	Low	2.9	3.2	3.3	3.4
	Medium	3.0	3.3	3.6	3.8
	High	3.1	3.4	3.7	4.0

Table 45. When precipitation is average.

Precipitation is "Average"		Trucks since Grading			
		None	Low	Medium	High
Trucks since Watering	None to Medium	2.7	3.0	3.3	3.6
	High	3.0	3.3	3.6	4.0

Table 46. When precipitation is high.

Precipitation is "High"		Trucks since Grading			
		None	Low	Medium	High
Trucks since Watering	None to High	2.7	3.3	3.6	4.0

Example of Rolling Resistence Calculation

If precipitation is none and number of trucks passing a particular segment since grading is 100, the grading values are: Medium = 67, High = 33; Low and None = 0 (Figure 48).

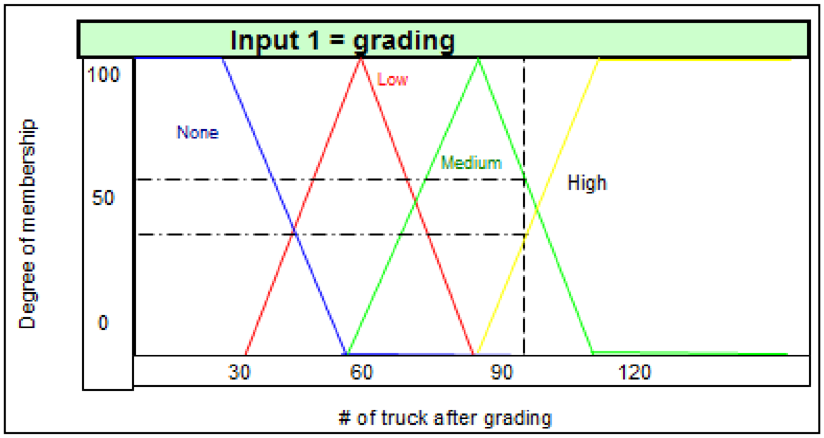


Figure 48. Fuzzification for input variable 1 – grading.

When precipitation is none and the number of trucks passing a particular segment since watering is 90, watering values are Medium = 100; High, Low and None = 0 (Figure 49).

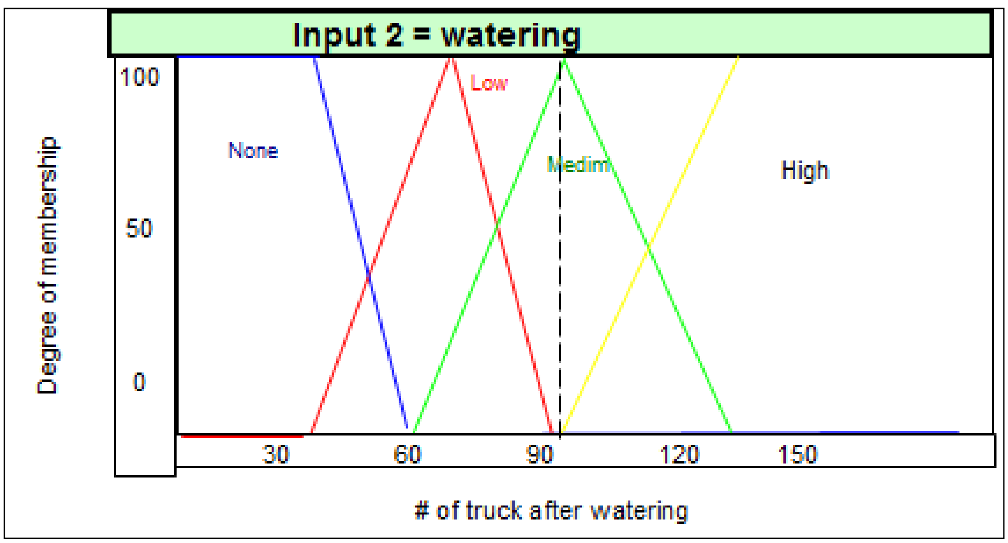


Figure 49. Fuzzification for the input 2 – watering.

After finding the values for input 1 and input 2, the rules are evaluated and the minimum value between the two inputs is chosen (Table 47).

Table 47. Rule evaluation.

Input 2 = 90	Input 1 = 100			
	None = 0	**Low = 0**	**Medium = 67**	**High = 33**
None = 0	min(0, 0) = 0 output: 2.7	min(0, 0) = 0 output: 2.8	min(0, 67) = 0 output: 2.9	min(0, 33) = 0 output: 3.1
Low = 0	min(0, 0) = 0 output: 2.9	min(0, 0) = 0 output: 3.2	min(0, 67) = 0 output: 3.3	min(0, 33) = 0 output: 3.4
Medium = 100	min(0, 100) = 0 output: 3.0	min(0, 100) = 0 output: 3.3	min(67, 100) = 67 output: 3.6	min(33, 100) = 33 output: 3.8
High = 0	min(0, 0) = 0 output: 3.1	min(0, 0) = 0 output: 3.4	min(0, 67) = 0 output: 3.8	min(0, 33) = 0 output: 4.0

The Accumation Defuzzification Method is applied to the the outputs and a discrete output value is obtained for the rolling resistance factor. Figure 50 shows that for this example, the rolling resistance factor is 3.7%.

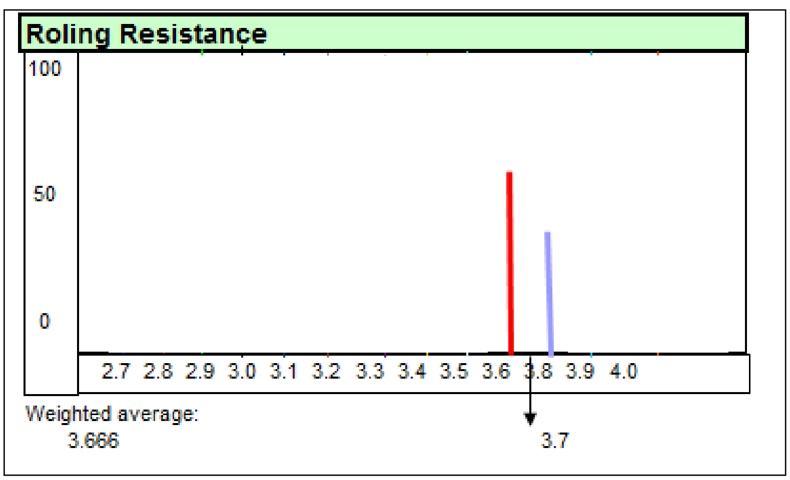


Figure 50. Accumulation defuzzification method for rolling resistance example.

Appendix 8: Altitude Derating of Vehicle Power

At the Lucy mine, the surface topography is 517 m elevation above sea level with a current pit depth of about 600 m. For a 600 m elevation change near sea level, the density of air changes by about 7%. Of this 7%, there is no efficiency loss for a CAT 793 D since the trucks are equipped with Electronic Unit Injection (EUI) which provides automatic increased fuel efficiency as altitude changes (Caterpillar 2, 2007).

Table 48. Altitude derating example.

ALTITUDE DERATING % *				
MODEL	0- 760 m	760-1500 m	1500-2300 m	2300-3000 m
785C*	100	100	100	93
789C*	100	100	100	93
793C*	100	100	100	100
793D	100	100	100	100
793D HAA	100	100	100	100
776D*	100	100	100	100

* EUI engine — Automatic altitude derating.

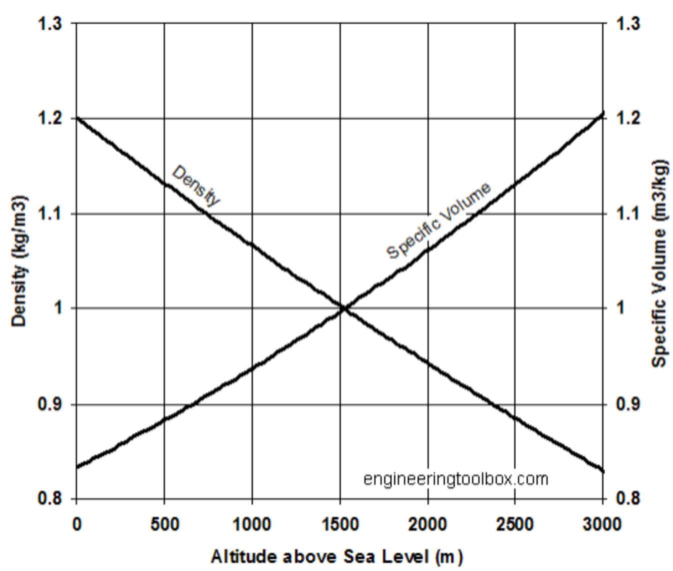
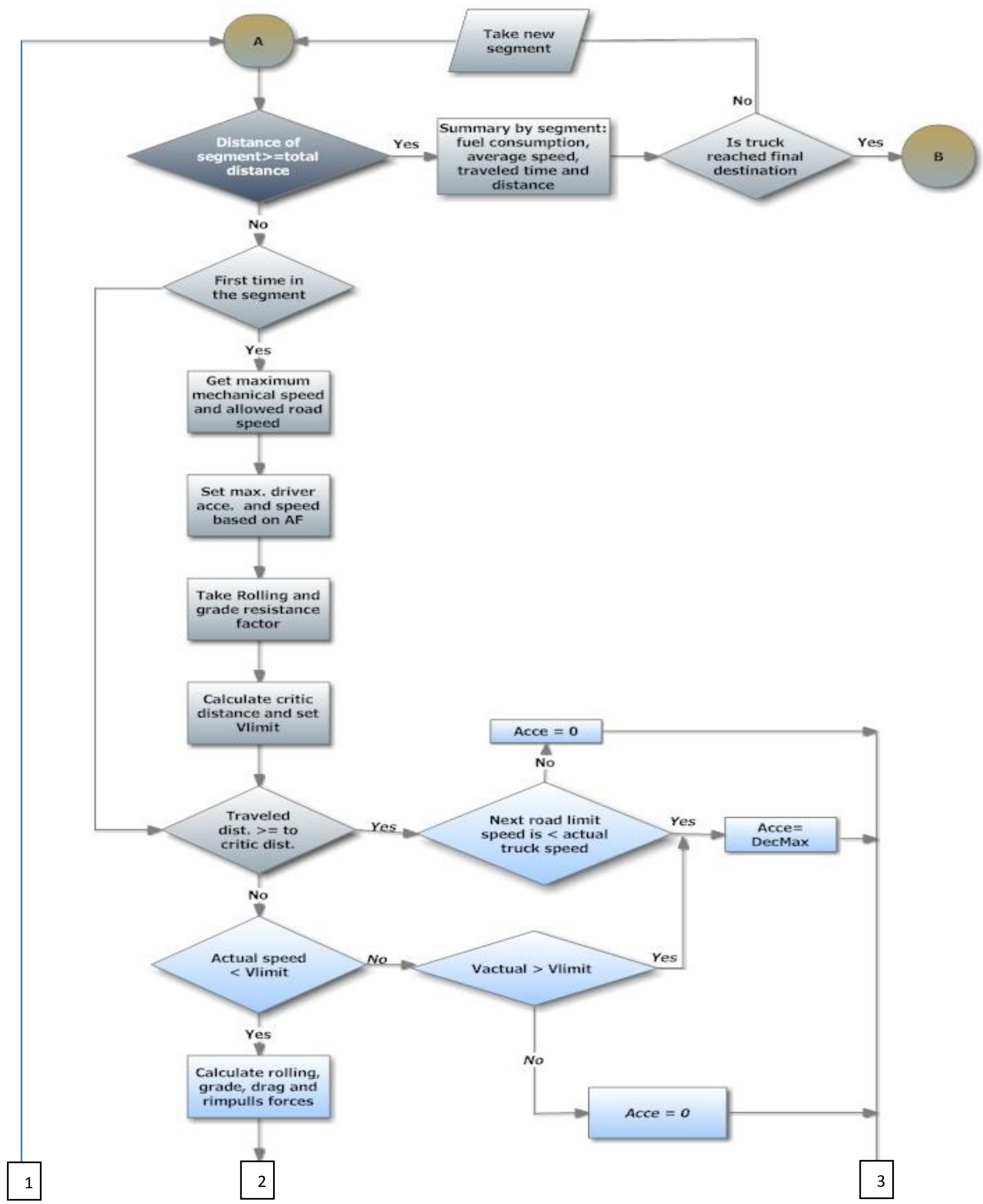


Figure 51. Air density.

Appendix 9: Flowchart: Vehicle Motion and Fuel Consumption Software



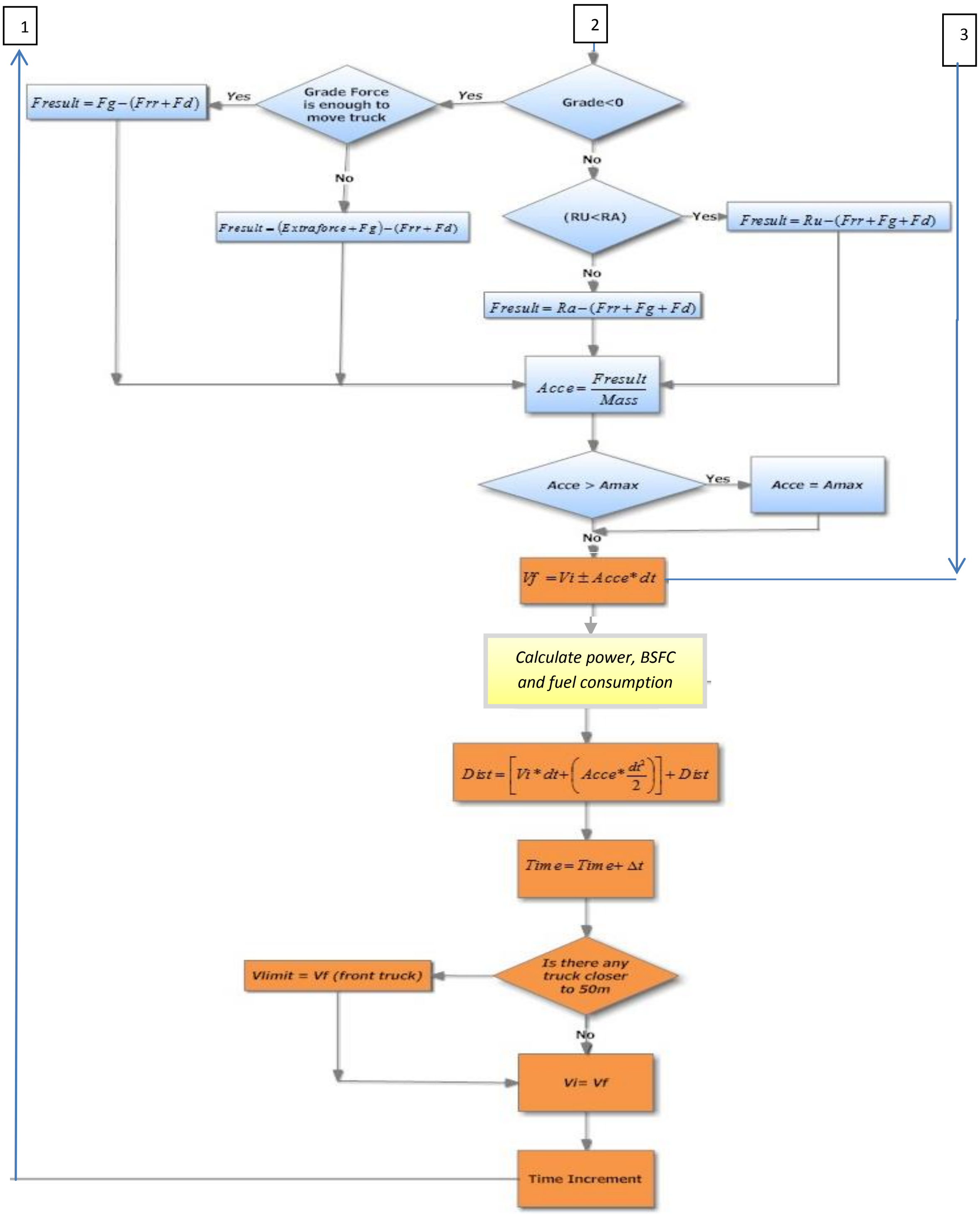


Figure 52. Vehicle motion flowchart. A - start of loop and B - end of loop

Appendix 10: Illustration of Critical Distance

As described in Chapter 5, if the sum of the distances of acceleration and deceleration is less than or equal to the total segment distance ($S1 + S2 \leq S$), then the truck can reach the maximum allowed speed and then reduce speed to adjust to the speed of the next segment (case 1). In this situation, the model only calculates the critical distance. When the length of the segment is not long enough ($S1 + S2 > S$) for the truck to develop the maximum speed and then reduce it to safe limits, it is necessary to calculate a maximum speed that the truck can develop in the segment and then safely reduce its speed (case 2).

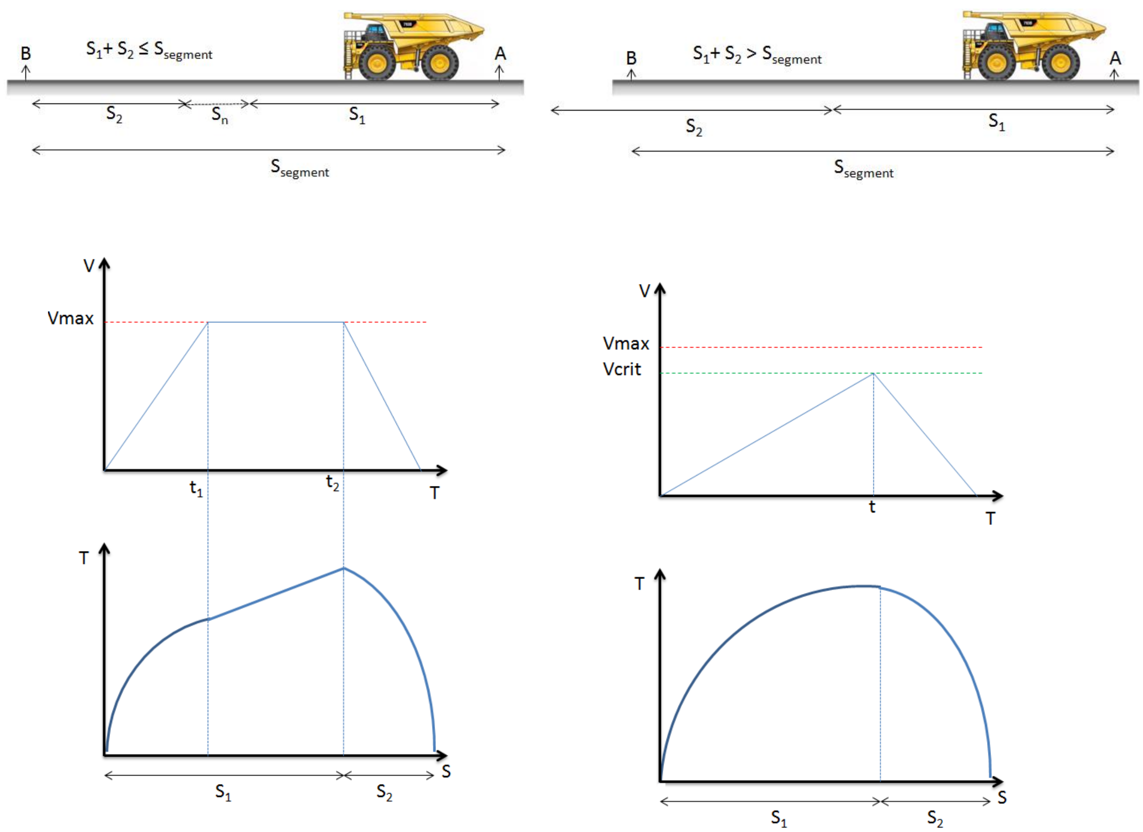


Figure 53. Illustration on the right shows case 1 while the left shows case 2. Top graphs show speed (V) vs. time (T) and bottom graphs show time (T) vs. distance (S).

Appendix 11: Estimating Gear Efficiency

Table 49. Gear efficiency

#	Linear equation	Gear	KM/h	RIMPULL KG (X1000)	POWER (KW)	EFFIC.	REDUCTION	RPM
1	R(v) = 228,04 +5,36*V	**1A**	0.03	103.49	9	0.50%	145.68	7
			0.40	104.05	114	6.33%		88
			0.81	104.65	229	12.74%		175
			1.21	105.26	346	19.22%		263
2	R(v) = 258,15-26,70*V	**1A'**	1.61	104.98	460	25.55%	145.68	350
			2.42	98.93	650	36.12%		525
			2.98	94.69	768	42.64%		647
			3.22	92.87	814	45.21%		700
			3.62	89.85	886	49.20%		787
			4.03	86.82	951	52.83%		875
			4.43	83.79	1010	56.08%		962
			4.83	80.76	1062	58.97%		1050
			5.23	77.73	1107	61.49%		1137
			5.64	74.71	1146	63.64%		1225
			6.04	71.68	1178	65.42%		1312
			6.44	68.65	1204	66.84%		1400
			6.84	65.62	1223	67.88%		1487
3	R(v) = 124,41+4,76*V	**1A'/1 B**	6.84	65.61	1222	67.87%	145.68	1488
			7.25	66.15	1305	72.45%		1575
			7.65	66.69	1389	77.10%		1663
			8.05	67.23	1473	81.81%		1750
4	R(v) = 255,36 - 21,43*V	**1B**	8.05	67.23	1473	81.81%	121.40	1458
			8.45	64.80	1491	82.80%		1531
			8.86	62.37	1504	83.49%		1604
			9.26	59.94	1511	83.88%		1677
			9.66	57.51	1513	83.98%		1750
			10.06	55.08	1509	83.78%		1823
			10.47	52.65	1500	83.29%		1896
			10.87	50.22	1486	82.50%		1969
5	R(v) = 189,04 - 11,6*V	**2**	10.87	50.23	1486	82.53%	88.29	1432
			11.27	48.92	1501	83.34%		1485
			11.59	47.86	1511	83.88%		1527
			12.08	46.28	1522	84.49%		1591
			12.56	44.71	1529	84.87%		1655
			12.88	43.65	1531	85.00%		1697
			13.29	42.34	1531	85.02%		1750
			13.69	41.02	1529	84.87%		1803
			14.09	39.71	1523	84.57%		1856

#	Linear equation	Gear	KM/H	RIMPULL KG (X1000)	POWER (KW)	EFFIC.	REDUCTION	RPM
6	R(v) = 123,62 - 4,95*V	**3**	14.09	36.43	1397	77.58%	60.70	1276
			14.49	35.87	1415	78.57%		1313
			14.90	35.30	1432	79.49%		1349
			15.30	34.74	1447	80.34%		1385
			15.70	34.18	1461	81.12%		1422
			16.10	33.62	1474	81.83%		1458
			16.51	33.06	1485	82.48%		1495
			16.91	32.50	1496	83.05%		1531
			17.31	31.94	1505	83.56%		1568
			17.71	31.37	1513	84.00%		1604
			18.12	30.81	1520	84.38%		1641
			18.52	30.25	1525	84.68%		1677
			18.92	29.69	1529	84.91%		1714
			19.32	29.13	1532	85.08%		1750
7	R(v) = 267,99 - 16,98*V	**3 / 4**	19.32	29.13	1533	85.09%		1750
			19.97	26.05	1416	78.63%		1808
8	R(v) = 98,57 - 3,34*V	**4**	19.97	25.92	1409	78.24%	49.38	1471
			20.53	25.39	1419	78.81%		1513
			20.93	25.02	1426	79.15%		1542
			21.34	24.64	1431	79.45%		1572
			21.74	24.26	1436	79.71%		1602
			22.14	23.88	1439	79.92%		1631
			22.54	23.50	1442	80.08%		1661
			22.95	23.12	1444	80.20%		1691
			23.75	22.36	1446	80.29%		1750
			24.15	21.99	1446	80.27%		1780
			24.96	21.23	1442	80.09%		1839
			25.36	20.85	1439	79.93%		1869
			25.76	20.47	1436	79.72%		1898
			26.17	20.09	1431	79.47%		1928
			26.57	19.71	1426	79.17%		1958
			26.97	19.33	1420	78.82%		1987
			27.38	18.96	1412.60	78.43%		2017
			28.02	18.35	1399.61	77.71%		2064
9	R(V) = 74,86 - 1,94*V	**5**	28.02	18.64	1422	78.96%	37.84	1582
			28.58	18.34	1427	79.22%		1614
			28.99	18.12	1429	79.37%		1636
			29.39	17.90	1432	79.50%		1659
			29.79	17.68	1434	79.60%		1682
			30.19	17.46	1435	79.67%		1705
			30.60	17.24	1436	79.71%		1727
			31.00	17.02	1436	79.73%		1750

#	Linear equation	Gear	KM/H	RIMPULL KG (X1000)	POWER (KW)	EFFIC.	REDUCTION	RPM
9			31.40	16.80	1435.77	79.72%		1773
			31.80	16.58	1435.14	79.69%		1795
			32.21	16.36	1434	79.62%		1818
			32.61	16.14	1432	79.53%		1841
			33.01	15.92	1430	79.42%		1864
			33.41	15.7	1428	79.28%		1886
			33.82	15.48	1425	79.11%		1909
			34.22	15.26	1421	78.91%		1932
			34.62	15.04	1417	78.69%		1955
			35.02	14.82	1413	78.44%		1977
			35.43	14.6	1408	78.16%		2000
10	R(V) = 189,23 - 7,14*V		35.43	14.58	1406	78.09%		2000
			35.83	13.77	1343	74.59%		2023
			36.23	12.96	1279	71.00%		2045
11	R(V) = 40,09 - 0,511* V	**6**	36.23	12.97	1279	71.03%	24.69	1335
			36.63	12.91	1288	71.49%		1350
			37.04	12.85	1296	71.96%		1364
			36.23	12.97	1279	71.03%		1335
			39.29	12.53	1340	74.41%		1447
			40.26	12.39	1358	75.39%		1483
			41.06	12.27	1372	76.18%		1513
			41.87	12.16	1386	76.94%		1542
			42.67	12.04	1399	77.67%		1572
			43.48	11.93	1412	78.38%		1602
			44.28	11.81	1424	79.05%		1631
			45.09	11.69	1435	79.70%		1661
			45.89	11.58	1447	80.32%		1691
			46.7	11.46	1457	80.91%		1720
			47.5	11.35	1467	81.47%		1750
12	R(V) = 148,9 - 4,2*V		47.5	11.34	1466	81.42%		1750
			48.31	10.39	1366	75.85%		1780
			49.11	9.43	1261	70.04%		1809
			49.92	8.48	1153	64.00%		1839
			50.72	7.53	1040	57.73%		1869
			51.53	6.58	923	51.23%		1898
			52.33	5.62	801	44.49%		1928
			53.14	4.67	676	37.53%		1958
			54.35	3.24	480	26.64%		2002

Appendix 12: BSFC and Power Linear Equations for a CAT 793D

Table 50. Linear equations for BSFC.

#	Linear equations	speed	BSFC
1	y=228-0.02x	1300	202
		1400	200
2	y=186-0.01x	1400	200
		1500	201
3	y=171+0.02x	1500	201
		1600	203
4	y=139+0.04x	1600	203
		1700	207
5	y=37+0.1x	1700	207
		1900	227

Table 51. Linear equations for engine power.

Linear Equations	RPM	Power
Y = 3.68*X - 624	200	112
	300	480
	200	112
	400	848
	507	1242
Y =0.447 *X + 1015	507	1242
	700	1328
	800	1373
	900	1417
	1301	1597
	1500	1686
	1600	1730
	1750	1797
Y= -4.62*X + 9884	1750	1799
	1800	1568
	1900	1106
	2000	644
X=2000	2000	584
	2000	400
	2000	300
	2000	200
	2000	0

Appendix 13: Economic Considerations

Interest rate	10.0%	
Tax Rate	50.0%	
All calculations in US dollars based on 1 Aust $ = 1 US $		
1 year in hours	8,760	
# tires per truck	6	
Initial tread depth	97 mm	Source: mine (shop visit)
Ave Time to Scrap a tire (hours)	5300 hours	Source: mine (shop visit)
Maintenance costs ($/h)	130	Assumption based on mine report
Operators per truck	4.2	Taking into consideration vacation and training
Labour per AHS	0.45	
Turnover	35%	Source: mine report
lbs in one tonne	2,205	
Conventional Truck Depreciation (years)	7.0*	Source: mine (visit)
Truck purchase price to site (Manual)	$4,000,000	
Truck purchase price to site (AHS)	$5,000,000	

* Used straight line depreciation

Table 52. Common costs.

Village Cost (fly-in/fly-out)	US$/person/night	62.73
Flight Cost	US$/person/flight	169.86
Tire Cost	US$/tire	33,000
Fuel Price per L	US$L delivered	0.90
Training cost (simulator)	US$ Real Qtr	25,000
Mining	US$/t	2.30
Quarterly wage	US$/person/Qtr	30,000
Labour costs - HR overheads	% of wage	15%
Hiring Cost	US$/new starter	3,200

See Appendix 14 for AHS infrastructure cost.

Appendix 14: AHS Infrastructure Cost Assumption

Table 53. AHS infrastructure cost assumption.

Element	Quant.	unit $	Total
Infrastructure Telecom / IT			
Basic transmission station	30	$30,000	$900,000
Servers (with redundancy)	8	$12,500	$100,000
Routers (24-ports/PoE)	10	$40,000	$400,000
Switches	20	$5,000	$100,000
Energy System (with Redundancy)	1	$150,000	$150,000
Network Adaptation (Cables CAT 6)	1	$200,000	$200,000
Monitoring System (Camera, SW specific, etc.)	1	$1,500,000	$1,500,000
Positioning System with redundancy (DGPS, antennas, etc.)	1	$200,000	$200,000
Subtotal			**$3,550,000**
Services			
Installation and Commissioning	1	$700,000	$700,000
Consulting (12 months)	4	$180,000	$720,000
Project Manager (6 months)	2	$100,000	$200,000
Transmission Link	2	$10,000	$20,000
Training	20	$50,000	$1,000,000
Transport/logistics	1	$500,000	$500,000
Subtotal			**$3,140,000**
Total			$6,690,000

Appendix 15: Weather Data

Table 54. Precipitation and wind data for the Lucy mine.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Relative Humidity (%)												
Maximum	92	98	88	99	98	99	99	96	99	86	98	99
Minimum	4	16	6	14	23	11	14	7	2	5	7	5
Daily Average	21	41	25	50	61	63	60	41	30	30	31	25
Wind Speed (m/s)												
Maximum	10.3	9.3	10.8	13.4	21.1	9.3	11.8	8.8	9.3	9.8	12.4	11.3
Minimum	0	0	1.3	0	0	0	0	0	0	0	0	0
Daily Avg	3.5	3.6	4.9	3.1	3.8	1.7	3.9	3	3.4	3.3	4.6	4.4
Wind Direction % {N=0 or 360,E=90,S=180,W=270}												
North	11	14	4	23	19	44	27	23	25	23	12	8
NorthEast	8	19	8	21	9	20	6	19	9	6	20	8
East	13	26	20	16	15	6	6	25	16	4	16	14
SouthEast	18	18	19	19	11	7	9	14	20	7	10	17
South	24	6	20	10	9	5	4	7	8	15	18	13
SouthWest	13	7	7	3	9	2	8	5	2	15	5	14
West	8	3	14	3	14	5	27	4	7	20	11	12
NorthWest	6	5	8	5	14	11	12	4	13	11	8	13

Table 55. Average hourly statistics for dry bulb temperatures (°C).

Average Hourly Statistics for Dry Bulb temperatures °C												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0:01- 1:00	30.5	24.4	26.8	21	15.2	12.3	11.7	12.5	16.3	19	22.8	27.3
1:01- 2:00	29.5	23.5	26.2	20.4	14.7	12	11.2	12.1	15.3	18	21.8	26.2
2:01- 3:00	28.3	22.7	25.4	19.8	14.1	11.5	10.6	11.3	14.2	16.9	20.9	25.1
3:01- 4:00	27.9	22.1	24.9	19.4	13.7	11	10.3	11.1	13.4	16.2	20.5	24.5
4:01- 5:00	26.6	21.5	23.8	18.7	13.1	10.4	9.5	10.1	12.5	15.4	20	23.5
5:01- 6:00	26.4	21.4	23.4	18.3	12.8	10	9.3	9.9	12.3	15.2	20.2	23.3
6:01- 7:00	**25.9**	**21.4**	**22.9**	**18.1**	**12.6**	**9.8**	**9.2**	**9.5**	**11.8**	**14.9**	**20.4**	**23**
7:01- 8:00	27.8	22.4	24	18.8	13.4	10.6	10.2	10.7	13.9	16.8	21.9	24.7
8:01- 9:00	29.3	23.6	25.2	19.7	14.4	11.6	11.3	11.9	15.5	18.4	23.4	26.2
9:01-10:00	31.9	25.4	27.2	21.1	16.2	13.2	12.9	14	18.5	21.1	25.6	28.8
10:01-11:00	33.2	26.8	28.7	22.5	17.5	14.6	14.3	15.4	19.8	22.5	26.9	30.1
11:01-12:00	35.2	28.5	30.6	24.1	19.2	16.3	15.9	17.3	22	24.6	28.7	32
12:01-13:00	36.6	29.9	32.2	25.5	20.4	17.6	17.3	18.9	23.3	26	29.9	33.2
13:01-14:00	38.1	31.1	33.7	26.6	21.6	18.7	18.3	20.4	24.9	27.5	31.2	34.8
14:01-15:00	38.8	31.7	34.4	27.2	22.1	19.2	18.8	21.1	25.4	28.1	31.8	35.3
15:01-16:00	**38.7**	**31.6**	**34.3**	**27.1**	**21.9**	**19**	**18.5**	**21.1**	**25**	**27.9**	**31.8**	**35.2**
16:01-17:00	38.7	31.6	34	26.8	21.3	18.4	18.2	20.8	24.6	27.6	31.6	34.9
17:01-18:00	38.1	30.9	33.2	26	20.4	17.4	17.4	20	23.7	26.8	31	34.2
18:01-19:00	37.5	30.2	32.1	25.2	19.2	16.3	16.6	18.8	22.6	25.9	30.2	33.2
19:01-20:00	36.2	29.1	30.9	23.9	18.1	15.1	15.4	17.6	21.4	24.5	28.9	32.2
20:01-21:00	35.1	28	29.8	23	17.2	14.2	14.4	16.4	20.3	23.4	27.7	31.2
21:01-22:00	34	27	28.8	22.2	16.4	13.4	13.6	15.4	19.4	22.2	26.4	30.2
22:01-23:00	32.9	26.1	28	21.6	15.9	12.9	13	14.4	18.4	21.1	25.1	29.3
23:01-24:00	31.8	25.2	27.3	21.1	15.4	12.5	12.4	13.6	17.5	20	23.9	28.3

Actual Data Years for Monthly Data*											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991	1990	1991	1989	1988	1987	1991	1987	1990	1990	1989	1987

**Data taken from nearest Airport*

Appendix 16: VIMS© and ExtendSim Data Used for Model Verification.

Table 56. VIMS© data.

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD1814	223.2	5.472	5.15	13.71	28.01	23.95	11.03	4.77	2.17	42.72	165.61	232.62	0.74
RD2011	211	5.15	5.633	14.13	31.15	21.87	10.85	3.35	5.02	41.93	159.93	228.84	0.76
RD2081	233.3	5.472	5.794	13.26	28.61	24.77	12.15	0.12	2.72	40.88	166.09	243.75	0.71
RD2018	221.5	5.15	4.828	13.46	28.54	22.95	10.15	1.55	5.42	41.15	158.04	230.44	0.71
RD1812	215.3	5.472	5.955	13.95	29.41	23.53	12.15	0.35	2.23	39.05	166.08	255.19	0.77
RD2023	241.2	5.472	5.15	12.33	29.95	26.63	10.32	0.22	2.02	40.00	184.54	276.81	0.77
RD2017	221.3	4.989	5.15	11.88	25.82	25.20	11.97	2.58	3.40	43.80	177.91	243.72	0.80
RD2020	215.9	5.15	5.15	13.70	27.35	22.55	11.30	6.18	3.45	44.47	176.97	238.79	0.82
RD1811	229.2	5.472	5.15	13.28	30.00	24.72	10.30	0.87	2.40	39.13	165.14	253.19	0.72
RD1805	215.3	4.989	5.15	12.89	25.86	23.22	11.95	4.25	2.88	43.33	174.60	241.76	0.81
RD2011	221.6	4.989	5.15	13.75	25.16	21.77	12.28	2.42	4.22	41.80	174.13	249.95	0.79
RD2016	209.9	5.15	5.311	13.67	27.20	22.60	11.72	4.73	4.43	44.23	175.55	238.12	0.84
RD2018	239.3	4.989	5.311	12.14	24.02	24.65	13.27	4.23	2.82	46.08	184.07	239.65	0.77
RD2017	230.1	5.955	5.15	15.12	27.80	23.63	11.12	3.37	2.47	41.23	160.41	233.41	0.70
RD1812	236.5	5.311	5.311	13.25	25.19	24.05	12.65	4.50	4.58	46.72	188.32	241.87	0.80
RD2020	223.8	5.955	5.15	14.25	24.43	25.07	12.65	8.85	2.55	50.13	172.24	206.13	0.77
RD2019	214.1	5.15	5.472	12.13	29.62	25.47	11.08	0.20	4.03	41.67	164.19	236.44	0.77
RD2011	224.9	5.472	5.15	12.99	28.09	25.28	11.00	0.43	2.43	40.03	165.61	248.21	0.74
RD2016	235	5.472	5.311	12.60	24.80	26.07	12.85	0.83	2.35	42.83	173.18	242.59	0.74
RD1809	219.5	5.633	5.633	14.35	25.38	23.55	13.32	4.88	2.72	45.22	178.39	236.71	0.81
RD2017	217	5.15	5.472	13.77	28.14	22.43	11.67	6.68	4.88	46.33	158.99	205.88	0.73
RD1812	227.8	5.472	5.311	13.10	25.26	25.07	12.62	7.75	2.35	48.62	174.13	214.90	0.76
RD2020	221.7	5.472	5.794	14.16	24.23	23.18	14.35	1.47	1.92	41.92	164.19	235.03	0.74
RD2023	211.2	5.472	5.955	14.02	25.58	23.42	13.97	3.73	2.65	44.60	167.98	225.98	0.80
RD1814	234.3	5.472	5.955	12.34	26.47	26.62	13.50	1.93	2.33	45.23	187.85	249.18	0.80
RD2011	214.7	5.472	5.15	12.81	30.10	25.63	10.27	1.50	2.17	40.63	168.45	248.74	0.78
RD2016	221	5.15	4.828	13.36	24.83	23.13	11.67	0.80	3.97	40.30	159.46	237.41	0.72
RD1811	230.1	5.472	5.15	13.19	26.11	24.90	11.83	2.07	2.13	41.88	166.56	238.60	0.72
RD2018	217.4	5.311	4.828	13.87	27.68	22.97	10.47	3.27	4.75	42.32	158.51	224.75	0.73
RD2017	226.1	5.633	5.15	13.62	26.34	24.82	11.73	4.87	2.00	44.07	161.35	219.69	0.71
RD1812	229.7	5.633	5.311	13.83	29.15	24.43	10.93	3.13	2.67	42.17	170.82	243.06	0.74
RD2081	213.7	4.989	5.311	10.85	22.84	27.58	13.95	8.07	3.13	53.63	178.39	199.56	0.83
RD2023	231.6	5.472	5.15	12.37	25.82	26.55	11.97	4.98	2.75	47.05	185.96	237.14	0.80

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD1805	215.7	5.472	5.311	12.81	22.90	25.63	13.92	5.72	3.62	49.78	202.52	244.08	0.94
RD1814	219.6	5.15	4.828	13.49	26.91	22.90	10.77	3.42	3.28	41.12	160.88	234.77	0.73
RD2019	211.5	5.15	4.828	12.34	27.33	25.03	10.60	5.28	3.22	45.25	159.46	211.44	0.75
RD2016	212	6.116	5.15	15.69	24.89	23.38	12.42	7.40	2.07	46.47	160.41	207.13	0.76
RD1811	216.7	5.15	4.828	13.45	28.78	22.97	10.07	0.73	3.67	38.60	159.93	248.60	0.74
RD2018	225.5	5.15	4.828	13.41	24.83	23.05	11.67	5.38	3.35	44.47	160.88	217.08	0.71
RD2020	221.7	5.15	4.828	12.95	27.81	23.87	10.42	2.27	3.40	41.17	163.25	237.93	0.74
RD2023	217.3	5.15	4.828	13.10	27.94	23.58	10.37	0.10	3.40	38.40	161.83	252.85	0.74
RD1805	220.3	5.955	5.15	12.09	24.62	29.55	12.55	0.10	2.37	48.13	177.44	221.19	0.81
RD2019	214.6	5.15	4.828	12.06	24.31	25.62	11.92	0.52	3.80	43.28	158.04	219.08	0.74
RD1809	235.4	5.955	5.311	12.80	26.93	27.92	11.83	3.15	2.52	46.18	179.33	232.99	0.76
RD2016	230.1	5.311	5.633	13.75	28.81	23.18	11.73	7.45	4.10	47.23	166.56	211.58	0.72
RD2018	225.6	5.955	5.15	14.99	23.62	23.83	13.08	1.57	2.48	42.17	162.30	230.94	0.72
RD2017	215.3	5.955	5.15	14.00	26.19	25.52	11.80	2.45	2.00	42.48	157.57	222.54	0.73
RD1812	237.4	5.15	4.989	12.99	24.30	23.78	12.32	3.43	7.18	47.72	167.50	210.62	0.71
RD2020	220.1	5.955	5.15	14.65	28.79	24.38	10.73	0.47	2.35	38.92	163.72	252.42	0.74
RD2081	222.6	5.955	5.15	14.91	26.56	23.97	11.63	1.07	1.85	39.30	158.99	242.73	0.71
RD2023	218.8	5.15	5.633	13.35	27.74	23.15	12.18	20.15	3.87	60.40	172.71	171.57	0.79
RD1811	198.2	5.15	5.472	14.02	24.72	22.03	13.28	20.93	3.80	60.92	163.72	161.26	0.83
RD1805	233.1	5.955	5.15	15.38	24.08	23.23	12.83	21.35	4.57	62.88	169.87	162.08	0.73
RD2016	226.5	5.311	4.828	14.56	26.95	21.88	10.75	17.17	3.62	54.40	164.19	181.09	0.72
RD2011	222	5.15	4.828	13.69	25.08	22.57	11.55	20.87	3.33	59.08	160.41	162.90	0.72
RD2023	227.4	5.472	5.15	13.50	27.88	24.32	11.08	0.13	2.45	38.78	166.09	256.94	0.73
RD2016	220.1	5.311	4.828	14.67	28.54	21.72	10.15	0.28	3.38	36.52	154.73	254.23	0.70
RD1812	215.3	5.472	5.794	13.99	25.78	23.47	13.48	3.13	2.97	43.78	178.86	245.11	0.83
RD1805	244	5.15	5.472	13.37	29.27	23.12	11.22	0.18	3.87	39.18	163.72	250.70	0.67
RD1807	205.3	5.15	5.633	14.13	29.82	21.87	11.33	0.72	3.45	38.20	153.78	241.54	0.75
RD2023	231.5	5.472	5.15	13.47	28.74	24.37	10.75	0.67	3.42	40.17	166.56	248.80	0.72
RD2011	202.1	5.472	5.15	15.31	29.95	21.45	10.32	2.67	2.22	37.47	151.42	242.48	0.75
RD2020	205.5	5.15	5.472	13.96	28.02	22.13	11.72	1.48	5.47	42.17	160.41	228.25	0.78
RD2018	225.1	5.15	4.989	13.64	28.64	22.65	10.45	3.37	3.60	41.05	185.96	271.80	0.83
RD2016	223.6	5.311	4.989	14.73	30.49	21.63	9.82	0.55	3.48	36.32	155.20	256.41	0.69
RD2019	214.4	5.472	5.15	14.38	29.24	22.83	10.57	2.53	4.57	41.55	171.29	247.35	0.80
RD1805	220.9	5.15	4.989	13.92	27.09	22.20	11.05	2.37	3.15	39.72	157.57	238.04	0.71
RD1812	228.1	5.633	5.311	14.61	27.75	23.13	11.48	1.47	4.52	41.90	164.19	235.12	0.72
RD2017	211.7	5.311	5.472	14.36	28.30	22.18	11.60	3.88	3.17	41.75	154.73	222.37	0.73
RD1809	226	5.472	5.633	14.32	26.13	22.93	12.93	11.95	2.67	51.93	193.06	223.04	0.85

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD1807	207.9	5.15	4.828	14.12	27.76	21.88	10.43	6.17	3.13	42.40	155.20	219.63	0.75
RD2011	227.2	5.15	4.828	14.17	25.26	21.80	11.47	9.68	3.28	47.02	156.62	199.87	0.69
RD2023	218.7	5.472	5.15	14.12	27.43	23.25	11.27	9.98	2.30	47.68	166.09	208.99	0.76
RD2020	231.3	5.472	5.15	13.14	26.19	24.98	11.80	4.18	3.92	45.92	172.71	225.68	0.75
RD2018	227.6	5.15	4.828	13.52	26.62	22.85	10.88	9.90	3.07	47.67	160.41	201.91	0.70
RD2019	215.7	5.955	5.15	15.86	29.20	22.53	10.58	0.10	3.20	37.30	151.89	244.33	0.70
RD1805	227.2	5.472	5.15	13.75	26.71	23.88	11.57	5.05	3.90	45.88	163.72	214.09	0.72
RD1812	224.5	5.311	4.989	14.13	28.06	22.55	10.67	3.72	3.38	41.85	160.41	229.97	0.71
RD2017	212.1	5.472	5.15	15.01	25.89	21.87	11.93	6.10	2.82	44.03	157.57	214.70	0.74
RD1807	218.2	5.15	4.828	13.90	27.72	22.23	10.45	4.42	3.60	41.35	155.68	225.89	0.71
RD1809	213.7	5.311	4.989	14.38	26.97	22.17	11.10	9.57	3.53	47.82	161.35	202.47	0.76
RD2011	225.4	5.472	5.15	13.88	27.03	23.65	11.43	1.70	2.95	40.53	157.57	233.24	0.70
RD2020	210.4	5.955	5.15	16.08	27.18	22.22	11.37	0.10	4.28	38.97	158.51	244.08	0.75
RD1807	227.4	5.472	5.311	13.62	26.82	24.10	11.88	17.40	2.62	56.82	169.87	179.39	0.75
RD2016	227.5	5.633	5.472	14.93	27.75	22.63	11.83	16.55	2.55	54.23	168.92	186.89	0.74
RD1812	204.9	5.633	5.472	14.99	30.92	22.55	10.62	17.90	3.57	56.07	200.15	214.20	0.98
RD2011	212.5	5.955	5.15	15.99	30.05	22.35	10.28	0.87	3.33	37.90	154.73	244.95	0.73
RD2019	215.6	5.15	4.828	14.01	28.63	22.05	10.12	8.18	3.63	44.62	171.29	230.35	0.79
RD1807	210.3	5.955	5.15	15.52	31.06	23.02	9.95	0.10	3.37	37.22	154.26	248.69	0.73
RD2017	214.1	5.472	5.15	14.47	27.88	22.68	11.08	0.20	2.67	37.77	158.51	251.83	0.74
RD1805	232.1	5.15	4.828	13.18	26.02	23.45	11.13	0.03	4.63	40.28	162.30	241.74	0.70
RD2016	226.3	5.633	5.311	15.05	30.64	22.45	10.40	2.92	3.63	40.37	160.41	238.43	0.71
RD2020	220.3	5.472	5.15	14.00	26.56	23.45	11.63	1.18	3.13	40.15	165.61	247.49	0.75
RD1812	200.9	6.116	5.311	15.85	29.83	23.15	10.68	0.07	2.83	38.12	151.89	239.09	0.76
RD2018	219	5.472	5.955	14.33	29.21	22.92	12.23	0.25	4.00	40.37	160.88	239.13	0.73
RD2019	216.5	5.15	4.989	14.12	29.49	21.88	10.15	0.10	4.07	37.15	154.26	249.13	0.71
RD1807	221	5.15	5.633	13.49	31.74	22.90	10.65	0.20	4.37	38.75	159.46	246.91	0.72
RD2017	215.1	5.472	5.15	14.79	26.08	22.20	11.85	1.35	2.83	39.02	154.73	237.94	0.72
RD2023	243.6	5.472	5.955	12.41	29.69	26.47	12.03	0.17	3.50	43.13	182.17	253.41	0.75
RD2011	226.3	5.15	5.472	14.35	28.59	21.53	11.48	3.83	5.55	43.27	154.73	214.57	0.68
RD2016	228	5.472	5.15	14.76	31.06	22.25	9.95	2.53	4.77	40.43	159.46	236.63	0.70
RD2020	219.6	5.472	5.15	14.67	29.66	22.38	10.42	3.02	3.10	39.58	163.72	248.16	0.75
RD2018	214.4	5.311	4.828	14.24	26.18	22.38	11.07	1.03	3.52	38.72	153.78	238.32	0.72
RD2019	215.9	5.955	5.15	16.13	29.11	22.15	10.62	0.05	3.57	37.17	152.84	246.73	0.71
RD1807	214.7	5.633	5.15	14.25	28.05	23.72	11.02	1.05	3.90	40.63	159.93	236.16	0.74
RD2017	219.3	5.472	5.15	14.53	26.56	22.60	11.63	0.22	3.77	39.20	156.62	239.73	0.71
RD2011	226.3	5.15	4.828	12.92	29.02	23.92	9.98	0.12	4.08	38.85	163.25	252.12	0.72

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2020	243.6	5.15	4.828	12.80	29.11	24.13	9.95	3.92	4.25	43.08	168.45	234.59	0.69
RD1812	239.9	5.311	4.989	13.90	27.38	22.93	10.93	8.20	4.57	47.82	163.25	204.84	0.68
RD2018	249.8	5.15	4.989	12.85	26.69	24.05	11.22	10.88	5.10	52.18	166.08	190.96	0.66
RD2017	226.4	5.311	4.989	14.83	26.89	21.48	11.13	13.67	3.60	50.88	156.62	184.68	0.69
RD2011	226	5.15	4.828	14.16	27.63	21.82	10.48	7.32	3.80	44.52	155.20	209.18	0.69
RD2016	227.3	5.633	5.633	14.98	24.43	22.57	13.83	5.62	3.63	46.45	181.23	234.09	0.80
RD2020	211.9	5.472	5.633	13.81	25.07	23.77	13.48	2.05	3.65	43.75	183.59	251.78	0.87
RD2016	229	6.116	5.311	15.99	29.23	22.95	10.90	4.73	3.53	42.82	160.41	224.78	0.70
RD2023	219.4	5.15	5.633	13.65	27.67	22.63	12.22	3.48	4.55	43.82	161.35	220.95	0.74
RD2020	222.1	5.955	5.15	14.78	26.15	24.17	11.82	0.10	3.20	40.00	167.98	251.97	0.76
RD2023	231.7	5.955	5.311	13.80	28.20	25.90	11.30	3.23	3.02	44.30	171.29	232.00	0.74
RD1805	229.9	5.15	5.633	13.72	28.52	22.52	11.85	1.68	4.27	41.67	161.83	233.03	0.70
RD2019	217.1	5.633	5.794	13.65	30.45	24.77	11.42	1.32	3.30	41.65	159.46	229.72	0.73
RD2018	232.6	5.15	5.633	13.70	27.26	22.55	12.40	9.52	5.00	50.28	159.46	190.27	0.69
RD1812	238.9	5.311	5.633	14.04	26.23	22.70	12.88	4.15	4.58	45.50	163.72	215.89	0.69
RD1808	199.9	5.311	5.633	14.83	27.11	21.48	12.47	17.58	2.63	55.22	159.93	173.79	0.80
RD1805	241.7	5.311	4.989	13.32	25.99	23.92	11.52	13.60	3.45	53.42	165.14	185.49	0.68
RD1812	228.9	6.116	5.311	15.51	26.63	23.67	11.97	2.07	3.53	43.13	160.88	223.79	0.70
RD2019	232	5.794	5.472	15.45	31.22	22.50	10.52	0.12	4.45	38.58	151.42	235.46	0.65
RD1805	228.6	5.15	4.828	13.37	27.33	23.12	10.60	0.47	3.42	39.20	160.88	246.25	0.70
RD1812	227.6	5.311	5.472	14.11	26.87	22.58	12.22	4.63	3.57	44.02	181.23	247.03	0.80
RD2016	218.9	5.472	5.633	15.26	28.72	21.52	11.77	4.17	2.75	40.95	158.51	232.26	0.72
RD2018	231.8	5.472	5.15	13.94	27.84	23.55	11.10	2.60	2.60	40.50	159.93	236.94	0.69
RD1808	227.5	5.472	5.311	14.39	27.20	22.82	11.72	0.22	2.67	38.08	157.09	247.50	0.69
RD2011	210.7	5.15	5.633	14.67	29.65	21.07	11.40	3.97	3.27	40.42	152.36	226.19	0.72
RD2019	222.7	5.472	5.472	14.30	29.10	22.97	11.28	0.78	2.75	38.73	160.41	248.48	0.72
RD2023	219.5	5.472	5.955	14.10	31.02	23.28	11.52	1.23	2.95	39.83	164.19	247.32	0.75
RD1805	244.4	5.15	4.989	12.95	28.69	23.87	10.43	0.50	3.53	39.35	163.72	249.64	0.67
RD1812	214.1	6.116	5.311	15.99	30.40	22.95	10.48	0.12	4.12	38.60	153.31	238.30	0.72
RD2020	209.2	5.955	5.15	16.89	32.41	21.15	9.53	0.13	4.70	36.15	154.73	256.81	0.74
RD2018	206.4	5.311	4.989	14.10	24.08	22.60	12.43	3.58	6.87	46.88	159.46	204.07	0.77
RD2081	212.4	5.633	5.794	13.68	21.59	24.70	16.10	6.22	4.27	53.08	191.64	216.61	0.90
RD2011	207.5	6.276	5.15	15.17	24.02	24.82	12.87	4.25	3.55	47.23	159.93	203.16	0.77
RD1808	236.8	6.116	5.311	14.62	26.52	25.10	12.02	11.28	3.23	54.40	168.92	186.31	0.71
RD2019	206.3	6.116	5.15	14.70	30.29	24.97	10.20	0.12	3.17	40.80	155.68	228.93	0.75
RD1805	234.1	6.116	5.15	13.82	27.35	26.55	11.30	3.27	2.55	44.55	171.76	231.33	0.73
RD2016	229.1	6.116	5.15	15.08	25.43	24.33	12.15	11.43	3.50	52.17	182.65	210.07	0.80
RD2018	202.2	4.989	5.955	14.06	24.93	21.28	14.33	13.50	3.45	53.73	160.88	179.64	0.80

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD1812	217.6	6.116	5.311	14.49	26.44	25.32	12.05	1.55	3.33	43.13	162.77	226.42	0.75
RD2081	216.3	5.955	5.311	13.98	23.58	25.55	13.52	3.80	3.00	47.02	158.99	202.89	0.74
RD1805	211.8	5.15	5.311	14.23	27.16	21.72	11.73	3.12	4.27	41.85	151.89	217.76	0.72
RD2018	224.4	5.955	5.15	15.08	28.61	23.70	10.80	0.08	3.17	38.47	156.62	244.30	0.70
RD2023	215.4	5.15	5.794	13.22	26.91	23.37	12.92	8.85	4.32	50.60	173.18	205.36	0.80
RD1811	202.7	4.989	5.311	13.17	29.15	22.73	10.93	2.72	3.30	41.03	158.04	231.09	0.78
RD2019	232.4	5.955	5.15	14.47	30.10	24.70	10.27	1.07	3.22	40.58	161.35	238.55	0.69
RD1812	223.4	5.15	5.472	13.58	30.08	22.75	10.92	5.27	5.23	45.27	165.14	218.89	0.74
RD2023	238.8	5.472	5.794	12.06	27.77	27.23	12.52	2.75	3.82	46.97	207.72	265.37	0.87
RD2018	225.9	5.472	5.15	13.99	26.49	23.47	11.67	10.03	3.88	49.80	176.49	212.64	0.78
RD1807	215.6	5.472	5.794	15.05	29.76	21.82	11.68	4.23	3.20	41.93	159.93	228.84	0.74
RD2011	235.4	5.955	5.15	13.98	25.97	25.57	11.90	5.72	2.47	46.70	167.98	215.82	0.71
RD2020	212.7	5.472	5.794	14.20	30.19	23.12	11.52	5.50	3.67	44.62	163.25	219.53	0.77
RD2023	199.2	5.955	5.311	15.53	29.23	23.00	10.90	8.35	3.05	45.97	159.93	208.76	0.80
RD2019	232.3	5.955	5.311	13.98	27.20	25.57	11.72	8.53	2.20	49.10	172.24	210.47	0.74
RD1811	229.9	5.472	5.955	12.34	28.74	26.62	12.43	8.52	4.02	52.62	186.90	213.13	0.81
RD2018	208.6	5.955	5.311	15.64	27.55	22.85	11.57	5.75	2.83	43.82	158.99	217.71	0.76
RD1807	233.3	5.472	5.15	13.38	26.83	24.53	11.52	5.85	3.50	46.28	167.03	216.53	0.72
RD2016	230.9	5.955	5.15	13.69	23.77	26.10	13.00	2.28	2.02	44.12	165.61	225.24	0.72
RD1805	211.7	5.955	5.15	15.47	26.26	23.10	11.77	0.07	2.18	37.85	151.89	240.78	0.72
RD2020	221	5.955	5.15	13.84	22.23	25.82	13.90	0.65	2.75	44.05	170.82	232.67	0.77
RD2019	212.6	5.633	5.794	13.98	27.37	24.18	12.70	1.77	3.85	43.55	165.14	227.52	0.78
RD1811	228.1	5.472	5.15	13.36	28.44	24.57	10.87	5.47	2.72	44.57	170.82	229.97	0.75
RD1807	217.6	5.955	5.15	15.73	28.57	22.72	10.82	5.35	2.40	42.80	158.51	222.22	0.73
RD2016	225.1	5.633	5.794	14.04	26.78	24.07	12.98	1.02	4.37	43.37	166.08	229.79	0.74
RD2020	211.1	5.472	5.794	14.04	31.70	23.38	10.97	2.00	3.43	40.65	163.72	241.65	0.78
RD2011	223.2	5.472	5.794	13.91	29.21	23.60	11.90	2.72	3.73	42.95	163.72	228.71	0.73
RD2019	204.1	5.633	5.633	14.35	26.72	23.55	12.65	2.78	2.85	42.92	177.44	248.07	0.87
RD2019	229.2	5.955	5.15	13.52	27.03	26.43	11.43	5.72	2.60	47.15	174.60	222.19	0.76
RD1811	234.9	5.472	5.794	12.83	28.00	25.58	12.42	1.32	2.72	42.90	180.75	252.80	0.77
RD2020	224.3	5.472	5.794	13.68	28.07	24.00	12.38	1.60	2.53	41.43	166.08	240.51	0.74
RD1807	220.2	5.472	5.794	14.40	29.17	22.80	11.92	3.27	2.72	41.52	160.41	231.82	0.73
RD2011	211.5	4.667	5.794	13.95	31.04	20.07	11.20	2.80	2.32	37.43	148.10	237.39	0.70
RD1805	234.7	4.667	5.472	12.40	26.23	22.58	12.52	1.75	2.23	40.05	158.51	237.47	0.68
RD2018	213.8	4.667	5.472	13.55	28.22	20.67	11.63	0.13	2.07	35.50	149.05	251.92	0.70
RD2020	215.2	4.667	5.794	12.99	27.02	21.55	12.87	5.18	1.98	45.05	156.15	207.97	0.73
RD1807	218.1	4.667	5.311	12.79	30.89	21.90	10.32	0.57	2.58	40.07	150.47	225.33	0.69
RD2016	222.8	5.633	5.633	14.11	25.10	23.95	13.47	1.42	2.42	42.00	162.30	231.86	0.73

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2017	221.3	5.472	5.311	13.34	24.96	24.62	12.77	1.42	2.15	41.87	157.09	225.14	0.71
RD2023	233.1	5.472	5.955	12.21	23.79	26.90	15.02	8.12	1.90	52.62	192.11	219.07	0.82
RD2016	223.5	4.828	5.311	14.50	27.79	19.98	11.47	2.78	1.77	36.85	145.27	236.52	0.65
RD1807	227.5	5.472	4.506	12.85	31.38	25.55	8.62	9.08	3.40	47.48	176.02	222.42	0.77
RD1805	245.6	5.311	5.472	11.01	23.04	28.95	14.25	7.90	2.63	71.85	197.31	164.77	0.80
RD2011	217.7	5.472	4.506	12.94	27.87	25.37	9.70	4.60	2.48	43.45	167.03	230.65	0.77
RD2023	226.2	5.633	5.311	13.49	26.08	25.05	12.22	0.12	2.88	41.22	171.29	249.35	0.76
RD1808	214.6	5.633	5.633	13.04	26.23	25.92	12.88	4.10	2.38	46.37	171.76	222.27	0.80
RD2017	213.3	4.828	5.633	13.95	23.36	20.77	14.47	7.70	2.75	46.75	149.52	191.90	0.70
RD2019	217.8	5.633	5.472	14.00	25.85	24.13	12.70	4.37	2.53	45.10	165.61	220.33	0.76
RD2020	219	5.472	4.506	12.90	30.49	25.45	8.87	4.47	2.23	41.80	173.18	248.59	0.79
RD2011	219.1	4.667	5.794	13.60	27.05	20.58	12.85	6.82	2.12	43.82	150.94	206.69	0.69
RD1808	210.9	5.15	5.311	14.15	29.92	21.83	10.65	0.13	3.13	36.60	156.62	256.76	0.74
RD1811	217.2	4.989	5.15	13.00	28.22	23.03	10.95	7.73	4.32	46.80	164.19	210.50	0.76
RD2018	237.7	4.989	5.311	13.23	27.01	22.63	11.80	7.18	3.12	45.83	158.51	207.51	0.67
RD2020	222.5	5.794	5.15	12.83	27.92	27.10	11.07	0.73	2.15	51.45	182.65	213.00	0.82
RD2023	212.7	5.15	5.311	13.48	27.99	22.92	11.38	5.75	2.87	43.70	161.83	222.19	0.76
RD1811	219.4	5.15	5.311	13.24	28.79	23.33	11.07	0.10	2.72	37.97	157.57	249.01	0.72
RD2023	231.3	5.472	5.311	12.59	29.46	26.08	10.82	1.22	2.25	41.27	175.55	255.24	0.76
RD2011	216.3	4.989	5.15	13.77	29.11	21.73	10.62	2.10	2.33	37.55	152.36	243.46	0.70
RD1807	213.3	4.989	5.311	13.32	27.99	22.47	11.38	2.78	3.47	41.48	153.31	221.74	0.72
RD1808	229.3	5.633	5.472	14.27	25.82	23.68	12.72	17.42	2.22	56.80	169.40	178.94	0.74
RD2023	222.9	5.633	5.15	14.37	25.82	23.52	11.97	7.17	2.28	45.80	168.92	221.30	0.76
RD2016	223.3	5.633	5.15	15.28	29.90	22.12	10.33	0.78	2.63	36.63	170.34	279.00	0.76
RD1809	224.1	5.15	4.989	13.63	24.77	22.67	12.08	20.60	2.72	59.05	166.09	168.76	0.74
RD2011	214.6	5.472	5.15	14.82	26.45	22.15	11.68	3.75	1.93	40.43	158.51	235.22	0.74
RD2020	220.5	5.472	5.15	12.88	26.64	25.48	11.60	0.52	2.32	40.98	172.71	252.85	0.78
RD2019	211.8	5.633	5.311	14.83	30.02	22.78	10.62	3.53	3.07	40.73	160.41	236.28	0.76
RD2018	212.7	5.633	5.311	15.08	27.27	22.42	11.68	2.83	2.60	41.08	156.15	228.05	0.73
RD2011	226.7	5.472	5.15	13.55	27.47	24.23	11.25	1.68	3.32	41.95	163.25	233.49	0.72
RD1808	210.3	5.633	5.311	14.42	29.28	23.43	10.88	2.03	2.05	39.30	160.41	244.90	0.76
RD1809	222.3	5.633	5.311	13.98	28.45	24.18	11.20	1.15	2.50	40.13	160.88	240.52	0.72
RD2019	224.7	5.15	4.828	13.42	26.45	23.03	10.95	1.60	2.92	39.20	156.62	239.73	0.70
RD1811	225.1	5.633	5.15	13.81	30.15	24.47	10.25	0.15	2.22	37.93	164.67	260.46	0.73
RD2016	208.8	5.633	5.311	15.20	30.64	22.23	10.40	0.07	3.23	37.00	151.89	246.31	0.73
RD2011	212.4	5.472	5.15	14.97	26.68	21.93	11.58	4.07	2.00	40.63	154.26	227.78	0.73
RD2023	227.4	5.633	5.311	13.67	25.84	24.72	12.33	5.00	2.82	45.90	168.45	220.20	0.74
RD1808	219.5	5.15	4.828	13.97	27.16	22.12	10.67	4.77	2.50	40.83	156.62	230.14	0.71

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD1807	230.3	5.472	5.15	12.79	26.95	25.67	11.47	4.72	2.33	45.15	178.86	237.69	0.78
RD1809	233.7	5.633	5.311	13.75	26.30	24.58	12.12	7.38	2.68	47.88	165.61	207.52	0.71
RD1805	222.9	5.633	5.311	13.85	27.99	24.40	11.38	6.35	2.52	45.95	165.14	215.63	0.74
RD1811	223.4	5.633	5.15	14.01	28.70	24.12	10.77	8.48	3.15	47.60	166.56	209.95	0.75
RD2016	230.6	5.633	5.311	14.33	28.79	23.58	11.07	10.07	2.97	48.72	165.61	203.97	0.72
RD1808	214.3	5.633	5.311	14.52	29.83	23.28	10.68	0.43	2.52	37.75	160.41	254.95	0.75
RD2023	218.8	5.472	4.667	14.29	28.62	22.98	9.78	0.13	2.98	36.67	156.62	256.29	0.72
RD1807	209.1	5.472	5.15	14.51	28.70	22.63	10.77	0.08	2.03	36.45	156.62	257.81	0.75
RD2020	223.1	5.472	5.311	14.84	27.67	22.12	11.52	1.37	2.00	37.70	159.46	253.78	0.71
RD1809	230.4	5.633	5.311	13.78	27.83	24.53	11.45	0.12	2.03	39.17	161.35	247.18	0.70
RD1805	204.6	5.472	4.506	14.78	28.11	22.22	9.62	1.15	2.47	36.45	150.47	247.69	0.74
RD2019	213	5.472	4.989	15.65	26.77	20.98	11.18	1.98	2.90	37.75	168.45	267.74	0.79
RD1811	222.8	5.633	5.15	14.18	28.05	23.83	11.02	2.75	4.22	42.73	164.67	231.20	0.74
RD2016	216.1	5.472	4.667	14.95	29.32	21.97	9.55	0.77	2.60	35.62	153.31	258.27	0.71
RD2011	210.9	6.116	5.15	15.03	27.03	24.42	11.43	3.65	2.83	45.07	175.07	233.09	0.83
RD2019	202.7	5.633	5.311	16.12	33.43	20.97	9.53	3.53	3.80	38.52	149.05	232.19	0.74
RD2018	228.1	5.633	5.311	15.13	29.69	22.33	10.73	9.17	2.85	45.90	155.68	203.50	0.68
RD2017	223.5	5.633	5.311	14.85	30.16	22.77	10.57	2.52	2.80	39.52	155.68	236.37	0.70
RD1807	198.1	5.472	5.15	14.61	22.64	22.47	13.65	4.52	2.75	44.25	166.09	225.20	0.84
RD2011	226.4	5.15	5.311	14.11	26.78	21.90	11.90	15.10	2.62	52.92	157.09	178.12	0.69
RD2020	221.7	5.633	5.633	13.56	25.44	24.93	13.28	3.42	2.38	45.47	181.23	239.16	0.82
RD1805	221.4	5.633	5.15	14.37	24.69	23.52	12.52	1.30	2.92	41.78	177.44	254.80	0.80
RD1809	209.9	5.311	5.311	13.80	26.19	23.08	12.17	2.27	2.58	41.30	169.40	246.10	0.81
RD1811	218.3	5.472	4.989	13.56	26.22	24.22	11.42	2.40	2.88	53.62	179.81	201.21	0.82
RD2017	213.5	5.311	5.311	14.31	29.92	22.27	10.65	0.05	2.62	37.08	152.84	247.29	0.72
RD1807	224.7	4.989	5.311	12.40	29.06	24.15	10.97	0.68	2.68	39.52	161.35	244.99	0.72
RD2011	211.2	5.472	4.506	15.08	29.33	21.77	9.22	0.10	3.13	35.00	150.47	257.95	0.71
RD1805	220.3	4.989	6.276	13.10	30.04	22.85	12.53	2.57	2.90	41.98	160.41	229.24	0.73
RD2019	222.5	5.955	5.472	14.62	27.36	24.43	12.00	2.37	2.90	42.62	164.19	231.17	0.74
RD2020	240.4	5.955	5.472	13.72	29.31	26.03	11.20	1.58	2.40	43.13	183.12	254.73	0.76
RD1809	223.2	5.472	4.667	12.35	28.82	26.58	9.72	0.12	2.60	40.20	166.08	247.89	0.74
RD2023	205.5	5.15	5.311	13.75	29.37	22.47	10.85	2.23	2.93	39.45	156.62	238.21	0.76
RD2017	219.4	5.15	4.828	13.68	28.17	22.58	10.28	0.12	2.82	36.95	151.89	246.64	0.69
RD1811	207	5.472	5.15	14.92	32.70	22.00	9.45	0.20	2.95	35.45	152.36	257.88	0.74
RD2016	211.5	5.472	5.15	14.25	28.74	23.03	10.75	1.70	2.50	38.85	158.99	245.54	0.75
RD1807	203.6	5.472	4.506	14.57	27.92	22.53	9.68	1.97	2.35	37.52	152.36	243.67	0.75
RD2020	209.9	5.472	5.15	13.19	28.79	24.90	10.73	1.08	3.23	44.67	166.56	223.74	0.79
RD1808	223.9	5.472	5.633	14.05	26.23	23.37	12.88	14.93	3.63	55.47	164.67	178.12	0.74

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2023	215.9	5.472	4.506	14.30	28.76	22.97	9.40	1.53	3.32	38.28	161.35	252.88	0.75
RD1807	204.2	4.989	5.311	12.77	29.41	23.43	10.83	1.43	3.00	39.50	159.46	242.22	0.78
RD1805	235.1	5.633	5.472	13.19	26.13	25.62	12.57	9.15	2.67	50.98	170.82	201.03	0.73
RD2020	216.8	4.989	5.633	13.60	25.54	22.02	13.23	7.10	2.80	46.18	160.41	208.40	0.74
RD2011	200.6	5.472	5.15	15.24	25.29	21.55	12.22	2.40	3.68	40.60	152.84	225.87	0.76
RD2023	215.6	5.472	5.311	14.20	28.88	23.12	11.03	1.47	2.75	39.40	158.51	241.39	0.74
RD1809	221.4	5.633	5.15	14.45	27.59	23.38	11.20	0.92	2.88	39.33	158.51	241.80	0.72
RD1805	223.7	5.472	4.828	14.40	26.66	22.80	10.87	3.22	2.50	40.37	161.35	239.83	0.72
RD2011	213.4	5.15	5.311	12.93	31.71	23.90	10.05	0.12	3.20	38.45	156.62	244.40	0.73
RD1814	218.3	5.15	5.311	13.89	30.35	22.25	10.50	3.88	3.42	41.03	159.46	233.17	0.73
RD1807	247.8	6.116	5.311	13.53	29.97	27.12	10.63	5.10	2.78	55.90	181.23	194.52	0.73
RD2023	213.1	4.828	5.955	14.14	29.53	20.48	12.10	8.55	1.92	43.82	154.26	211.23	0.72
RD2017	195	4.828	5.311	14.91	24.86	19.43	12.82	0.70	1.92	36.12	138.64	230.32	0.71
RD1809	231	4.828	5.794	13.63	30.90	21.25	11.25	0.12	2.02	35.52	150.47	254.20	0.65
RD1808	233.7	4.828	5.955	14.12	29.90	20.52	11.95	1.05	2.02	36.40	150.00	247.25	0.64
RD2018	209.2	5.955	4.506	15.01	29.23	23.80	9.25	0.67	2.60	37.12	155.20	250.89	0.74
RD2016	238	5.633	4.506	14.27	27.49	23.68	9.83	3.85	2.48	41.10	158.04	230.72	0.66
RD1805	229.3	4.828	5.794	13.48	24.31	21.48	14.30	4.90	2.80	44.55	198.26	267.02	0.86
RD1814	220.3	5.633	4.506	14.46	29.23	23.37	9.25	5.55	2.02	41.22	159.93	232.82	0.73
RD2019	230.4	5.633	5.794	13.78	23.44	24.53	14.83	4.85	1.87	47.12	166.56	212.10	0.72
RD2020	213.3	5.472	5.794	14.01	27.55	23.43	12.62	9.77	2.30	48.97	164.19	201.19	0.77
RD2017	239.3	5.633	4.506	13.82	27.87	24.45	9.70	5.13	2.65	42.97	160.88	224.66	0.67
RD1808	244	5.633	4.667	13.51	31.40	25.02	8.92	3.48	1.82	40.13	166.56	249.01	0.68
RD2023	220.8	5.633	4.506	13.74	29.02	24.60	9.32	3.55	2.28	40.73	163.72	241.16	0.74
RD1811	195.7	5.15	5.311	12.31	28.03	25.10	11.37	0.32	3.02	40.50	150.00	222.22	0.77
RD2018	227.9	5.472	5.794	13.36	30.19	24.58	11.52	1.87	2.05	40.82	168.92	248.32	0.74
RD2016	222.8	4.828	5.311	14.12	30.99	20.52	10.28	0.62	2.48	34.95	145.74	250.20	0.65
RD1807	221.4	5.472	5.311	13.38	29.01	24.53	10.98	0.52	1.88	38.80	165.61	256.10	0.75
RD1814	203.2	5.472	5.311	14.64	32.08	22.43	9.93	0.12	1.82	35.30	156.62	266.21	0.77
RD2017	217.3	5.633	5.311	14.46	28.03	23.37	11.37	0.28	2.15	38.48	157.57	245.67	0.73
RD1808	226.4	5.633	5.311	14.33	29.73	23.58	10.72	3.95	1.77	40.98	159.46	233.45	0.70
RD2019	223.4	5.472	5.311	13.44	27.08	24.43	11.77	2.82	2.23	42.35	164.19	232.62	0.73
RD1809	207.2	5.472	4.506	13.11	31.26	25.05	8.65	0.43	1.80	37.20	162.30	261.77	0.78
RD2020	239	5.472	5.15	13.40	28.88	24.50	10.70	1.93	2.12	40.08	164.67	246.49	0.69
RD2023	237.4	5.472	5.311	11.75	27.55	27.95	11.57	2.13	2.12	45.43	190.69	251.83	0.80
RD1811	217.9	5.472	5.15	14.19	26.71	23.13	11.57	0.60	2.35	38.37	155.68	243.45	0.71
RD1812	233.8	5.472	5.311	11.78	29.28	27.87	10.88	3.95	2.52	45.85	180.28	235.92	0.77
RD2018	225.9	5.633	5.311	13.12	26.63	25.77	11.97	0.77	1.77	41.83	168.92	242.28	0.75

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2011	207.3	5.472	5.15	14.35	23.35	22.88	13.23	5.87	2.05	45.30	153.78	203.69	0.74
RD2081	216	5.633	5.311	13.48	23.52	25.07	13.55	7.75	3.67	50.78	250.31	295.74	1.16
RD1814	227.2	5.472	5.15	13.18	27.55	24.92	11.22	6.22	2.27	45.60	172.24	226.63	0.76
RD2017	215	5.633	5.311	14.47	29.69	23.35	10.73	2.55	2.25	39.80	158.51	238.97	0.74
RD1809	234.2	4.828	5.311	13.79	28.33	21.00	11.25	5.03	2.15	40.47	153.78	228.01	0.66
RD1808	226.1	4.828	5.311	13.65	25.03	21.22	12.73	3.92	2.15	43.85	150.94	206.54	0.67
RD2020	223.7	5.472	5.15	14.44	27.67	22.73	11.17	5.12	2.20	42.07	158.99	226.77	0.71
RD2019	236.3	4.667	5.311	11.78	29.87	23.77	10.67	4.67	2.03	43.28	165.61	229.57	0.70
RD1811	223.6	5.472	5.15	13.86	24.69	23.68	12.52	4.97	2.22	44.35	159.93	216.37	0.72
RD2023	233.3	5.472	5.311	12.27	30.35	26.75	10.50	2.40	3.85	44.32	183.12	247.92	0.78
RD2018	211.6	4.828	5.311	13.32	27.35	21.75	11.65	3.53	2.12	40.80	152.36	224.06	0.72
RD1812	221.7	5.472	5.311	13.39	28.88	24.52	11.03	1.83	3.23	41.22	166.56	242.46	0.75
RD2016	233.4	5.472	5.311	13.49	29.92	24.33	10.65	6.23	3.12	45.30	164.67	218.10	0.71
RD2011	224.1	4.667	5.472	13.97	26.77	20.05	12.27	18.52	1.97	54.07	148.10	164.36	0.66
RD2081	210.2	5.633	5.311	12.70	29.83	26.62	10.68	0.20	2.23	40.48	169.40	251.06	0.81
RD2017	206	4.828	5.311	13.99	28.45	20.70	11.20	1.30	1.83	36.40	141.95	233.99	0.69
RD1809	225.3	5.633	4.506	13.71	30.04	24.65	9.00	0.17	2.30	37.18	160.41	258.84	0.71
RD2019	224.4	5.472	4.506	13.29	26.77	24.70	10.10	1.47	2.05	39.20	161.35	246.97	0.72
RD1811	221.1	5.472	5.955	13.56	22.64	24.22	15.78	5.50	2.15	48.42	166.09	205.82	0.75
RD2018	236.5	5.472	4.506	13.86	28.26	23.68	9.57	1.17	2.25	37.47	156.62	250.82	0.66
RD1812	224.5	5.633	5.311	13.37	29.37	25.28	10.85	1.10	1.92	40.58	169.40	250.44	0.75
RD2023	206.2	5.633	5.311	14.63	29.64	23.10	10.75	0.75	1.98	37.28	160.88	258.90	0.78
RD2016	224.2	5.633	5.311	13.98	28.03	24.18	11.37	1.55	2.57	40.52	162.30	240.35	0.72
RD2081	231.7	5.15	4.828	12.60	24.90	24.52	11.63	3.25	5.40	46.27	167.03	216.61	0.72
RD2017	217.6	5.633	4.506	13.58	24.62	24.88	10.98	1.27	2.47	40.57	157.57	233.05	0.72
RD1809	219.7	5.633	5.633	14.28	23.94	23.67	14.12	15.45	1.90	55.92	170.82	183.29	0.78
RD1807	235.1	5.633	5.794	13.67	23.46	24.72	14.82	13.03	2.33	55.90	178.39	191.47	0.76
RD2020	226.3	5.633	5.472	12.83	23.23	26.33	14.13	15.10	2.03	58.88	182.65	186.11	0.81
RD2019	229.1	5.633	5.311	14.54	28.49	23.25	11.18	11.85	2.65	49.92	165.61	199.07	0.72
RD2018	242.2	5.15	5.472	13.02	27.75	23.73	11.83	17.08	4.97	58.92	173.18	176.37	0.72
RD1812	220.1	5.633	5.633	14.00	29.26	24.15	11.55	13.40	2.47	52.33	170.34	195.30	0.77
RD2016	208.6	5.955	5.472	15.16	26.80	23.57	12.25	17.25	2.38	56.32	158.51	168.88	0.76
RD1814	223.8	4.828	5.472	14.36	26.99	20.17	12.17	16.38	3.08	52.95	156.15	176.94	0.70
RD2017	227.4	4.828	5.955	14.21	20.92	20.38	17.08	18.80	2.08	59.33	155.67	157.42	0.68
RD1807	235.2	5.472	5.311	12.48	29.64	26.32	10.75	2.45	2.52	42.80	180.28	252.73	0.77
RD2020	227.5	4.667	5.311	13.27	30.49	21.10	10.45	1.72	1.82	36.38	151.89	250.48	0.67
RD1812	223.5	5.15	4.828	12.80	30.65	24.13	9.45	0.12	5.05	39.43	162.77	247.67	0.73
RD2018	204.6	4.828	5.311	14.12	29.69	20.52	10.73	0.07	1.97	34.68	145.74	252.12	0.71

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2023	236.3	5.472	5.955	12.18	30.94	26.95	11.55	1.03	2.63	42.88	189.74	265.48	0.80
RD1811	228.3	4.989	5.311	12.26	26.12	24.42	12.20	1.02	5.60	44.23	163.25	221.43	0.72
RD2016	220	5.633	5.633	13.76	30.27	24.57	11.17	0.62	2.85	40.32	164.19	244.35	0.75
RD1805	227.6	4.828	5.472	13.65	28.72	21.22	11.43	0.80	1.95	36.67	157.09	257.06	0.69
RD1808	235.9	5.633	5.794	12.90	28.04	26.20	12.40	7.30	2.63	49.70	188.80	227.92	0.80
RD1809	202.6	5.633	5.311	14.39	29.10	23.48	10.95	0.43	2.18	38.08	159.93	251.97	0.79
RD2019	211.2	4.828	5.15	14.10	31.06	20.55	9.95	0.07	2.10	34.50	148.10	257.57	0.70
RD1812	234.2	4.828	5.311	13.59	28.45	21.32	11.20	1.53	2.08	37.30	152.84	245.85	0.65
RD2023	225.6	5.633	5.311	12.79	28.45	26.42	11.20	2.42	2.85	43.75	184.07	252.43	0.82
RD1811	226.6	5.472	5.15	12.48	25.75	26.30	12.00	2.02	2.43	43.67	175.55	241.21	0.77
RD2016	226.2	5.633	5.311	13.85	29.32	24.40	10.87	4.87	2.07	43.08	166.08	231.30	0.73
RD2017	230.1	5.633	4.506	13.94	28.97	24.25	9.33	2.98	2.08	39.93	158.99	238.88	0.69
RD1809	213.9	5.633	5.311	12.96	28.88	26.08	11.03	3.20	2.50	43.75	169.87	232.97	0.79
RD2019	216.2	5.633	4.506	14.10	28.97	23.97	9.33	3.97	2.28	40.38	161.83	240.44	0.75
RD2020	220	4.667	5.794	12.50	26.40	22.40	13.17	5.95	2.30	44.98	164.67	219.64	0.75
RD1808	220.1	5.633	5.311	13.56	27.55	24.93	11.57	1.33	2.35	40.97	166.09	243.25	0.75
RD2081	236.1	4.667	5.472	12.16	28.18	23.03	11.65	1.82	2.40	40.38	192.11	285.43	0.81
RD1814	221.2	5.633	4.506	14.22	26.21	23.77	10.32	1.17	2.72	38.97	159.46	245.53	0.72
RD2023	225.9	5.633	5.311	13.65	28.08	24.77	11.35	5.12	2.05	44.12	173.66	236.18	0.77
RD1811	229.4	5.472	5.311	13.06	25.60	25.13	12.45	4.20	2.75	45.52	166.56	219.56	0.73
RD2016	203.1	5.633	5.311	14.35	24.54	23.55	12.98	5.38	1.63	44.58	162.30	218.42	0.80
RD1807	204.5	5.633	5.633	15.36	26.13	22.00	12.93	8.53	2.95	47.47	222.39	281.12	1.09
RD2018	229.3	5.633	5.633	14.07	26.51	24.02	12.75	2.83	2.77	43.32	179.33	248.40	0.78
RD1812	232.8	5.472	5.955	12.24	27.73	26.83	12.88	0.83	2.57	43.85	252.20	345.09	1.08
RD1808	215	5.472	5.794	13.62	26.78	24.10	12.98	2.68	3.15	43.73	187.85	257.72	0.87
RD2011	219.3	5.472	5.633	14.40	25.04	22.80	13.50	4.15	3.02	44.92	169.87	226.91	0.77
RD2016	226.8	5.633	5.794	14.69	27.77	23.00	12.52	5.52	2.80	44.73	180.28	241.81	0.79
RD2018	228.3	4.828	5.311	13.90	28.08	20.83	11.35	4.48	2.60	40.12	152.84	228.59	0.67
RD1808	216.9	5.955	5.311	14.49	26.34	24.65	12.10	0.27	2.38	40.07	160.41	240.21	0.74
RD2017	224.9	4.828	5.955	14.57	27.91	19.88	12.80	0.55	2.25	36.57	146.68	240.69	0.65
RD1805	227.5	4.828	5.955	13.52	27.07	21.43	13.20	0.87	2.98	39.65	158.99	240.59	0.70
RD2011	226.5	5.955	5.311	14.28	29.55	25.02	10.78	1.60	1.77	40.05	158.04	236.77	0.70
RD2016	238.7	4.828	5.311	13.96	26.89	20.75	11.85	6.38	2.07	42.20	155.20	220.67	0.65
RD2018	217	5.955	4.506	14.40	26.21	24.82	10.32	3.30	2.25	41.52	161.35	233.19	0.74
RD1814	217.7	4.828	5.955	12.47	23.18	23.23	15.42	30.03	2.45	73.55	214.35	174.86	0.98
RD2020	240.1	4.667	5.794	12.81	31.09	21.87	11.18	5.15	2.68	41.90	159.46	228.34	0.66
RD1808	216.2	4.828	5.955	13.64	27.48	21.23	13.00	2.70	2.80	40.53	154.26	228.34	0.71
RD1812	221.9	4.828	5.955	13.74	30.11	21.08	11.87	4.22	1.83	39.83	156.62	235.92	0.71

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2011	240.5	4.667	5.794	12.87	27.30	21.75	12.73	0.27	1.93	37.98	151.42	239.18	0.63
RD2081	233.2	5.472	5.311	13.09	28.12	25.08	11.33	5.40	2.32	44.87	169.40	226.53	0.73
RD2018	220.5	4.828	5.955	13.25	29.57	21.87	12.08	4.43	2.15	44.55	159.46	214.76	0.72
RD1809	235.6	4.828	5.955	12.55	30.24	23.08	11.82	3.75	2.03	45.95	162.30	211.93	0.69
RD2011	224.6	5.794	4.506	14.37	31.50	24.20	8.58	0.03	2.28	36.37	144.79	238.89	0.64
RD1814	232.9	5.633	4.506	13.31	30.38	25.40	8.90	0.27	2.00	37.63	161.83	258.01	0.69
RD2018	217.2	5.794	4.506	13.90	31.02	25.02	8.72	4.28	2.22	44.27	162.77	220.63	0.75
RD1807	215.5	5.633	4.506	13.12	29.76	25.77	9.08	0.33	2.50	39.58	152.36	230.95	0.71
RD1808	214.1	5.472	5.15	13.92	30.44	23.58	10.15	5.92	4.32	44.95	158.04	210.96	0.74
RD1812	231.4	5.794	4.667	14.09	30.33	24.67	9.23	2.73	2.62	40.08	161.35	241.53	0.70
RD2011	228.5	5.633	5.472	14.41	23.88	23.45	13.75	2.37	2.97	43.68	156.15	214.47	0.68
RD2023	222	5.633	5.794	12.87	27.96	26.27	12.43	0.50	2.57	42.72	177.91	249.90	0.80
RD1814	213.7	4.828	5.633	13.40	27.82	21.62	12.15	0.45	2.03	38.22	151.42	237.72	0.71
RD2081	212.5	5.472	4.506	14.06	30.10	23.35	8.98	2.62	7.67	52.35	171.29	196.32	0.81
RD1809	224.2	5.472	4.506	13.12	29.93	25.03	9.03	1.88	2.17	38.90	162.77	251.06	0.73
RD2018	231.8	5.633	5.472	13.67	29.49	24.72	11.13	2.75	2.65	42.08	169.40	241.52	0.73
RD1807	226.3	5.472	5.472	13.68	25.32	24.00	12.97	0.15	1.93	39.95	166.56	250.15	0.74
RD1812	230.6	4.828	5.633	13.05	27.48	22.20	12.30	5.58	1.98	45.42	160.88	212.54	0.70
RD1809	215.8	4.828	5.955	14.05	28.06	20.62	12.73	11.62	2.45	48.70	158.04	194.71	0.73
RD1814	210.2	5.472	5.633	12.24	23.77	26.83	14.22	8.25	1.95	52.28	189.74	217.75	0.90
RD1805	232.8	5.472	5.15	13.13	24.02	25.00	12.87	7.23	5.05	51.18	202.05	236.85	0.87
RD2011	218.4	4.667	5.794	13.76	24.00	20.35	14.48	0.08	2.60	38.42	147.63	230.57	0.68
RD2016	227.3	4.828	5.955	13.48	30.63	21.48	11.67	0.08	2.08	36.38	148.58	245.02	0.65
RD1808	192.1	5.472	5.633	14.74	22.71	22.27	14.88	11.87	6.03	55.83	163.72	175.94	0.85
RD2023	202	4.828	5.311	13.74	25.56	21.08	12.47	5.35	3.08	43.83	152.84	209.21	0.76
RD1814	217.7	5.472	5.15	11.69	26.00	28.08	11.88	1.38	4.30	46.78	170.34	218.47	0.78
RD1805	223.3	6.116	5.311	13.02	27.71	28.18	11.50	1.47	3.45	45.58	179.81	236.68	0.81
RD2081	207.6	5.15	5.15	13.55	23.65	22.80	13.07	3.67	3.65	44.12	180.28	245.19	0.87
RD1807	219.5	4.667	5.955	12.10	29.09	23.13	12.28	2.82	3.05	42.73	165.61	232.53	0.75
RD1814	222.5	4.828	5.955	11.29	30.19	25.67	11.83	0.98	1.92	41.63	158.04	227.76	0.71
RD1808	197.7	5.472	5.472	15.15	29.58	21.67	11.10	5.03	3.17	41.75	158.51	227.81	0.80
RD1805	216.1	4.828	5.311	13.44	27.87	21.55	11.43	1.40	2.93	38.83	152.36	235.41	0.71
RD2016	227.3	5.472	5.472	14.65	22.21	22.42	14.78	6.08	3.13	47.30	157.09	199.27	0.69
RD2020	229.3	4.667	5.311	12.60	28.20	22.22	11.30	4.52	2.30	41.27	155.20	225.66	0.68
RD2023	199.1	5.472	4.828	14.54	26.99	22.58	10.73	2.65	2.87	39.92	159.46	239.69	0.80
RD1807	208.8	5.472	5.15	14.62	23.98	22.45	12.88	7.38	3.68	47.45	154.73	195.65	0.74
RD2081	196.2	5.15	4.828	13.64	26.74	22.65	10.83	1.93	3.08	39.87	149.05	224.32	0.76
RD2016	225.4	4.828	6.116	13.60	28.19	21.30	13.02	5.73	3.13	44.27	152.84	207.16	0.68

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2023	215.9	4.828	5.955	13.88	29.90	20.87	11.95	0.82	3.27	38.50	154.26	240.40	0.71
RD1805	215	5.15	5.472	13.74	23.26	22.48	14.12	6.18	2.38	46.17	161.83	210.32	0.75
RD2018	212.5	5.472	5.15	13.65	29.06	24.05	10.63	9.13	4.48	49.20	162.30	197.93	0.76
RD2081	208.2	5.472	4.506	14.83	26.55	22.13	10.18	3.62	3.78	40.70	154.73	228.10	0.74
RD1807	234.5	4.828	5.472	12.04	24.69	24.05	13.30	13.67	3.72	55.53	175.08	189.16	0.75
RD2016	251.1	5.633	4.506	13.22	26.51	25.57	10.20	2.45	3.33	42.53	165.61	233.62	0.66
RD1812	212.1	4.989	5.15	13.56	30.44	22.08	10.15	7.78	2.50	43.48	176.02	242.88	0.83
RD2016	230.8	5.794	5.472	13.44	26.51	25.87	12.38	18.53	3.72	61.65	169.40	164.86	0.73
RD2018	223.8	5.633	5.15	14.21	28.44	23.78	10.87	6.25	3.17	44.92	173.18	231.34	0.77
RD1805	212.1	5.633	5.15	13.95	27.63	24.23	11.18	0.77	2.58	39.83	167.50	252.31	0.79
RD2023	221.5	5.794	5.311	14.38	28.58	24.18	11.15	0.20	2.78	39.23	160.88	246.04	0.73
RD1809	210.6	5.15	4.828	14.01	28.22	22.05	10.27	1.40	2.40	37.30	156.15	251.18	0.74
RD1812	218.3	5.15	4.828	13.94	27.63	22.17	10.48	3.62	3.42	40.60	163.72	241.95	0.75
RD2016	230.6	5.311	5.15	13.76	26.22	23.17	11.78	56.35	5.87	98.38	176.02	107.35	0.76
RD2018	238.3	5.311	5.472	13.37	20.63	23.83	15.92	50.60	5.72	96.98	196.84	121.78	0.83
RD2023	214.1	5.633	5.794	14.41	26.30	23.45	13.22	7.58	2.85	48.00	246.52	308.16	1.15
RD2011	227.7	5.794	5.311	14.54	28.71	23.92	11.10	0.23	3.03	39.38	158.04	240.77	0.69
RD1805	221.9	5.633	5.633	14.47	25.48	23.35	13.27	3.78	2.72	44.23	224.76	304.87	1.01
RD1812	219.1	5.633	5.311	14.77	32.46	22.88	9.82	1.68	3.27	38.48	167.03	260.42	0.76
RD1809	248.8	5.633	5.472	14.42	28.51	23.43	11.52	3.12	2.30	41.38	166.56	241.49	0.67
RD2023	217.5	5.472	5.311	14.06	27.79	23.35	11.47	0.98	2.13	38.97	161.83	249.18	0.74
RD1812	229.3	5.794	5.311	15.05	32.41	23.10	9.83	0.55	1.82	35.92	168.92	282.19	0.74
RD1805	232	5.472	5.311	13.70	28.79	23.97	11.07	0.15	2.18	38.23	159.93	250.99	0.69
RD1809	235.6	5.633	5.311	14.47	29.92	23.35	10.65	0.25	1.98	37.17	160.88	259.72	0.68
RD2016	233.7	5.633	5.794	13.76	26.71	24.57	13.02	3.33	2.30	44.08	174.60	237.64	0.75
RD2018	204	5.633	5.794	14.27	25.04	23.68	13.88	4.93	1.92	45.25	175.55	232.77	0.86
RD2020	205.1	4.989	5.15	13.65	24.69	21.93	12.52	5.65	2.85	43.77	170.34	233.53	0.83
RD2011	214.4	5.472	5.633	14.70	24.34	22.33	13.88	7.38	2.72	47.02	176.97	225.84	0.83
RD2016	237.3	5.794	5.472	13.33	29.10	26.08	11.28	0.10	4.08	44.22	169.87	230.51	0.72
RD2018	231.6	5.472	5.311	12.83	27.79	25.60	11.47	7.17	2.37	47.30	169.40	214.88	0.73
RD1805	226.3	5.472	5.472	14.02	24.29	23.42	13.52	16.70	3.10	57.68	168.45	175.22	0.74
RD1812	230.5	5.15	5.794	13.03	26.27	23.72	13.23	20.23	2.13	60.03	184.07	183.96	0.80
RD2081	228	5.15	5.15	13.58	27.43	22.75	11.27	16.30	2.77	54.67	186.43	204.62	0.82
RD1809	232	4.828	5.15	13.83	25.43	20.95	12.15	7.22	2.40	43.87	164.67	225.23	0.71
RD2016	239.2	4.828	5.311	13.37	29.46	21.67	10.82	0.17	2.27	36.47	148.10	243.68	0.62
RD1812	235.2	5.15	4.828	13.34	29.06	23.17	9.97	1.87	2.15	37.78	163.25	259.24	0.69
RD2081	222.6	4.828	5.311	13.48	27.99	21.48	11.38	3.38	2.18	39.58	150.94	228.80	0.68
RD1812	222.5	4.989	5.472	12.74	30.68	23.50	10.70	1.37	2.43	47.23	160.41	203.76	0.72

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2023	215.9	4.828	5.311	12.35	23.46	23.45	13.58	4.40	2.10	48.00	161.35	201.69	0.75
RD1807	229.7	5.633	5.633	13.31	24.49	25.40	13.80	8.87	2.27	51.17	299.05	350.68	1.30
RD1809	196.5	5.633	4.506	14.16	26.59	23.87	10.17	4.10	2.82	41.68	154.73	222.72	0.79
RD2016	225.4	5.633	4.667	13.54	28.33	24.97	9.88	4.47	2.67	43.02	159.93	223.08	0.71
RD1805	215.4	5.633	4.506	13.95	30.21	24.23	8.95	3.12	2.32	39.53	159.93	242.73	0.74
RD2023	228.8	5.633	4.506	12.84	25.27	26.32	10.70	0.18	2.48	40.48	168.45	249.66	0.74
RD1809	217.3	4.828	5.311	13.42	27.55	21.58	11.57	2.13	2.42	38.60	151.89	236.10	0.70
RD1807	233.1	4.828	5.15	12.46	28.97	23.25	10.67	3.40	2.93	41.58	168.92	243.74	0.72
RD1812	224.5	5.794	4.667	13.56	29.17	25.63	9.60	1.95	2.63	40.72	169.87	250.32	0.76
RD2011	232.1	5.472	4.506	13.00	29.33	25.25	9.22	0.58	3.07	48.43	153.31	189.92	0.66
RD1805	224.6	4.828	5.311	12.79	29.01	22.65	10.98	2.30	3.83	41.35	162.77	236.19	0.72
RD1809	211.9	5.633	4.667	13.94	32.75	24.25	8.55	0.02	2.35	36.03	157.09	261.58	0.74
RD1812	216.2	5.633	5.472	13.53	30.73	24.98	10.68	0.07	1.98	38.53	163.25	254.19	0.76
RD2016	224.9	5.794	5.472	13.98	27.40	24.87	11.98	3.23	3.55	44.40	204.89	276.87	0.91
RD1805	215.8	5.633	4.506	14.10	29.12	23.97	9.28	0.03	2.17	36.38	162.30	267.65	0.75
RD1809	221.5	4.828	5.311	13.19	24.83	21.97	12.83	4.43	3.13	43.42	155.20	214.48	0.70
RD1805	223.2	5.633	5.311	13.45	26.37	25.13	12.08	0.15	1.93	40.45	168.45	249.87	0.75
RD1809	210.8	5.633	4.667	13.63	29.95	24.80	9.35	2.22	2.60	39.97	161.35	242.23	0.77
RD2016	235.7	5.15	4.828	13.51	26.54	22.87	10.92	3.55	2.97	41.23	159.93	232.73	0.68
RD2011	207.4	5.633	4.506	14.10	28.21	23.97	9.58	0.52	2.72	38.20	150.94	237.08	0.73
RD1805	203.8	5.633	4.667	13.05	24.31	25.90	11.52	2.80	3.63	60.07	169.40	169.21	0.83
RD1809	222.2	5.955	5.472	15.15	25.82	23.58	12.72	11.80	1.87	50.73	165.61	195.86	0.75
RD1812	211.9	5.955	5.472	14.60	25.45	24.47	12.90	15.35	2.22	59.08	176.49	179.23	0.83
RD2023	225.9	5.15	5.472	12.29	23.23	25.15	14.13	17.12	2.68	60.12	179.33	178.99	0.79
RD2011	227	5.955	5.472	13.69	25.75	26.10	12.75	14.22	1.90	56.10	169.87	181.68	0.75
RD1805	207.6	5.955	5.311	14.58	30.94	24.50	10.30	0.15	2.13	38.07	161.35	254.32	0.78
RD1812	220.6	5.15	5.311	12.72	28.97	24.28	11.00	1.20	2.20	39.88	165.14	248.43	0.75
RD2023	231.5	5.955	5.311	12.63	27.95	28.28	11.40	1.50	1.98	44.18	184.07	249.96	0.80
RD1805	232.5	4.667	5.794	11.48	25.59	24.40	13.58	0.18	2.52	41.92	173.18	247.90	0.74
RD1812	232.1	4.828	5.311	12.41	27.01	23.35	11.80	0.08	1.98	37.98	153.31	242.17	0.66
RD2018	221.8	5.15	5.472	13.79	28.43	22.40	11.55	12.47	4.20	51.38	163.25	190.62	0.74
RD2023	206.8	5.15	5.472	12.46	26.69	24.80	12.30	10.28	4.88	53.23	174.60	196.80	0.84
RD2011	217.4	4.828	5.794	14.11	24.54	20.53	14.17	3.18	2.65	41.43	149.52	216.53	0.69
RD2016	222.4	5.15	5.472	13.29	26.09	23.25	12.58	19.70	4.67	61.32	171.29	167.61	0.77
RD2020	222.2	4.828	5.311	13.67	29.32	21.18	10.87	2.48	2.12	37.60	153.78	245.40	0.69
RD2018	212.3	4.828	5.311	14.54	30.30	19.92	10.52	5.48	1.78	38.47	146.68	228.80	0.69
RD1809	243.2	4.828	5.633	12.61	25.90	22.97	13.05	1.72	2.07	40.83	178.86	262.82	0.74
RD2023	215.9	4.828	5.794	12.84	27.81	22.57	12.50	2.28	1.72	40.28	175.55	261.47	0.81

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD1812	218.3	4.989	5.15	13.29	28.44	22.52	10.87	1.48	2.97	39.08	176.02	270.23	0.81
RD2016	234.5	5.15	4.989	11.51	29.35	26.85	10.20	0.83	3.55	42.33	195.90	277.65	0.84
RD2020	248.7	4.667	5.794	12.13	25.66	23.08	13.55	3.35	1.90	42.95	186.90	261.10	0.75
RD2018	204.4	5.15	5.311	13.47	25.36	22.93	12.57	4.95	3.68	45.02	172.71	230.19	0.84
RD2011	234.5	4.667	5.633	12.67	22.58	22.10	14.97	6.98	2.42	47.27	170.34	216.23	0.73
RD2016	241.5	4.828	5.472	12.40	25.75	23.37	12.75	5.28	2.25	44.70	167.50	224.84	0.69
RD2018	209.1	4.828	5.311	13.04	27.91	22.22	11.42	2.15	2.55	39.97	158.04	237.26	0.76
RD2023	220.2	5.15	4.828	12.69	25.34	24.35	11.43	4.67	4.25	45.92	169.87	221.97	0.77
RD1812	241.7	4.828	5.633	13.01	28.20	22.27	11.98	2.53	2.27	40.33	165.61	246.37	0.69
RD2023	216	4.828	5.311	12.71	24.67	22.78	12.92	0.67	2.07	39.68	158.51	239.67	0.73
RD2023	206.3	4.989	5.15	14.04	28.26	21.32	10.93	44.42	3.75	81.32	197.31	145.59	0.96
RD1809	227.3	4.828	5.794	13.97	21.35	20.73	16.28	28.37	2.70	69.87	186.43	160.10	0.82
RD2011	236.8	4.828	5.633	13.61	22.89	21.28	14.77	9.75	2.07	49.17	202.52	247.14	0.86
RD2016	219.2	4.828	5.794	14.23	22.55	20.35	15.42	20.63	2.90	60.42	254.57	252.81	1.16
RD2017	216	4.989	4.989	13.86	23.36	21.60	12.82	7.92	2.95	46.00	173.18	225.89	0.80
RD2018	217.7	4.989	5.15	13.30	22.78	22.50	13.57	25.43	3.80	66.23	176.97	160.31	0.81
RD2020	218.9	4.989	4.989	13.09	22.39	22.87	13.37	18.07	3.38	58.75	198.73	202.96	0.91
RD2020	223.5	4.828	5.311	13.58	24.61	21.33	12.95	5.53	2.13	43.25	153.31	212.68	0.69
RD1805	212.6	5.472	4.667	14.31	25.23	22.95	11.10	3.33	3.08	41.23	158.99	231.35	0.75
RD2017	214	4.828	5.311	14.38	30.40	20.15	10.48	6.80	1.97	40.13	146.21	218.59	0.68
RD2016	228.7	5.633	4.506	14.98	29.44	22.57	9.18	8.00	3.22	43.87	160.88	220.05	0.70
RD2020	227.6	5.472	4.506	13.46	26.33	24.38	10.27	13.17	2.25	50.83	169.87	200.50	0.75
RD1809	227.8	5.633	4.667	14.53	25.97	23.27	10.78	12.05	2.20	49.05	163.72	200.27	0.72
RD2018	220	5.15	4.828	13.70	26.02	22.55	11.13	2.62	2.77	39.98	155.68	233.61	0.71
RD1805	221.4	4.989	5.15	11.89	24.24	25.18	12.75	7.63	3.03	50.10	177.44	212.50	0.80
RD2023	232.4	5.955	5.311	12.81	30.30	27.88	10.52	4.93	2.20	53.82	189.74	211.55	0.82
RD2017	220.4	5.633	4.506	14.75	29.49	22.92	9.17	7.60	2.43	42.85	156.62	219.31	0.71
RD2016	226	5.794	5.311	14.92	30.25	23.30	10.53	0.07	1.93	52.45	167.50	191.62	0.74
RD1805	208.9	5.633	5.794	14.12	23.78	23.93	14.62	19.00	2.27	61.40	174.60	170.62	0.84
RD1812	220.7	5.633	5.472	14.77	26.37	22.88	12.45	11.33	2.37	50.30	164.19	195.86	0.74
RD2020	230.1	5.633	5.15	13.94	24.82	24.25	12.45	5.75	3.68	47.15	174.13	221.59	0.76
RD1812	204.4	4.828	5.472	14.44	27.25	20.07	12.05	5.10	1.72	39.70	146.68	221.69	0.72
RD1805	208.4	4.828	5.311	14.34	26.48	20.20	12.03	0.88	1.68	36.13	148.58	246.72	0.71
RD2017	201.7	4.828	5.311	12.85	29.37	22.55	10.85	0.53	1.92	36.83	149.05	242.80	0.74
RD2016	220.5	4.828	5.311	14.18	29.55	20.43	10.78	0.08	2.40	35.18	150.94	257.41	0.68
RD2018	217	4.828	5.311	13.78	26.59	21.02	11.98	1.32	2.28	37.82	147.16	233.48	0.68
RD1809	228.9	4.828	5.311	11.95	29.55	24.23	10.78	2.05	2.18	40.13	161.35	241.23	0.70
RD2020	216.6	4.828	5.311	13.61	22.55	21.28	14.13	2.95	2.52	41.90	153.78	220.21	0.71

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2016	229.2	4.989	5.15	13.32	25.89	22.47	11.93	16.27	3.87	55.45	167.98	181.76	0.73
RD1809	223.3	4.989	4.989	13.90	25.12	21.53	11.92	2.43	3.17	39.75	169.40	255.69	0.76
RD2020	224.6	4.828	5.794	13.99	26.11	20.70	13.32	3.50	2.43	40.83	166.08	244.04	0.74
RD2017	207.6	4.828	5.794	14.84	28.93	19.52	12.02	1.82	2.10	36.58	159.93	262.31	0.77
RD2018	226.2	4.828	5.794	13.34	24.00	21.72	14.48	1.17	2.30	40.50	164.19	243.25	0.73
RD1809	225.9	4.828	5.633	13.74	24.49	21.08	13.80	41.42	2.03	80.00	170.34	127.76	0.75
RD1805	207.1	4.989	5.472	13.18	25.68	22.72	12.78	4.68	2.57	43.92	178.39	243.72	0.86
RD2016	226.8	4.828	5.794	13.93	28.30	20.80	12.28	7.78	1.98	44.23	172.24	233.63	0.76
RD1812	213.6	4.828	5.472	14.01	27.17	20.68	12.08	6.18	2.57	42.65	151.42	213.01	0.71
RD1809	209.2	5.633	4.667	14.28	27.01	23.67	10.37	7.88	2.15	52.00	160.41	185.09	0.77
RD1805	228.3	5.472	5.311	13.14	23.04	24.98	13.83	6.60	2.07	48.33	176.97	219.68	0.78
RD2018	220.8	5.633	5.15	14.43	27.18	23.42	11.37	1.37	2.35	39.32	166.56	254.18	0.75
RD2016	220	4.989	4.989	12.69	29.11	23.58	10.28	16.60	2.40	53.63	160.88	179.98	0.73
RD2017	208.4	5.633	5.311	14.69	28.45	23.00	11.20	2.10	3.03	40.37	157.57	234.21	0.76
RD2023	236.9	4.828	5.311	11.95	30.45	24.25	10.47	3.50	1.97	41.18	173.66	253.00	0.73
RD2018	235.7	4.989	5.311	13.58	25.16	22.05	12.67	2.13	2.43	40.17	152.84	228.30	0.65
RD2020	231.7	4.828	5.311	12.72	30.20	22.77	10.55	3.53	2.33	40.32	159.46	237.31	0.69
RD2016	245.6	4.828	5.311	13.53	28.62	21.42	11.13	0.10	2.02	35.53	156.15	263.67	0.64
RD1809	236.2	4.828	5.311	13.75	29.37	21.07	10.85	0.12	2.03	34.87	150.94	259.75	0.64
RD1812	217.7	4.828	5.311	14.54	29.19	19.92	10.92	0.72	2.20	34.57	145.74	252.97	0.67
RD2018	199.5	6.276	4.989	15.07	29.79	24.98	10.05	0.32	2.05	54.45	162.30	178.84	0.81
RD1805	223	5.15	5.311	13.51	20.69	22.87	15.40	6.60	2.33	48.57	181.23	223.89	0.81
RD2023	222	4.828	5.794	13.63	27.59	21.25	12.60	4.63	1.85	41.75	176.49	253.65	0.80
RD2018	214.1	4.828	5.955	14.04	26.50	20.63	13.48	0.07	4.38	39.45	153.78	233.89	0.72
RD1805	219.4	4.828	5.311	14.25	29.69	20.33	10.73	0.17	1.90	34.33	149.52	261.30	0.68
RD2020	217.9	4.828	5.311	13.49	27.35	21.47	11.65	0.10	2.10	36.25	149.52	247.49	0.69
RD1809	238.8	4.828	5.472	12.96	29.23	22.35	11.23	3.43	1.92	40.47	157.09	232.92	0.66
RD2017	222.6	4.828	5.311	12.57	27.01	23.05	11.80	0.17	2.07	37.88	159.46	252.56	0.72
RD2020	204.2	4.828	5.633	13.97	24.34	20.73	13.88	5.08	2.38	43.00	150.47	209.96	0.74
RD1812	217.6	5.15	4.989	13.52	29.06	22.85	10.30	0.02	3.02	37.77	158.51	251.83	0.73
RD1805	212.8	5.15	4.828	13.44	29.86	22.98	9.70	0.10	2.78	36.70	158.51	259.15	0.74
RD2018	229.8	4.828	5.311	14.08	28.71	20.57	11.10	1.47	2.63	36.80	149.05	243.02	0.65
RD1805	221.2	5.955	5.311	14.78	28.58	24.17	11.15	0.37	2.83	39.53	163.72	248.48	0.74
RD2017	218.8	6.598	4.667	15.70	26.88	25.22	10.42	2.48	2.10	55.43	161.83	175.16	0.74
RD2020	206.1	4.989	5.311	12.47	26.85	24.00	11.87	14.45	2.72	53.85	168.45	187.69	0.82
RD1805	240.3	4.989	5.794	11.69	25.91	25.62	13.42	16.55	3.38	60.07	186.90	186.70	0.78
RD2023	206	5.15	5.472	13.25	32.67	23.32	10.05	0.10	2.95	37.18	160.88	259.60	0.78
RD1805	231.6	4.828	5.311	13.23	30.74	21.90	10.37	0.13	1.90	35.38	157.09	266.39	0.68

Truck #	Payload (tonnes)	Loaded Travel Dist. (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded time (min)	Travel Empty time (min)	Unload. time (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
RD2018	223	4.828	5.311	14.48	27.63	20.00	11.53	0.10	2.08	34.53	142.90	248.28	0.64
RD1812	220.5	4.989	5.311	12.67	27.51	23.63	11.58	6.95	5.05	48.17	163.25	203.35	0.74
RD2023	227.5	5.15	4.989	12.33	25.62	25.07	11.68	3.02	3.03	43.98	177.91	242.70	0.78
RD1812	213.6	4.828	5.311	13.67	26.41	21.18	12.07	2.60	2.03	40.30	147.63	219.80	0.69
RD2023	205.3	4.989	5.311	13.57	26.48	22.07	12.03	5.95	2.45	43.50	164.19	226.47	0.80
RD1812	226.8	4.989	6.116	12.78	30.88	23.42	11.88	0.12	2.92	39.45	165.14	251.16	0.73
RD2023	203.3	5.15	4.828	13.40	24.90	23.07	11.63	0.30	2.43	38.50	159.93	249.25	0.79
RD2023	207.7	4.828	5.311	13.74	28.37	21.08	11.23	1.23	2.22	36.72	152.36	248.98	0.73
RD2018	210.2	4.828	5.955	14.31	26.93	20.25	13.27	4.32	2.47	41.37	166.09	240.90	0.79
RD1812	228.2	4.989	5.311	12.70	27.39	23.57	11.63	0.95	3.90	41.32	180.75	262.49	0.79
RD2023	203.9	4.828	5.794	13.56	27.05	21.37	12.85	5.68	3.05	44.15	172.24	234.07	0.84
RD2018	216.3	5.955	5.472	15.73	29.53	22.72	11.12	2.45	2.03	39.63	160.41	242.84	0.74
RD1812	217.6	6.116	5.311	14.59	28.49	25.15	11.18	0.10	2.05	39.42	161.35	245.61	0.74
RD2018	217.6	4.828	5.955	13.81	31.07	20.98	11.50	1.43	2.32	39.68	152.36	230.37	0.70
RD2023	208.2	5.633	4.506	13.10	30.32	25.80	8.92	0.65	2.02	38.03	168.92	266.49	0.81
RD2023	226.3	5.15	4.828	12.96	27.81	23.85	10.42	0.12	4.75	40.00	167.03	250.55	0.74
RD2018	206.3	4.828	5.311	13.14	29.97	22.05	10.63	2.60	2.47	39.37	159.93	243.76	0.78
RD2023	217.8	4.989	5.311	13.57	24.58	22.07	12.97	0.50	2.75	40.13	159.46	238.40	0.73

Table 57. Manual data from extendSim.

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
233.11	5.422	6.771	12.41	24.80	26.21	16.38	5.24	1.92	49.76	185.48	223.67	0.80
215.38	5.608	5.969	13.46	26.33	24.99	13.60	1.17	1.98	41.75	170.70	245.34	0.79
224.12	5.731	5.997	13.23	25.77	25.99	13.96	0.80	2.36	43.11	177.07	246.46	0.79
220.74	5.443	5.991	13.12	26.87	24.90	13.38	29.00	2.20	69.48	171.26	147.90	0.78
216.21	5.548	6.103	13.41	26.70	24.82	13.72	2.72	3.39	44.65	169.94	228.38	0.79
221.84	5.556	5.932	13.15	25.99	25.35	13.70	1.46	2.33	42.83	173.20	242.63	0.78
237.90	5.680	5.909	12.27	25.36	27.79	13.98	2.42	1.85	46.04	190.64	248.46	0.80
228.38	5.654	6.740	12.89	25.50	26.32	15.86	5.10	2.56	49.84	185.74	223.63	0.81
209.03	5.788	6.768	13.98	24.82	24.84	16.36	1.81	2.83	45.84	177.38	232.15	0.85
215.04	5.572	6.021	13.54	26.08	24.70	13.85	3.85	1.86	44.25	168.69	228.72	0.78
229.00	5.655	6.543	12.67	24.21	26.78	16.21	3.20	1.87	48.06	188.28	235.05	0.82
232.32	5.391	5.983	12.46	23.82	25.96	15.07	15.63	2.34	59.00	176.52	179.50	0.76
225.90	5.753	6.844	13.95	26.67	24.75	15.40	12.67	1.84	54.65	177.53	194.91	0.79
224.41	5.713	6.523	14.01	29.88	24.46	13.10	4.46	2.02	44.04	175.81	239.51	0.78

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
210.69	5.880	5.949	14.66	29.75	24.07	12.00	0.66	2.23	38.96	167.00	257.20	0.79
233.54	5.677	5.864	13.15	29.86	25.90	11.78	3.71	2.56	43.95	180.06	245.82	0.77
217.36	5.782	5.846	14.29	29.85	24.28	11.75	1.45	5.67	43.14	169.36	235.53	0.78
233.27	5.647	5.799	13.29	29.97	25.50	11.61	2.53	2.95	42.59	177.09	249.50	0.76
207.32	5.714	5.942	14.79	29.81	23.18	11.96	2.25	1.98	39.37	163.29	248.84	0.79
230.05	5.715	6.595	13.66	29.84	25.10	13.26	2.08	3.20	43.64	179.58	246.88	0.78
230.46	5.647	6.545	13.45	29.94	25.19	13.12	4.93	1.96	45.20	179.62	238.43	0.78
225.96	5.600	6.477	13.50	29.81	24.90	13.04	1.27	2.99	42.18	177.70	252.74	0.79
232.56	5.436	6.643	12.77	27.14	25.54	14.69	1.76	2.45	44.43	182.95	247.05	0.79
218.85	5.640	6.638	13.57	28.40	24.93	14.02	0.79	2.58	42.33	178.62	253.18	0.82
220.75	5.581	5.921	13.55	28.19	24.72	12.60	1.60	2.64	41.56	171.07	246.97	0.77
219.06	5.735	5.890	14.14	28.46	24.34	12.42	1.38	2.33	40.48	168.63	249.97	0.77
233.19	5.497	5.912	12.70	28.04	25.96	12.65	0.65	3.04	42.30	177.49	251.74	0.76
219.27	5.578	6.583	13.49	27.78	24.81	14.22	1.07	2.05	42.15	177.20	252.26	0.81
214.96	5.515	6.618	13.81	28.10	23.97	14.13	7.19	4.01	49.29	170.90	208.01	0.80
232.79	5.488	6.567	12.81	28.45	25.70	13.85	1.52	2.19	43.26	182.33	252.87	0.78
210.24	5.664	5.996	14.29	27.53	23.78	13.07	9.39	2.34	48.58	164.20	202.79	0.78
201.01	5.718	6.937	14.48	25.64	23.69	16.23	2.73	2.47	45.12	172.45	229.31	0.86
220.93	5.681	6.599	13.67	28.16	24.94	14.06	0.64	2.77	42.41	177.90	251.71	0.81
228.14	5.680	5.954	13.11	28.25	26.00	12.65	1.28	3.52	43.44	178.65	246.75	0.78
229.07	5.546	5.985	13.20	27.93	25.21	12.86	0.85	2.53	41.45	172.84	250.21	0.75
219.21	5.687	5.989	13.68	28.06	24.94	12.81	29.94	2.24	69.92	172.21	147.78	0.79
205.31	5.706	5.949	14.38	27.42	23.80	13.02	4.11	1.78	42.71	165.08	231.89	0.80
212.57	5.637	6.539	14.16	28.07	23.89	13.98	2.49	3.00	43.35	170.07	235.41	0.80
204.47	5.682	6.561	14.53	27.89	23.46	14.11	5.32	2.98	45.88	168.86	220.83	0.83
232.99	5.470	6.698	13.01	27.89	25.23	14.41	1.55	2.60	43.80	179.15	245.42	0.77
221.76	5.707	5.938	13.70	27.13	24.99	13.13	6.96	2.39	47.48	172.10	217.49	0.78
212.84	4.593	6.769	10.93	27.26	25.21	14.90	1.28	1.94	43.33	178.15	246.71	0.84
205.79	5.667	6.618	14.49	28.52	23.46	13.92	2.67	2.63	42.69	169.77	238.61	0.82
206.07	5.627	6.695	14.25	27.99	23.69	14.35	1.27	3.34	42.65	171.39	241.10	0.83
205.59	5.739	6.559	14.38	28.24	23.94	13.94	1.26	2.86	42.00	172.11	245.85	0.84
217.06	5.525	6.488	14.07	28.41	23.56	13.70	1.59	2.20	41.05	168.35	246.03	0.78
219.07	5.785	5.921	13.88	27.93	25.01	12.72	5.35	2.56	45.64	172.38	226.62	0.79
216.20	5.557	6.577	13.78	27.72	24.19	14.24	0.76	2.43	41.61	172.01	248.01	0.80
209.07	5.548	5.962	14.04	28.03	23.71	12.76	2.69	2.87	42.03	164.54	234.87	0.79
226.67	5.824	7.142	13.53	24.11	25.84	17.78	2.58	2.34	48.53	185.14	228.91	0.82
212.75	5.621	5.990	14.26	25.90	23.65	13.87	2.38	2.51	42.42	164.51	232.70	0.77
232.57	5.675	6.515	13.04	27.81	26.10	14.05	5.66	2.67	48.48	184.25	228.02	0.79

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
209.55	5.663	5.863	14.24	27.66	23.86	12.72	1.01	2.49	40.08	164.75	246.62	0.79
230.79	5.689	6.070	12.99	28.39	26.28	12.83	12.33	1.98	53.42	179.91	202.08	0.78
211.68	5.553	5.964	14.14	28.49	23.56	12.56	1.58	2.84	40.54	163.86	242.50	0.77
225.91	5.733	5.848	13.48	27.37	25.51	12.82	3.37	3.23	44.93	174.81	233.44	0.77
234.59	5.510	6.586	12.79	28.22	25.85	14.00	0.91	2.24	43.01	182.98	255.28	0.78
220.45	5.763	6.545	13.73	28.25	25.18	13.90	1.65	4.37	45.11	178.69	237.67	0.81
213.22	5.623	6.632	14.13	28.36	23.87	14.03	0.64	2.18	40.73	170.82	251.64	0.80
238.53	5.560	5.971	12.37	28.09	26.96	12.75	6.59	3.24	49.54	186.37	225.72	0.78
243.19	5.910	6.691	12.32	23.93	28.77	16.77	4.26	1.95	51.76	212.47	246.30	0.87
224.62	5.581	6.032	13.33	27.31	25.12	13.25	4.34	2.21	44.91	172.83	230.89	0.77
218.51	5.662	5.910	13.88	28.30	24.47	12.53	0.77	2.76	40.53	169.22	250.54	0.77
212.92	5.821	5.930	14.20	27.74	24.60	12.83	5.25	2.38	45.05	169.87	226.24	0.80
240.68	5.941	5.930	12.42	27.63	28.70	12.88	15.61	2.43	59.62	202.02	203.32	0.84
213.94	5.682	6.508	14.23	28.32	23.95	13.79	1.81	2.56	42.11	170.44	242.85	0.80
210.95	5.577	6.024	14.09	27.76	23.75	13.02	1.38	2.25	40.41	164.64	244.48	0.78
220.52	5.676	6.623	13.70	27.75	24.86	14.32	4.47	2.57	46.23	177.44	230.31	0.80
213.14	5.747	5.938	14.15	28.01	24.37	12.72	1.71	2.91	41.70	168.14	241.90	0.79
215.21	5.681	6.051	13.85	27.76	24.61	13.08	1.39	2.33	41.41	169.55	245.64	0.79
234.94	5.456	6.579	12.67	27.87	25.83	14.16	3.87	2.38	46.25	182.60	236.91	0.78
206.65	5.815	5.929	14.72	27.89	23.70	12.75	10.48	1.93	48.87	163.52	200.75	0.79
227.04	5.524	7.027	13.06	25.94	25.37	16.26	15.52	3.01	60.17	180.25	179.75	0.79
210.65	5.571	5.955	13.93	28.18	24.00	12.68	1.01	1.94	39.63	166.31	251.77	0.79
219.88	5.614	6.003	13.56	28.40	24.85	12.69	6.90	1.73	46.17	171.98	223.47	0.78
201.76	5.713	6.532	14.57	27.92	23.52	14.04	0.45	2.23	40.24	169.92	253.37	0.84
203.36	5.615	5.976	14.57	27.52	23.13	13.03	10.02	3.36	49.53	161.23	195.30	0.79
219.80	5.583	6.003	13.50	27.88	24.81	12.92	0.85	3.10	41.68	171.24	246.52	0.78
226.18	5.552	6.509	13.17	27.86	25.29	14.02	5.40	2.25	46.95	179.32	229.16	0.79
238.42	5.700	5.948	12.51	27.82	27.33	12.83	3.92	2.59	46.67	189.18	243.19	0.79
207.61	5.642	6.060	14.19	27.89	23.86	13.04	5.86	2.33	45.08	165.80	220.66	0.80
220.41	5.540	6.556	13.21	28.40	25.17	13.85	1.35	2.41	42.78	179.14	251.24	0.81
233.04	5.535	6.440	12.79	27.36	25.97	14.12	4.35	2.11	46.55	182.48	235.20	0.78
210.51	5.542	6.665	13.81	24.11	24.09	16.59	0.62	3.43	44.73	172.34	231.21	0.82
212.48	5.593	6.035	13.80	25.75	24.32	14.06	3.98	2.23	44.59	167.71	225.65	0.79
219.56	5.634	6.635	13.34	25.79	25.33	15.43	6.39	2.89	50.05	180.47	216.36	0.82
236.61	5.647	5.944	12.44	25.35	27.24	14.07	1.47	2.19	44.97	185.12	246.97	0.78
223.28	5.765	5.928	13.18	24.28	26.24	14.65	1.26	2.06	44.20	178.69	242.54	0.80
218.11	5.612	6.547	13.08	24.83	25.75	15.82	11.08	1.99	54.64	182.43	200.31	0.84
239.15	5.701	6.669	12.15	23.51	28.16	17.02	4.55	2.23	51.96	200.18	231.16	0.84

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
225.98	5.548	6.036	13.09	26.62	25.42	13.60	11.46	2.65	53.14	174.19	196.68	0.77
223.45	5.475	6.717	12.74	25.02	25.79	16.11	2.21	2.29	46.40	182.28	235.69	0.82
226.17	5.437	6.648	12.70	26.58	25.69	15.01	1.47	1.88	44.05	181.68	247.47	0.80
218.13	5.606	6.002	13.24	26.87	25.40	13.40	2.83	2.44	44.08	174.71	237.82	0.80
209.96	5.487	5.912	13.70	25.28	24.03	14.04	1.83	2.12	42.02	165.67	236.55	0.79
216.91	5.412	6.143	13.35	26.76	24.33	13.77	32.86	2.06	73.02	167.22	137.40	0.77
203.53	5.500	5.944	13.94	25.18	23.68	14.17	5.51	3.02	46.37	164.44	212.77	0.81
214.45	5.608	6.564	13.47	25.34	24.98	15.54	1.23	2.72	44.48	177.02	238.79	0.83
216.03	5.658	6.574	13.85	26.04	24.51	15.15	4.54	1.82	46.02	174.32	227.27	0.81
225.57	5.473	6.661	12.98	25.00	25.29	15.99	3.16	2.20	46.64	178.96	230.24	0.79
226.47	5.608	6.042	13.09	25.51	25.70	14.21	13.29	3.21	56.41	176.09	187.30	0.78
231.85	5.662	6.554	12.79	24.48	26.56	16.07	1.47	2.43	46.52	184.79	238.36	0.80
217.00	5.613	6.648	13.50	25.13	24.95	15.87	3.47	2.43	46.72	176.85	227.11	0.81
238.25	5.628	6.683	12.40	25.87	27.24	15.50	5.17	2.37	50.29	193.44	230.79	0.81
236.52	5.520	6.572	12.29	25.33	26.94	15.57	8.98	3.29	54.78	189.84	207.94	0.80
216.95	5.477	6.033	13.21	25.71	24.88	14.08	3.60	2.19	44.76	170.02	227.91	0.78
204.20	5.709	5.928	14.32	26.44	23.91	13.45	0.72	3.04	41.12	165.90	242.07	0.81
229.40	5.435	6.668	12.58	25.18	25.93	15.89	5.06	3.16	50.03	182.22	218.52	0.79
238.44	5.554	6.923	12.15	23.87	27.43	17.40	4.76	2.60	52.20	195.41	224.62	0.82
227.02	5.608	5.940	12.83	24.04	26.24	14.83	4.57	2.31	47.95	177.85	222.55	0.78
218.15	5.732	6.039	13.35	26.30	25.75	13.78	1.83	2.55	43.92	176.21	240.74	0.81
226.72	5.389	6.705	12.58	26.43	25.70	15.22	0.51	2.08	43.51	181.72	250.62	0.80
217.67	5.602	5.994	13.28	25.07	25.31	14.35	3.12	2.62	45.40	172.64	228.18	0.79
207.80	5.612	6.003	13.96	25.42	24.12	14.17	0.88	2.36	41.53	166.34	240.30	0.80
231.67	5.383	6.055	12.37	25.94	26.11	14.01	6.33	7.70	54.15	177.33	196.50	0.77
214.22	5.587	6.639	13.69	25.68	24.49	15.51	1.21	1.96	43.17	174.46	242.47	0.81
215.02	5.563	6.614	13.58	23.30	24.58	17.03	7.90	2.79	52.30	174.90	200.65	0.81
220.33	5.776	5.885	13.29	26.36	26.08	13.40	0.58	3.37	43.43	178.08	246.04	0.81
225.80	5.617	6.030	12.91	25.99	26.11	13.92	12.41	2.31	54.75	178.07	195.13	0.79
208.19	4.729	6.849	11.04	22.88	25.71	17.96	9.70	3.43	56.79	181.90	192.17	0.87
218.19	5.757	5.997	13.42	26.44	25.74	13.61	0.86	2.75	42.97	176.02	245.78	0.81
239.72	5.885	6.019	12.07	25.43	29.24	14.20	2.81	2.81	49.06	203.75	249.19	0.85
238.87	5.559	5.958	12.20	25.20	27.33	14.19	4.28	2.91	48.71	188.08	231.67	0.79
223.67	4.972	5.969	11.08	24.42	26.93	14.67	8.36	2.04	51.99	182.98	211.16	0.82
216.96	5.528	6.085	13.42	26.15	24.72	13.97	0.46	2.34	41.49	169.37	244.95	0.78
227.82	5.437	6.542	12.84	25.54	25.41	15.37	2.99	1.89	45.66	179.51	235.89	0.79
206.83	5.597	6.682	14.06	25.88	23.88	15.49	5.09	2.10	46.56	172.08	221.73	0.83
239.86	5.963	5.946	12.27	25.97	29.15	13.74	5.41	1.80	50.10	203.12	243.27	0.85

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
225.29	5.640	6.601	13.09	26.00	25.85	15.23	1.96	2.17	45.21	182.80	242.61	0.81
221.75	5.868	5.950	13.34	24.52	26.39	14.56	0.60	2.02	43.57	179.74	247.55	0.81
212.29	5.583	6.079	13.67	24.93	24.51	14.63	23.10	2.10	64.34	168.25	156.91	0.79
224.67	5.663	6.701	13.11	24.88	25.91	16.16	13.36	1.84	57.26	183.40	192.17	0.82
219.93	5.685	6.601	13.26	23.99	25.73	16.51	2.74	2.53	47.51	182.82	230.88	0.83
228.70	5.541	6.003	12.91	24.14	25.75	14.92	3.52	2.32	46.52	175.39	226.23	0.77
198.91	5.770	5.986	14.79	23.18	23.40	15.49	1.29	2.47	42.66	162.50	228.58	0.82
212.93	5.617	5.980	13.67	25.98	24.65	13.81	1.81	2.06	42.34	169.07	239.58	0.79
212.06	5.734	6.005	13.89	24.96	24.77	14.43	1.80	2.04	43.05	169.81	236.68	0.80
226.95	5.518	6.540	12.94	24.38	25.59	16.10	4.27	3.13	49.09	180.16	220.21	0.79
227.13	5.514	6.528	12.77	24.41	25.91	16.04	10.48	2.02	54.46	183.27	201.91	0.81
238.76	5.732	6.676	12.07	24.09	28.49	16.63	2.82	2.09	50.02	202.40	242.79	0.85
221.60	5.522	6.637	13.19	24.62	25.12	16.18	1.78	2.76	45.83	178.45	233.63	0.81
242.32	5.825	6.662	12.35	27.93	28.31	14.31	1.41	2.69	46.73	206.24	264.83	0.85
224.36	5.633	6.568	13.41	28.26	25.20	13.95	3.36	2.99	45.50	179.05	236.11	0.80
225.25	5.625	5.948	13.29	27.87	25.39	12.80	3.79	2.88	44.86	174.33	233.15	0.77
231.91	5.616	5.990	13.04	27.06	25.85	13.28	6.55	2.32	48.00	176.61	220.74	0.76
229.75	5.547	5.954	13.10	28.11	25.41	12.71	0.87	1.85	40.84	174.42	256.23	0.76
240.34	5.848	6.598	12.48	28.44	28.11	13.92	2.38	2.71	47.12	204.52	260.43	0.85
237.72	5.627	6.558	12.50	28.33	27.02	13.89	3.05	2.05	46.01	194.33	253.43	0.82
219.83	5.771	6.630	13.66	28.23	25.35	14.09	7.18	2.47	49.09	180.65	220.80	0.82
218.59	5.734	5.918	13.71	28.10	25.08	12.64	7.46	2.96	48.14	172.78	215.34	0.79
221.40	5.714	7.199	13.66	25.88	25.11	16.69	1.68	1.95	45.42	180.12	237.91	0.81
225.86	5.478	5.921	13.33	27.92	24.66	12.73	2.45	2.49	42.33	169.49	240.24	0.75
222.44	5.608	6.620	13.42	28.16	25.06	14.10	1.54	2.54	43.25	178.57	247.75	0.80
215.68	5.512	5.972	13.64	28.02	24.25	12.79	2.45	2.81	42.30	167.26	237.25	0.78
214.31	5.703	5.888	14.04	28.24	24.37	12.51	22.84	2.59	62.31	168.09	161.85	0.78
230.61	5.650	5.942	13.05	28.03	25.97	12.72	2.72	2.35	43.77	177.60	243.48	0.77
207.73	5.715	5.993	14.49	28.15	23.67	12.78	0.46	2.62	39.52	164.97	250.48	0.79
214.36	5.658	6.652	13.92	27.67	24.38	14.42	1.87	2.10	42.78	173.20	242.93	0.81
220.52	5.645	6.563	13.60	28.06	24.90	14.03	1.07	2.27	42.28	177.67	252.15	0.81
224.19	5.544	6.581	13.42	27.72	24.79	14.24	3.61	2.65	45.29	175.85	232.97	0.78
224.83	5.744	6.461	13.40	27.77	25.71	13.96	1.21	2.25	43.13	181.70	252.74	0.81
217.32	5.774	6.613	14.05	27.97	24.65	14.19	0.81	2.12	41.76	176.21	253.16	0.81
233.41	5.505	6.581	12.86	28.20	25.69	14.00	8.01	3.21	50.91	181.43	213.82	0.78
232.95	5.552	6.602	12.88	28.01	25.86	14.14	3.49	2.86	46.36	182.07	235.67	0.78
216.51	5.625	5.970	13.76	26.98	24.52	13.28	0.91	3.71	42.42	168.33	238.08	0.78
217.83	5.677	6.113	13.82	27.80	24.64	13.19	15.06	1.87	54.77	170.30	186.55	0.78

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
235.07	5.565	6.546	12.74	28.48	26.20	13.79	0.74	1.95	42.68	185.91	261.34	0.79
230.55	5.364	6.076	12.74	27.52	25.26	13.25	2.68	2.30	43.49	172.23	237.64	0.75
226.26	5.639	7.117	13.17	23.78	25.69	17.96	1.77	1.92	47.34	183.95	233.15	0.81
228.55	5.584	5.973	13.14	26.22	25.49	13.67	2.31	3.34	44.80	174.77	234.07	0.76
228.01	5.560	6.029	13.20	27.56	25.26	13.13	0.61	3.36	42.36	173.15	245.27	0.76
220.14	5.593	5.996	13.48	27.88	24.89	12.90	1.78	2.55	42.13	171.89	244.81	0.78
223.63	5.732	6.492	13.58	28.51	25.32	13.66	2.28	2.35	43.61	180.45	248.26	0.81
219.39	5.697	5.986	13.65	28.27	25.04	12.71	2.44	2.93	43.11	173.42	241.35	0.79
233.94	5.483	5.973	12.61	28.38	26.09	12.63	2.37	1.99	43.07	179.34	249.82	0.77
229.25	5.406	6.714	13.08	25.93	24.79	15.54	2.31	4.93	47.57	177.57	223.96	0.77
219.10	5.924	6.565	14.17	27.87	25.08	14.13	2.41	2.49	44.11	177.97	242.08	0.81
209.86	4.425	6.514	10.74	27.51	24.73	14.21	3.63	2.69	45.25	175.16	232.23	0.83
233.63	5.287	5.153	12.35	22.50	25.69	13.74	3.30	2.84	45.58	175.75	231.37	0.75
213.95	5.470	5.743	13.75	24.45	23.87	14.09	2.63	2.44	43.03	160.71	224.10	0.75
238.71	5.437	5.990	12.12	25.12	26.92	14.31	5.54	3.64	50.41	181.44	215.97	0.76
208.56	5.434	5.922	13.96	25.56	23.34	13.90	1.35	4.50	43.10	159.15	221.57	0.76
211.02	5.475	5.856	13.74	24.24	23.90	14.49	1.19	2.17	41.76	161.36	231.84	0.76
220.44	5.467	5.816	13.32	24.89	24.62	14.02	9.16	2.06	49.86	165.93	199.66	0.75
214.01	5.403	5.893	13.66	25.44	23.74	13.90	1.78	2.32	41.73	161.04	231.52	0.75
220.92	5.553	4.795	13.18	24.17	25.28	11.91	0.74	2.39	40.31	173.21	257.80	0.78
227.50	5.472	4.812	12.98	23.82	25.29	12.12	7.32	2.36	47.09	172.12	219.29	0.76
234.33	5.395	5.912	12.55	25.38	25.79	13.98	2.92	2.08	44.76	175.43	235.15	0.75
242.57	5.812	4.868	12.10	24.29	28.81	12.03	2.74	2.53	46.11	200.58	261.03	0.83
239.91	5.874	5.873	12.22	24.48	28.84	14.40	5.88	2.26	51.38	200.41	234.03	0.84
232.74	5.343	4.975	12.58	25.68	25.49	11.62	3.13	2.46	42.71	174.72	245.45	0.75
213.20	5.356	5.966	13.64	26.47	23.56	13.52	0.80	3.46	41.35	159.92	232.06	0.75
204.76	5.518	5.900	14.12	26.71	23.44	13.26	3.91	2.38	42.99	161.91	225.97	0.79
203.96	5.540	4.816	14.18	26.20	23.44	11.03	0.97	1.83	37.27	163.16	262.64	0.80
217.77	5.504	5.943	13.40	26.41	24.65	13.50	6.29	2.93	47.37	168.62	213.55	0.77
214.60	5.470	5.829	13.60	26.15	24.13	13.38	2.60	2.00	42.11	164.75	234.74	0.77
226.03	5.439	5.885	12.93	26.10	25.25	13.53	1.95	2.35	43.07	169.80	236.53	0.75
205.27	5.512	5.905	14.10	25.57	23.45	13.86	1.02	2.64	40.97	160.26	234.73	0.78
218.26	5.521	4.753	13.28	23.99	24.93	11.89	8.45	2.80	48.07	171.59	214.17	0.79
213.98	5.397	4.905	13.72	26.07	23.59	11.29	11.57	2.83	49.28	161.83	197.04	0.76
216.02	5.256	5.979	13.27	24.62	23.77	14.57	1.02	2.83	42.19	160.53	228.27	0.74
224.08	5.522	4.823	13.75	30.15	24.10	9.60	1.01	2.11	36.82	166.03	270.55	0.74
236.81	5.521	4.858	13.13	30.07	25.23	9.69	4.80	4.50	44.23	176.36	239.24	0.74
231.80	5.489	5.747	13.34	29.83	24.68	11.56	2.05	1.97	40.26	169.59	252.72	0.73

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
227.86	5.519	5.776	13.60	29.86	24.35	11.61	13.89	2.33	52.17	166.76	191.80	0.73
228.04	5.517	5.810	13.65	29.79	24.25	11.70	5.26	1.88	43.09	166.86	232.35	0.73
217.79	5.696	5.762	14.48	27.97	23.59	12.36	3.58	2.40	41.93	162.81	232.94	0.75
225.18	5.533	4.609	13.90	24.78	23.89	11.16	1.53	2.14	38.72	165.92	257.10	0.74
216.68	5.554	4.814	14.37	30.17	23.19	9.57	2.18	2.67	37.61	160.70	256.34	0.74
206.26	5.735	4.461	15.02	23.80	22.92	11.25	9.04	2.26	45.46	160.69	212.09	0.78
224.31	5.513	5.734	13.83	29.88	23.92	11.51	25.52	3.17	64.12	164.66	154.08	0.73
233.54	5.511	5.504	12.68	23.85	26.09	13.85	5.10	2.45	47.48	177.86	224.74	0.76
216.13	5.350	5.894	13.30	23.71	24.14	14.92	1.16	3.23	43.45	162.57	224.50	0.75
207.73	5.400	4.844	13.91	24.85	23.29	11.70	3.80	3.56	42.35	159.99	226.65	0.77
205.48	5.541	5.893	14.09	25.84	23.60	13.68	3.93	2.50	43.71	160.69	220.55	0.78
222.10	5.434	5.880	13.06	24.65	24.96	14.31	18.28	2.11	59.66	170.05	171.01	0.77
233.07	5.369	5.846	12.63	26.74	25.51	13.12	3.43	3.56	45.61	170.72	224.57	0.73
207.10	5.536	5.889	14.12	25.54	23.53	13.84	1.96	2.41	41.74	161.66	232.41	0.78
217.63	5.557	4.946	13.54	25.78	24.62	11.51	2.31	2.28	40.72	167.18	246.33	0.77
228.43	5.484	4.811	12.86	26.45	25.59	10.92	7.19	1.91	45.60	175.47	230.90	0.77
213.40	5.458	4.872	13.61	25.21	24.05	11.60	0.85	2.61	39.11	166.05	254.76	0.78
237.17	5.564	5.885	12.13	26.27	27.53	13.44	5.09	2.00	48.06	188.38	235.18	0.79
219.62	5.532	4.863	13.71	28.64	24.21	10.19	0.64	3.45	38.48	166.11	259.00	0.76
234.35	5.280	4.891	12.58	28.14	25.19	10.43	1.26	2.81	39.70	171.61	259.38	0.73
210.67	5.405	4.825	14.06	28.23	23.06	10.25	12.01	2.39	47.71	158.97	199.90	0.75
216.19	5.444	4.965	14.04	28.55	23.26	10.43	1.87	2.90	38.47	159.75	249.18	0.74
218.93	5.571	4.870	13.71	28.36	24.38	10.31	1.29	2.73	38.72	168.35	260.90	0.77
216.04	5.335	4.899	13.66	28.12	23.43	10.45	1.84	2.11	37.84	162.42	257.58	0.75
218.90	5.622	5.898	13.78	27.75	24.48	12.75	3.04	2.00	42.28	168.10	238.58	0.77
199.17	5.535	5.836	14.78	27.75	22.47	12.62	0.93	2.46	38.48	155.13	241.92	0.78
225.79	5.571	5.396	13.38	21.31	24.98	15.19	1.88	2.20	44.24	171.38	232.42	0.76
222.84	5.462	4.894	13.41	27.82	24.45	10.56	2.01	2.62	39.63	167.18	253.14	0.75
220.11	5.561	5.904	13.80	28.07	24.18	12.62	0.87	2.80	40.47	165.65	245.58	0.75
230.17	5.441	5.937	13.16	28.13	24.81	12.67	1.94	2.39	41.80	167.88	240.95	0.73
226.02	5.535	5.885	13.32	28.41	24.93	12.43	21.46	1.98	60.79	168.70	166.51	0.75
232.16	5.397	4.894	12.97	28.46	24.96	10.32	4.32	2.67	42.27	170.51	242.03	0.73
221.79	5.424	4.808	13.53	27.83	24.06	10.37	1.14	2.37	37.94	165.67	262.01	0.75
203.41	5.462	5.758	14.36	28.21	22.82	12.25	1.76	2.86	39.68	156.50	236.63	0.77
227.66	5.365	5.937	13.23	28.05	24.33	12.70	6.44	2.37	45.84	167.25	218.90	0.73
198.93	5.588	4.895	14.87	28.21	22.54	10.41	1.09	2.10	36.14	156.93	260.52	0.79
213.53	5.572	5.049	14.42	21.66	23.18	13.99	2.76	2.76	42.68	159.91	224.79	0.75
210.04	5.610	5.809	14.81	26.67	22.72	13.07	2.70	2.39	40.88	157.29	230.85	0.75

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
202.16	4.097	5.702	9.94	27.34	24.74	12.51	11.61	2.45	51.31	167.86	196.30	0.83
220.26	5.644	5.799	14.25	29.89	23.77	11.64	1.20	2.40	39.01	164.00	252.25	0.74
236.75	5.505	5.732	13.06	28.66	25.29	12.00	0.69	2.37	40.36	174.18	258.98	0.74
209.29	5.780	5.836	14.95	29.86	23.19	11.73	6.82	1.73	43.47	157.63	217.57	0.75
209.91	5.600	4.850	14.70	30.18	22.86	9.64	0.44	2.35	35.29	158.95	270.23	0.76
230.35	5.344	5.778	13.24	29.90	24.22	11.60	1.97	2.26	40.04	166.05	248.80	0.72
229.69	5.506	4.814	13.65	30.16	24.19	9.58	2.68	2.79	39.25	167.30	255.75	0.73
226.59	5.594	5.752	13.77	29.77	24.37	11.59	2.98	1.61	40.55	167.11	247.23	0.74
221.51	5.590	5.765	14.21	29.92	23.61	11.56	1.45	2.57	39.19	163.29	250.00	0.74
231.31	5.024	4.772	11.12	30.15	27.12	9.50	11.91	2.00	50.52	182.66	216.93	0.79
208.63	5.411	5.002	13.92	25.06	23.31	11.98	2.38	3.20	40.87	160.23	235.22	0.77
208.18	5.663	5.868	14.21	25.35	23.92	13.89	2.00	5.42	45.23	164.35	218.03	0.79
213.13	5.509	5.929	13.75	25.07	24.04	14.19	2.56	2.05	42.84	163.89	229.55	0.77
221.77	5.542	4.790	13.32	25.82	24.96	11.13	0.47	2.29	38.85	171.45	264.80	0.77
237.28	5.422	5.928	12.25	25.19	26.56	14.12	2.57	3.72	46.97	181.96	232.45	0.77
223.65	5.442	5.986	13.17	25.81	24.79	13.92	2.99	2.25	43.95	169.83	231.88	0.76
211.50	5.469	5.876	13.80	26.65	23.78	13.23	2.83	2.05	41.89	163.47	234.14	0.77
238.54	5.426	4.814	11.94	25.05	27.26	11.53	1.54	2.63	42.97	185.30	258.76	0.78
229.91	5.383	4.754	12.65	24.92	25.53	11.45	2.73	2.12	41.83	172.25	247.06	0.75
205.72	5.486	4.751	14.19	25.39	23.19	11.23	0.74	2.33	37.48	161.09	257.88	0.78
219.47	5.482	5.906	13.31	25.37	24.71	13.97	2.58	2.43	43.69	168.60	231.54	0.77
205.80	5.680	4.901	14.75	28.60	23.11	10.28	4.39	3.02	40.80	159.77	234.94	0.78
225.04	5.362	4.989	13.27	27.83	24.24	10.76	2.25	2.22	39.46	166.69	253.43	0.74
220.97	5.448	4.858	13.46	28.59	24.29	10.19	0.54	2.86	37.88	166.37	263.50	0.75
208.14	5.691	5.837	14.26	28.05	23.94	12.49	2.14	1.70	40.27	159.49	237.60	0.77
238.37	5.568	5.999	12.54	26.64	26.65	13.51	8.00	1.82	49.99	185.78	222.99	0.78
233.60	5.462	4.914	12.97	28.27	25.28	10.43	6.26	3.04	45.00	171.63	228.83	0.73
209.01	5.496	4.919	14.29	28.39	23.08	10.40	3.86	2.24	39.58	158.68	240.55	0.76
217.70	5.454	4.858	13.69	28.57	23.90	10.20	9.54	2.79	46.44	164.44	212.44	0.76
216.03	5.373	4.880	13.68	27.82	23.56	10.52	5.26	2.25	41.59	161.00	232.28	0.75
211.85	5.322	4.878	13.82	28.16	23.11	10.39	0.77	2.41	36.69	158.82	259.76	0.75
224.31	5.627	5.751	13.84	28.21	24.40	12.23	2.31	2.86	41.79	166.21	238.61	0.74
224.03	5.405	5.814	13.41	27.95	24.18	12.48	2.40	3.41	42.48	165.12	233.24	0.74
233.17	5.272	5.834	12.62	28.26	25.07	12.39	35.53	2.30	75.28	169.86	135.38	0.73
216.76	5.313	4.869	13.84	27.88	23.04	10.48	17.48	2.81	53.81	158.07	176.26	0.73
227.46	5.423	4.897	13.14	27.82	24.77	10.56	0.87	2.24	38.44	168.63	263.19	0.74
211.25	5.615	5.883	14.21	28.51	23.71	12.38	3.74	2.35	42.18	164.12	233.47	0.78
220.96	5.532	4.882	13.65	27.43	24.31	10.68	1.60	1.96	38.55	166.86	259.71	0.76

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
218.17	5.403	4.779	13.25	24.14	24.48	11.88	0.61	2.21	39.18	167.29	256.21	0.77
217.83	5.555	4.797	13.41	24.08	24.85	11.95	4.74	2.81	44.35	171.71	232.29	0.79
218.98	5.404	5.923	13.20	26.07	24.57	13.63	3.69	2.95	44.84	168.54	225.51	0.77
239.56	5.658	5.924	12.28	24.48	27.65	14.52	4.60	2.03	48.80	191.46	235.39	0.80
208.55	5.335	5.790	13.77	25.83	23.24	13.45	1.69	2.35	40.74	158.19	232.98	0.76
230.08	5.372	4.757	12.62	23.72	25.54	12.03	7.84	2.64	48.04	175.32	218.95	0.76
214.92	5.390	4.766	13.42	25.44	24.10	11.24	7.80	2.18	45.33	165.73	219.39	0.77
221.17	5.414	4.775	13.13	23.43	24.75	12.23	6.17	2.03	45.18	171.21	227.39	0.77
219.91	5.540	5.069	13.28	22.29	25.02	13.65	2.26	2.96	43.89	170.71	233.36	0.78
219.25	5.402	5.925	13.38	26.86	24.23	13.24	6.71	2.74	46.91	166.21	212.58	0.76
205.59	5.451	5.947	14.06	26.15	23.26	13.65	1.75	2.25	40.91	158.96	233.13	0.77
225.20	5.476	4.838	12.96	25.77	25.36	11.26	4.36	1.73	42.71	173.94	244.35	0.77
214.19	5.490	5.903	13.60	26.52	24.23	13.36	3.91	2.33	43.83	163.93	224.41	0.77
236.94	5.564	5.957	12.29	25.67	27.17	13.93	1.93	2.40	45.42	187.72	247.96	0.79
225.97	5.421	5.895	12.89	25.01	25.24	14.14	3.45	2.43	45.26	171.47	227.30	0.76
232.89	5.386	4.848	12.55	25.12	25.76	11.58	1.39	2.09	40.82	174.32	256.23	0.75
218.45	5.570	4.791	13.55	25.61	24.66	11.23	1.19	2.34	39.42	169.27	257.66	0.77
233.55	5.373	4.863	12.49	26.66	25.82	10.95	3.15	2.00	41.92	176.66	252.84	0.76
220.60	5.409	5.817	13.27	25.13	24.46	13.89	1.95	2.71	43.02	165.30	230.52	0.75
232.48	5.358	5.856	12.61	25.94	25.50	13.55	6.99	2.14	48.17	171.32	213.38	0.74
240.34	5.663	5.227	12.48	21.95	27.22	14.29	0.52	2.39	44.41	192.46	260.02	0.80
222.94	5.479	5.878	13.43	28.25	24.47	12.48	6.41	2.58	45.94	166.69	217.68	0.75
221.14	5.437	5.860	13.47	28.13	24.21	12.50	8.19	2.27	47.18	165.19	210.08	0.75
221.32	5.552	5.816	13.64	28.25	24.43	12.35	1.07	2.62	40.47	166.42	246.75	0.75
219.93	5.487	5.851	13.54	27.44	24.31	12.79	1.11	1.90	40.11	165.08	246.94	0.75
227.89	5.551	5.877	13.34	27.37	24.96	12.88	9.13	2.42	49.39	171.04	207.77	0.75
206.81	5.553	4.886	14.40	28.67	23.13	10.23	1.21	2.47	37.03	159.76	258.83	0.77
207.59	5.591	5.838	14.60	27.77	22.98	12.61	3.38	2.37	41.34	157.81	229.03	0.76
210.56	5.587	4.861	14.28	28.48	23.47	10.24	1.67	2.28	37.67	161.75	257.62	0.77
211.20	5.421	5.852	14.01	27.45	23.22	12.79	2.63	2.30	40.93	159.88	234.36	0.76
219.27	5.538	4.854	13.73	28.55	24.19	10.20	1.05	2.70	38.14	168.40	264.94	0.77
232.94	5.363	4.892	12.93	28.57	24.89	10.27	14.42	3.11	52.69	169.50	193.00	0.73
227.97	5.491	4.927	13.19	28.22	24.98	10.47	13.10	2.39	50.95	169.89	200.07	0.75
239.65	5.590	5.872	12.50	28.23	26.83	12.48	2.67	2.09	44.08	186.49	253.82	0.78
226.34	5.414	5.925	13.27	27.64	24.47	12.86	1.18	2.65	41.17	166.64	242.88	0.74
217.69	5.546	4.772	13.90	27.68	23.94	10.34	3.47	2.41	40.16	163.96	244.95	0.75
208.40	5.639	5.860	14.43	27.38	23.44	12.84	6.31	2.15	44.76	160.07	214.59	0.77
220.49	5.682	5.813	13.91	28.20	24.51	12.37	1.76	2.04	40.68	168.85	249.02	0.77

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
198.71	5.586	5.881	14.79	28.23	22.66	12.50	0.78	2.43	38.37	156.84	245.22	0.79
205.08	4.825	4.880	11.39	28.42	25.43	10.30	1.79	2.02	39.54	173.21	262.85	0.84
213.92	5.390	4.874	13.86	28.66	23.33	10.21	5.87	2.54	41.96	160.37	229.35	0.75
216.22	5.410	4.728	13.88	27.04	23.38	10.49	4.76	2.00	40.64	162.54	240.00	0.75
225.18	5.360	5.903	13.21	27.99	24.34	12.66	1.15	2.50	40.65	165.35	244.06	0.73
222.92	5.427	4.889	13.06	25.80	24.93	11.37	0.73	2.79	39.82	169.74	255.74	0.76
205.24	5.537	4.787	14.24	24.77	23.32	11.60	1.06	2.61	38.59	160.49	249.55	0.78
230.04	5.384	5.982	12.60	25.99	25.63	13.81	4.40	2.29	46.13	173.73	225.98	0.76
221.92	5.471	5.891	13.30	25.76	24.69	13.72	0.76	2.34	41.51	166.55	240.71	0.75
228.14	5.404	5.893	12.79	24.29	25.36	14.55	1.45	2.04	43.40	172.30	238.18	0.76
213.17	5.377	4.827	13.60	25.16	23.72	11.51	1.13	1.87	38.23	162.00	254.25	0.76
220.38	5.567	4.781	13.46	24.63	24.82	11.65	2.06	1.98	40.51	170.19	252.06	0.77
212.59	5.541	4.866	13.97	26.24	23.80	11.13	1.15	2.17	38.25	164.34	257.79	0.77
218.14	5.629	5.786	13.52	24.37	24.99	14.25	11.99	2.44	53.67	170.61	190.73	0.78
224.61	5.562	4.992	13.88	25.30	24.03	11.84	3.84	2.37	42.09	166.76	237.73	0.74
198.78	5.730	5.791	15.51	29.82	22.17	11.65	0.67	1.88	36.37	155.03	255.77	0.78
227.70	5.596	4.827	13.70	29.99	24.50	9.66	2.49	3.42	40.07	168.65	252.55	0.74
216.63	5.604	5.807	14.46	29.85	23.25	11.67	2.07	2.58	39.57	159.24	241.48	0.74
235.07	5.520	5.818	13.34	29.87	24.83	11.69	30.92	2.42	69.86	170.43	146.38	0.73
236.39	5.601	5.805	13.20	29.87	25.45	11.66	2.34	3.57	43.03	175.52	244.76	0.74
223.63	5.574	5.707	13.92	29.88	24.02	11.46	4.27	2.28	42.04	165.03	235.56	0.74
212.82	5.541	4.735	14.43	30.02	23.04	9.46	2.59	2.23	37.33	158.74	255.15	0.75
222.73	5.594	4.837	14.13	30.05	23.76	9.66	1.99	2.07	37.48	164.93	264.04	0.74
205.10	5.582	4.783	14.93	30.13	22.43	9.52	2.82	2.57	37.34	156.00	250.64	0.76
206.77	5.607	5.785	14.91	29.90	22.55	11.61	4.63	2.20	41.00	157.26	230.13	0.76
238.62	5.373	5.756	12.83	29.86	25.13	11.57	1.58	2.74	41.02	173.08	253.17	0.73
223.52	5.431	4.915	13.34	28.70	24.43	10.28	2.74	2.99	40.43	167.65	248.79	0.75
214.09	5.440	4.869	13.92	28.61	23.45	10.21	0.66	1.89	36.22	160.53	265.93	0.75
222.75	5.466	4.894	13.40	28.35	24.48	10.36	2.13	2.01	38.98	169.20	260.47	0.76
219.44	5.511	4.851	13.60	28.66	24.31	10.16	16.45	2.19	53.11	166.98	188.64	0.76
225.72	5.457	5.906	13.20	27.87	24.81	12.71	4.92	2.85	45.29	168.78	223.62	0.75
225.14	5.561	4.837	13.50	28.21	24.72	10.29	1.73	2.21	38.94	170.44	262.58	0.76
209.08	5.498	5.828	14.28	27.69	23.10	12.63	1.36	2.54	39.62	157.35	238.27	0.75
223.09	5.449	5.833	13.40	28.44	24.39	12.31	0.65	2.47	39.82	165.54	249.46	0.74
217.50	5.667	5.212	13.93	22.18	24.42	14.10	2.09	1.98	42.59	167.48	235.96	0.77
216.86	5.334	5.876	13.71	28.08	23.34	12.56	4.36	1.69	41.95	159.17	227.68	0.73
217.80	5.548	5.906	13.71	28.11	24.27	12.61	1.48	2.82	41.18	165.92	241.77	0.76
230.97	5.512	4.891	13.06	27.75	25.31	10.58	1.28	1.82	38.99	172.00	264.68	0.74

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
219.01	5.518	5.966	13.77	26.40	24.04	13.56	0.71	2.42	40.74	165.07	243.13	0.75
231.29	5.323	5.860	12.90	28.40	24.76	12.38	3.56	1.77	42.48	168.32	237.76	0.73
202.48	5.595	5.841	14.77	27.63	22.73	12.68	1.71	2.94	40.06	157.12	235.32	0.78
207.45	5.580	5.857	14.55	28.49	23.00	12.34	11.55	2.79	49.68	158.40	191.30	0.76
220.64	5.587	4.915	13.72	27.44	24.43	10.75	3.04	2.61	40.83	167.01	245.42	0.76
221.84	5.524	4.901	13.62	28.61	24.34	10.28	3.06	2.33	40.01	166.82	250.19	0.75
209.94	5.553	4.899	14.21	28.44	23.45	10.34	2.84	2.21	38.83	161.11	248.96	0.77
225.26	5.514	5.860	13.23	27.92	25.00	12.59	2.24	2.37	42.21	171.13	243.28	0.76
239.24	5.578	5.287	12.54	21.67	26.69	14.64	3.25	3.04	47.62	185.21	233.38	0.77
210.89	5.445	5.920	14.06	27.61	23.23	12.87	3.64	2.16	41.90	158.68	227.24	0.75
228.70	5.484	5.874	13.31	28.51	24.72	12.36	7.76	1.88	46.73	167.72	215.35	0.73
206.32	5.543	5.879	14.39	27.97	23.12	12.61	0.90	2.36	38.98	159.38	245.33	0.77
218.80	5.429	5.832	13.33	27.69	24.44	12.64	1.59	2.16	40.84	167.94	246.75	0.77
227.26	5.476	5.879	13.33	28.08	24.65	12.56	3.67	1.91	42.79	167.61	235.01	0.74
206.87	5.551	5.826	14.42	28.09	23.10	12.45	0.55	1.96	38.06	161.31	254.30	0.78
239.57	5.632	4.693	12.49	23.49	27.04	11.99	1.15	2.13	42.31	189.90	269.29	0.79
227.48	5.515	4.867	13.37	28.50	24.76	10.25	7.03	1.90	43.93	169.04	230.87	0.74
227.26	5.467	5.835	13.27	27.67	24.72	12.65	7.76	1.76	46.89	168.34	215.41	0.74
226.38	5.555	4.845	13.49	28.50	24.71	10.20	2.22	3.53	40.67	169.02	249.38	0.75
235.95	5.328	5.778	12.53	27.78	25.51	12.48	14.39	2.28	54.66	173.51	190.46	0.74
220.63	5.525	5.066	13.60	24.09	24.37	12.62	12.44	1.80	51.23	169.36	198.33	0.77
204.25	5.494	5.886	14.55	28.42	22.65	12.43	1.79	3.05	39.92	158.54	238.29	0.78
218.36	5.483	5.726	13.69	28.16	24.04	12.20	1.20	3.19	40.64	163.82	241.87	0.75
230.14	5.344	5.824	12.92	27.89	24.82	12.53	1.70	2.37	41.42	168.64	244.27	0.73
212.30	5.426	4.766	13.91	27.98	23.41	10.22	1.26	2.44	37.33	162.09	260.49	0.76
204.69	5.587	5.923	14.63	28.10	22.91	12.65	2.95	2.49	41.00	157.68	230.74	0.77
201.15	5.569	5.844	14.74	27.37	22.67	12.81	5.00	2.71	43.20	157.93	219.36	0.79
241.40	5.678	4.887	12.31	27.93	27.67	10.50	1.17	3.29	42.64	194.67	273.94	0.81
227.79	5.405	5.856	13.15	28.30	24.67	12.42	5.37	2.07	44.53	168.01	226.40	0.74
224.16	5.503	4.912	13.36	28.43	24.71	10.37	1.15	2.63	38.85	168.81	260.72	0.75
223.62	5.347	4.957	13.18	27.97	24.35	10.63	1.24	2.61	38.83	166.06	256.57	0.74
211.21	5.439	4.872	13.78	25.25	23.68	11.58	1.61	1.71	38.58	163.66	254.54	0.77
215.57	5.413	4.829	13.60	24.10	23.89	12.02	8.49	3.92	48.32	164.98	204.86	0.77
225.49	5.597	6.021	13.22	26.00	25.41	13.90	1.84	2.04	43.18	172.55	239.74	0.77
216.58	5.504	5.867	13.47	25.65	24.52	13.73	1.52	2.15	41.93	167.20	239.26	0.77
224.89	5.513	5.837	13.11	25.65	25.24	13.65	3.04	3.14	45.07	172.06	229.06	0.77
226.66	5.527	5.792	13.10	24.76	25.32	14.04	2.24	2.47	44.06	172.14	234.40	0.76
208.42	5.543	4.914	14.05	24.58	23.67	12.00	4.97	2.22	42.86	164.73	230.59	0.79

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
217.74	5.527	4.836	13.37	24.35	24.80	11.92	7.52	2.13	46.37	169.60	219.44	0.78
209.63	5.398	4.731	13.98	25.24	23.17	11.25	46.88	2.19	83.49	159.36	114.53	0.76
209.52	5.544	4.753	14.68	30.12	22.66	9.47	2.12	2.34	36.59	157.79	258.72	0.75
213.39	5.548	5.733	14.48	29.91	22.98	11.50	0.70	2.07	37.25	159.01	256.11	0.75
220.07	5.585	4.828	14.15	30.08	23.69	9.63	1.26	5.33	39.91	164.54	247.36	0.75
200.20	5.737	5.746	15.38	29.87	22.38	11.54	12.02	2.34	48.28	155.75	193.57	0.78
225.86	5.571	5.819	13.87	29.77	24.10	11.73	5.78	1.95	43.56	165.41	227.83	0.73
214.03	5.614	5.754	14.66	29.87	22.97	11.56	14.78	2.09	51.40	158.14	184.60	0.74
230.13	5.622	4.840	13.58	29.98	24.85	9.69	7.89	4.67	47.09	170.22	216.90	0.74
221.51	5.567	4.806	14.11	29.96	23.67	9.63	2.54	2.25	38.09	163.91	258.20	0.74
212.55	5.541	5.761	14.57	29.94	22.81	11.55	0.61	2.36	37.33	158.27	254.41	0.74
224.19	5.590	5.762	13.96	29.89	24.02	11.57	2.42	2.57	40.57	165.55	244.82	0.74
219.48	5.583	4.737	14.19	28.12	23.62	10.11	2.10	2.05	37.88	164.35	260.33	0.75
230.33	5.623	5.760	13.51	29.83	24.96	11.59	2.26	2.72	41.53	169.69	245.17	0.74
228.12	5.486	4.784	13.63	30.19	24.15	9.51	1.76	2.60	38.02	166.88	263.35	0.73
206.79	5.812	4.807	15.25	30.09	22.86	9.59	4.59	2.00	39.04	160.25	246.31	0.77
234.13	5.504	4.856	13.12	29.99	25.18	9.72	1.26	2.98	39.13	174.79	267.99	0.75
232.53	5.628	5.776	13.53	29.83	24.95	11.62	2.17	1.83	40.57	170.20	251.70	0.73
237.41	5.624	4.818	13.07	29.92	25.81	9.66	7.11	3.48	46.07	179.77	234.15	0.76
233.99	5.454	5.756	13.27	29.86	24.66	11.57	3.57	2.00	41.78	168.27	241.62	0.72
217.12	5.563	5.792	14.27	29.88	23.38	11.63	1.98	2.62	39.61	160.03	242.38	0.74
222.04	5.537	4.819	13.92	30.12	23.87	9.60	6.40	2.74	42.60	165.35	232.89	0.74
220.08	5.677	5.777	14.37	29.91	23.70	11.59	2.07	3.01	40.37	163.89	243.60	0.74
216.13	5.360	5.530	13.42	22.22	23.96	14.93	2.46	2.89	44.24	164.75	223.45	0.76
223.47	5.505	5.904	13.10	26.43	25.21	13.40	4.11	1.97	44.69	170.29	228.63	0.76
215.37	5.552	5.017	13.71	26.00	24.29	11.58	3.06	3.17	42.10	165.23	235.48	0.77
225.54	5.361	5.828	12.91	24.97	24.92	14.00	0.52	2.08	41.52	167.73	242.38	0.74
217.06	5.375	5.731	13.35	24.98	24.16	13.77	25.29	2.63	65.85	164.36	149.77	0.76
205.11	5.423	5.900	14.16	25.79	22.97	13.73	0.76	2.08	39.54	157.23	238.61	0.77
221.96	5.394	5.913	13.22	25.74	24.48	13.78	1.67	2.39	42.32	165.42	234.53	0.75
217.51	5.361	4.923	13.21	26.48	24.35	11.16	2.46	1.96	39.93	168.69	253.47	0.78
233.34	5.414	4.870	12.71	24.81	25.56	11.78	1.14	2.27	40.75	173.04	254.77	0.74
220.58	5.519	5.948	13.23	26.91	25.03	13.26	1.62	2.83	42.75	170.62	239.46	0.77
220.75	5.418	4.753	13.06	24.39	24.90	11.69	1.44	2.39	40.42	171.09	253.98	0.78
243.93	5.715	5.889	11.98	25.48	28.63	13.87	3.38	2.28	48.15	199.53	248.62	0.82
221.61	5.611	5.218	13.57	20.93	24.80	14.96	7.77	2.39	49.92	169.26	203.42	0.76
233.97	5.314	5.968	12.78	27.85	24.95	12.86	5.88	3.34	47.03	169.11	215.77	0.72
229.08	5.325	5.900	13.07	27.54	24.44	12.85	1.83	2.47	41.59	166.33	239.96	0.73

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
206.88	5.506	5.814	14.31	27.82	23.09	12.54	3.52	2.30	41.44	160.59	232.49	0.78
213.80	5.573	5.825	14.06	28.13	23.79	12.42	2.81	3.09	42.12	163.25	232.56	0.76
217.95	5.688	5.880	13.78	27.76	24.77	12.71	2.30	2.81	42.59	170.54	240.28	0.78
231.21	5.412	5.854	13.15	27.59	24.70	12.73	2.67	2.18	42.29	167.06	237.03	0.72
232.94	5.391	4.933	12.93	28.23	25.01	10.48	1.43	3.45	40.37	170.50	253.39	0.73
215.73	5.363	4.869	13.61	28.67	23.64	10.19	1.55	4.00	39.38	163.73	249.45	0.76
229.53	5.460	5.909	13.10	27.45	25.01	12.92	2.68	1.87	42.47	168.57	238.16	0.73
228.72	5.450	4.922	13.16	28.30	24.84	10.44	0.45	2.38	38.12	171.56	270.04	0.75
207.19	5.665	5.811	14.50	27.76	23.44	12.56	7.31	1.94	45.25	160.48	212.78	0.77
219.60	5.577	5.046	13.67	24.71	24.47	12.25	25.45	3.57	65.74	168.09	153.42	0.77
218.75	5.553	5.795	13.84	27.25	24.08	12.76	8.55	2.33	47.72	164.37	206.66	0.75
239.00	5.593	4.918	12.55	28.42	26.74	10.39	1.93	2.15	41.20	184.79	269.09	0.77
218.33	5.553	5.871	13.52	27.78	24.63	12.68	4.23	2.58	44.13	167.55	227.82	0.77
220.18	5.490	5.862	13.55	28.12	24.31	12.51	0.32	2.58	39.71	167.68	253.35	0.76
218.16	5.657	5.869	14.02	28.54	24.20	12.34	17.93	3.02	57.49	166.90	174.17	0.77
240.20	5.743	5.876	12.54	27.65	27.48	12.75	3.06	2.37	45.67	191.98	252.23	0.80
202.72	5.593	4.957	14.64	28.24	22.92	10.53	8.86	2.28	44.59	159.25	214.30	0.79
207.16	5.467	4.853	14.23	27.65	23.05	10.53	0.83	2.98	37.39	159.58	256.12	0.77
215.11	5.402	4.838	13.74	27.50	23.58	10.56	1.04	2.14	37.31	160.88	258.70	0.75
221.31	5.380	5.857	13.29	28.27	24.28	12.43	1.10	1.87	39.68	164.98	249.45	0.75
242.88	5.729	4.867	12.27	27.83	28.02	10.49	4.58	2.16	45.25	198.67	263.40	0.82
218.45	5.548	4.803	13.83	28.11	24.07	10.25	0.44	2.58	37.35	164.59	264.41	0.75
235.31	5.373	4.957	12.78	27.86	25.23	10.68	4.36	2.32	42.57	170.71	240.58	0.73
216.39	5.558	5.847	13.93	27.10	23.93	12.95	4.05	2.21	43.14	163.57	227.50	0.76
216.87	5.460	5.866	13.80	27.85	23.74	12.64	3.56	3.33	43.27	160.96	223.20	0.74
212.13	5.543	4.811	14.26	28.03	23.32	10.30	3.89	2.68	40.18	162.10	242.06	0.76
218.69	5.487	5.840	13.57	28.44	24.26	12.32	2.81	2.28	41.68	165.88	238.79	0.76
217.96	5.510	4.948	13.73	28.53	24.08	10.41	2.39	2.48	39.36	167.30	255.03	0.77
215.08	5.465	5.957	13.97	27.53	23.48	12.98	16.67	3.94	57.06	160.04	168.27	0.74
217.74	5.564	5.555	13.81	23.63	24.18	14.11	2.02	2.48	42.79	166.55	233.55	0.76
236.18	5.398	5.713	12.62	25.68	25.65	13.35	0.77	2.86	42.63	175.63	247.18	0.74
207.10	5.450	5.886	14.38	28.10	22.74	12.57	1.59	3.27	40.17	156.66	234.02	0.76
213.91	5.488	4.880	14.21	27.85	23.17	10.51	1.87	2.20	37.75	158.76	252.32	0.74
215.31	5.517	5.877	14.03	27.95	23.59	12.62	68.37	1.81	106.38	160.33	90.43	0.74
210.77	5.445	5.851	14.15	27.95	23.08	12.56	0.74	2.55	38.94	158.17	243.75	0.75
213.75	5.518	5.766	14.05	27.82	23.57	12.44	0.84	2.74	39.59	162.73	246.65	0.76
215.16	5.471	4.904	13.94	28.56	23.54	10.30	6.34	2.19	42.37	163.01	230.83	0.76
212.54	5.459	4.961	14.03	26.61	23.35	11.19	1.77	2.37	38.68	160.01	248.23	0.75

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
217.17	5.420	4.898	13.83	28.08	23.51	10.47	5.90	1.88	41.76	161.06	231.44	0.74
234.96	5.359	5.852	12.82	28.04	25.08	12.52	5.52	2.17	45.30	169.76	224.84	0.72
212.22	5.358	5.836	13.90	28.41	23.12	12.33	6.32	2.53	44.30	157.71	213.59	0.74
221.19	5.452	4.716	13.19	24.37	24.80	11.61	5.43	3.41	45.24	168.40	223.31	0.76
208.85	5.477	4.747	13.91	24.63	23.62	11.56	2.11	3.28	40.57	164.24	242.87	0.79
219.60	5.501	5.793	13.34	25.64	24.73	13.56	1.92	2.01	42.22	168.58	239.58	0.77
218.84	5.342	4.919	13.16	25.32	24.37	11.66	2.74	2.24	41.01	167.33	244.84	0.76
225.54	5.442	4.802	12.99	25.44	25.14	11.33	3.94	1.85	42.26	173.14	245.82	0.77
223.21	5.440	4.886	12.99	24.15	25.12	12.14	1.66	2.58	41.50	172.88	249.95	0.77
220.67	5.492	5.939	13.24	25.52	24.89	13.97	11.01	2.49	52.36	169.75	194.52	0.77
214.61	5.573	5.014	14.42	29.67	23.19	10.14	4.16	1.67	39.17	160.34	245.61	0.75
213.44	5.563	5.811	14.49	29.91	23.04	11.66	3.00	2.44	40.14	159.08	237.81	0.75
217.55	5.606	4.826	14.31	30.13	23.51	9.61	1.00	2.55	36.67	163.73	267.86	0.75
233.89	5.452	5.728	13.19	29.85	24.80	11.51	6.59	2.72	45.62	169.73	223.24	0.73
220.33	5.602	5.779	14.27	29.87	23.56	11.61	0.89	3.72	39.78	162.76	245.48	0.74
210.64	5.631	5.745	14.64	29.90	23.08	11.53	4.14	2.90	41.65	159.05	229.11	0.76
223.31	5.546	5.785	13.90	29.84	23.94	11.63	2.19	3.03	40.79	164.99	242.67	0.74
232.37	5.557	4.879	13.41	30.04	24.86	9.74	9.42	2.55	46.58	170.85	220.09	0.74
220.78	5.633	4.829	14.11	29.94	23.96	9.68	1.27	2.14	37.05	165.64	268.22	0.75
198.68	5.737	5.862	15.49	29.80	22.22	11.80	4.50	2.58	41.11	154.97	226.19	0.78
220.04	5.629	4.791	14.22	29.94	23.75	9.60	1.11	2.44	36.90	164.20	266.96	0.75
216.29	5.565	5.781	14.41	29.88	23.17	11.61	3.79	2.78	41.35	159.46	231.38	0.74
236.28	5.396	5.435	12.29	21.37	26.34	15.26	4.04	2.47	48.12	181.60	226.46	0.77
210.12	5.563	6.003	13.93	26.16	23.97	13.77	3.50	1.90	43.14	164.69	229.03	0.78
220.38	5.458	5.849	13.22	26.02	24.78	13.49	1.95	3.25	43.46	169.30	233.73	0.77
234.46	5.349	5.989	12.54	25.41	25.59	14.14	9.17	2.07	50.98	171.71	202.11	0.73
229.52	5.394	5.896	12.81	25.52	25.27	13.87	3.30	2.29	44.72	170.00	228.09	0.74
219.20	5.386	5.970	13.12	26.36	24.64	13.59	5.44	2.94	46.61	167.20	215.23	0.76
218.24	5.494	4.884	13.34	25.95	24.71	11.30	0.90	2.10	39.00	170.37	262.08	0.78
209.59	5.441	4.908	13.84	25.29	23.58	11.64	1.31	3.68	40.21	163.51	243.98	0.78
228.36	5.386	5.935	12.66	25.28	25.53	14.09	1.29	2.95	43.86	173.19	236.93	0.76
234.42	5.396	5.960	12.34	26.07	26.24	13.72	6.04	1.77	47.77	178.41	224.11	0.76
234.29	5.329	4.793	12.49	24.35	25.60	11.81	3.75	2.34	43.50	174.51	240.72	0.74
224.68	5.549	4.943	13.18	25.06	25.26	11.84	10.89	1.96	49.95	171.63	206.14	0.76
237.77	5.538	5.318	13.01	24.54	25.53	13.00	17.93	1.88	58.35	177.24	182.26	0.75
222.32	5.731	5.757	14.19	29.81	24.23	11.59	1.62	2.52	39.96	166.35	249.78	0.75
204.33	5.550	4.836	15.03	30.17	22.16	9.62	6.66	3.32	41.76	155.31	223.14	0.76
230.21	5.543	5.737	13.55	29.84	24.55	11.53	5.14	2.62	43.84	167.91	229.78	0.73

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
223.54	5.596	5.747	13.95	29.91	24.07	11.53	3.69	1.97	41.25	165.56	240.79	0.74
218.28	5.616	5.717	14.22	29.87	23.69	11.48	1.60	2.26	39.04	163.88	251.86	0.75
230.28	5.498	5.664	13.50	25.77	24.44	13.19	2.13	2.13	41.88	168.11	240.82	0.73
216.77	5.641	4.804	14.51	30.19	23.33	9.55	4.22	3.97	41.07	161.52	235.99	0.75
228.54	5.611	4.840	13.72	29.99	24.54	9.68	3.51	2.07	39.81	169.16	254.96	0.74
219.55	5.701	4.826	14.23	30.18	24.03	9.60	1.66	1.93	37.22	166.17	267.88	0.76
212.62	5.621	5.745	14.65	29.87	23.01	11.54	1.62	2.09	38.27	157.89	247.57	0.74
205.36	5.503	4.952	13.86	26.05	23.82	11.41	2.50	2.68	40.40	164.97	245.00	0.80
225.63	5.521	4.826	13.12	22.86	25.25	12.67	3.25	2.15	43.32	171.63	237.72	0.76
229.01	5.347	4.903	12.84	25.81	24.98	11.40	8.15	2.85	47.38	169.75	214.98	0.74
232.45	5.404	5.834	12.68	25.83	25.56	13.55	4.45	3.09	46.64	171.40	220.49	0.74
210.95	5.477	4.794	13.71	25.39	23.96	11.33	1.94	2.62	39.85	163.66	246.43	0.78
224.71	5.609	4.829	13.19	24.90	25.52	11.64	0.69	2.58	40.44	174.63	259.11	0.78
217.76	5.560	4.783	13.39	25.41	24.92	11.29	9.82	2.17	48.20	169.75	211.30	0.78
208.39	5.477	5.869	14.04	25.80	23.40	13.65	5.35	1.81	44.21	159.32	216.21	0.76
220.56	5.467	5.250	13.28	24.24	24.70	13.00	3.50	1.94	43.15	168.43	234.22	0.76
236.28	5.509	5.941	12.40	26.74	26.65	13.33	1.74	1.96	43.68	183.45	251.98	0.78
232.16	5.403	4.815	12.52	23.86	25.90	12.11	1.87	3.13	43.00	174.42	243.38	0.75
209.61	5.412	5.854	13.82	24.98	23.49	14.06	1.87	2.03	41.45	161.41	233.62	0.77
227.14	5.262	5.926	12.68	25.81	24.90	13.77	15.24	2.59	56.50	169.81	180.34	0.75
231.42	5.418	5.899	12.63	24.69	25.73	14.34	2.04	2.63	44.73	174.21	233.67	0.75
236.79	5.537	4.891	12.27	24.24	27.07	12.11	1.82	1.87	42.86	188.29	263.57	0.80
214.39	5.479	4.849	13.62	24.86	24.14	11.70	4.53	2.40	42.77	164.14	230.25	0.77
227.12	5.454	4.859	12.93	23.22	25.31	12.56	1.09	1.78	40.73	172.30	253.82	0.76
232.27	5.446	4.714	12.67	23.97	25.78	11.80	10.22	2.85	50.66	176.63	209.21	0.76
238.68	5.575	4.977	12.29	25.77	27.21	11.59	2.00	2.85	43.65	188.05	258.48	0.79
223.28	5.534	4.828	13.18	26.58	25.19	10.90	1.81	1.88	39.79	173.20	261.19	0.78
203.31	4.729	5.841	11.02	24.31	25.74	14.42	2.90	2.08	45.14	172.36	229.12	0.85
225.49	5.466	5.842	13.03	25.67	25.17	13.66	1.65	1.93	42.41	171.06	242.03	0.76
218.75	5.525	4.854	13.40	24.52	24.74	11.88	3.02	1.96	41.59	169.51	244.53	0.77
237.89	5.536	4.856	12.20	25.10	27.23	11.61	3.98	2.05	44.87	188.15	251.59	0.79
206.48	5.533	4.831	14.00	24.52	23.71	11.82	2.80	2.51	40.84	164.43	241.58	0.80
223.97	5.600	4.882	13.86	29.82	24.23	9.82	2.85	2.10	39.00	166.77	256.56	0.74
221.77	5.602	5.824	14.13	29.74	23.79	11.75	0.94	3.00	39.48	163.80	248.95	0.74
231.80	5.501	5.734	13.52	29.92	24.42	11.50	2.09	2.22	40.23	167.69	250.12	0.72
218.69	5.588	5.730	14.21	29.92	23.59	11.49	0.68	2.50	38.26	163.05	255.68	0.75
226.28	5.545	4.830	13.84	30.18	24.04	9.60	1.17	2.69	37.50	166.11	265.78	0.73
214.98	5.670	5.800	14.49	29.72	23.48	11.71	6.54	2.13	43.86	160.36	219.36	0.75

Payload (tonnes)	Loaded Travel Distance (Km)	Travel Empty Distance (Km)	Loaded Speed (Km/h)	Empty Speed (Km/h)	Travel loaded (min)	Travel Empty (min)	Unloading (min)	Loading Time (min)	Cycle Time (min)	Fuel (L)	Fuel Rate (L/Hr)	Fuel (L/t)
221.45	5.663	5.658	14.13	29.64	24.04	11.45	2.27	2.83	40.60	165.58	244.71	0.75
219.68	5.581	5.772	14.16	29.92	23.65	11.58	1.49	2.08	38.80	163.62	253.00	0.74
216.36	5.559	4.577	14.36	24.67	23.23	11.13	5.68	1.90	41.94	161.14	230.53	0.74
206.94	5.634	4.785	15.04	30.18	22.47	9.52	1.33	1.92	35.24	156.69	266.76	0.76
215.51	5.575	4.795	14.40	30.18	23.22	9.53	1.06	1.93	35.74	160.57	269.54	0.75
227.69	5.519	5.695	13.73	28.83	24.12	11.85	2.79	1.81	40.57	166.02	245.55	0.73

Appendix 17: Economic Analysis - AHS Achieving Same Production as Manual

Table 58. Capital and annual costs for 9 manual trucks.

9 manual trucks - baseline case	Year							
	0	1	2	3	4	5	6	7
Opex		$50,168,726	$50,168,726	$50,168,726	$50,168,726	$50,168,726	$50,168,726	$50,168,726
Total fuel		$10,054,465	$10,054,465	$10,054,465	$10,054,465	$10,054,465	$10,054,465	$10,054,465
Tire		$1,843,515	$1,843,515	$1,843,515	$1,843,515	$1,843,515	$1,843,515	$1,843,515
Maintenance		$399,719	$399,719	$399,719	$399,719	$399,719	$399,719	$399,719
Labour costs		$5,708,249	$5,708,249	$5,708,249	$5,708,249	$5,708,249	$5,708,249	$5,708,249
Turnover costs		$42,336	$42,336	$42,336	$42,336	$42,336	$42,336	$42,336
Training		$330,750	$330,750	$330,750	$330,750	$330,750	$330,750	$330,750
Extra Mining costs		$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692
Depreciation		$5,142,857	$5,142,857	$5,142,857	$5,142,857	$5,142,857	$5,142,857	$5,142,857
CAPEX	$36,000,000							
Investment Costs	$36,000,000	-	-	-	-	-	-	-
Start Up Issues		-						
Infrastructure	-	-	-	-	-	-	-	-

Table 59. Capital and annual costs for 7 AHS.

7 AHS Trucks - baseline case	Year							
	0	1	2	3	4	5	6	7
OPEX		$44,627,680	$44,627,680	$44,627,680	$44,627,680	$44,627,680	$44,627,680	$44,627,680
Total fuel		$10,137,484	$10,137,484	$10,137,484	$10,137,484	$10,137,484	$10,137,484	$10,137,484
Tire		$1,942,339	$1,942,339	$1,942,339	$1,942,339	$1,942,339	$1,942,339	$1,942,339
Maintenance		$271,034	$271,034	$271,034	$271,034	$271,034	$271,034	$271,034
Labour costs		$483,603	$483,603	$483,603	$483,603	$483,603	$483,603	$483,603
Turnover costs		$3,528	$3,528	$3,528	$3,528	$3,528	$3,528	$3,528
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692
Depreciation		$5,427,143	$5,427,143	$5,427,143	$5,427,143	$5,427,143	$5,427,143	$5,427,143
CAPEX	$42,190,000							
Investment Costs	$35,000,000	-	-	-	-	-	-	-
Start Up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Table 60. Capital and annual costs for 8 AHS.

8 AHS Trucks	Year							
	0	1	2	3	4	5	6	7
OPEX		$46,075,788	$46,075,788	$46,075,788	$46,075,788	$46,075,788	$46,075,788	$46,075,788
total fuel		$11,603,186	$11,603,186	$11,603,186	$11,603,186	$11,603,186	$11,603,186	$11,603,186
Tire		$1,736,264	$1,736,264	$1,736,264	$1,736,264	$1,736,264	$1,736,264	$1,736,264
Maintenance		$389,925	$389,925	$389,925	$389,925	$389,925	$389,925	$389,925
Labour costs		$552,690	$552,690	$552,690	$552,690	$552,690	$552,690	$552,690
Turnover costs		$4,032	$4,032	$4,032	$4,032	$4,032	$4,032	$4,032
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692
Depreciation		$5,298,750	$5,298,750	$5,298,750	$5,298,750	$5,298,750	$5,298,750	$5,298,750
CAPEX	$47,190,000							
Investment Costs	$40,000,000	-	-	-	-	-	-	-
Start -up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Table 61. Capital and annual costs for 9 AHS.

9 AHS Trucks	Year							
	0	1	2	3	4	5	6	7
OPEX		$47,110,918	$47,110,918	$47,110,918	$47,110,918	$47,110,918	$47,110,918	$47,110,918
Total fuel		$12,549,278	$12,549,278	$12,549,278	$12,549,278	$12,549,278	$12,549,278	$12,549,278
Tire		$1,643,425	$1,643,425	$1,643,425	$1,643,425	$1,643,425	$1,643,425	$1,643,425
Maintenance		$502,211	$502,211	$502,211	$502,211	$502,211	$502,211	$502,211
Labour costs		$621,776	$621,776	$621,776	$621,776	$621,776	$621,776	$621,776
Turnover costs		$4,536	$4,536	$4,536	$4,536	$4,536	$4,536	$4,536
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692
Depreciation		$5,198,889	$5,198,889	$5,198,889	$5,198,889	$5,198,889	$5,198,889	$5,198,889
CAPEX	$52,190,000							
Investment Costs	$45,000,000	-	-	-	-	-	-	-
Start-up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Appendix 18: Economic Analysis - AHS Operating at Default Speeds

Table 62. Capital and annual costs for 9 manual trucks.

9 manual trucks - baseline case	Year							
	0	1	2	3	4	5	6	7
OPEX		$50,168,726	$50,168,726	$50,168,726	$50,168,726	$50,168,726	$50,168,726	$50,168,726
Total fuel		$10,054,465	$10,054,465	$10,054,465	$10,054,465	$10,054,465	$10,054,465	$10,054,465
Tire		$1,843,515	$1,843,515	$1,843,515	$1,843,515	$1,843,515	$1,843,515	$1,843,515
Maintenance		$399,719	$399,719	$399,719	$399,719	$399,719	$399,719	$399,719
Labour costs		$5,708,249	$5,708,249	$5,708,249	$5,708,249	$5,708,249	$5,708,249	$5,708,249
Turnover costs		$42,336	$42,336	$42,336	$42,336	$42,336	$42,336	$42,336
Training		$330,750	$330,750	$330,750	$330,750	$330,750	$330,750	$330,750
Extra Mining costs		$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692
Depreciation		$5,142,857	$5,142,857	$5,142,857	$5,142,857	$5,142,857	$5,142,857	$5,142,857
CAPEX	$36,000,000							
Investment Costs	$36,000,000	-	-	-	-	-	-	-
Start-up Issues		-						
Infrastructure	-	-	-	-	-	-	-	-

Table 63. Capital and annual costs for 7 AHS trucks.

7 AHS Trucks - baseline case	Year							
	0	1	2	3	4	5	6	7
OPEX		$44,627,680	$44,627,680	$44,627,680	$44,627,680	$44,627,680	$44,627,680	$44,627,680
Total fuel		$10,137,484	$10,137,484	$10,137,484	$10,137,484	$10,137,484	$10,137,484	$10,137,484
Tire		$1,942,339	$1,942,339	$1,942,339	$1,942,339	$1,942,339	$1,942,339	$1,942,339
Maintenance		$271,034	$271,034	$271,034	$271,034	$271,034	$271,034	$271,034
Labour costs		$483,603	$483,603	$483,603	$483,603	$483,603	$483,603	$483,603
Turnover costs		$3,528	$3,528	$3,528	$3,528	$3,528	$3,528	$3,528
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692	$31,789,692
Depreciation		$5,027,143	$5,027,143	$5,027,143	$5,027,143	$5,027,143	$5,027,143	$5,027,143
CAPEX	$42,190,000							
Investment Costs	$35,000,000	-	-	-	-	-	-	-
Start-up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Table 64. Capital and annual costs for 8 AHS trucks.

8 AHS Trucks	Year							
	0	1	2	3	4	5	6	7
OPEX		$51,512,884	$51,512,884	$51,512,884	$51,512,884	$51,512,884	$51,512,884	$0
total fuel		$11,603,186	$11,603,186	$11,603,186	$11,603,186	$11,603,186	$11,603,186	$0
Tire		$1,736,264	$1,736,264	$1,736,264	$1,736,264	$1,736,264	$1,736,264	$0
Maintenance		$389,925	$389,925	$389,925	$389,925	$389,925	$389,925	$0
Labour costs		$552,690	$552,690	$552,690	$552,690	$552,690	$552,690	$0
Turnover costs		$4,032	$4,032	$4,032	$4,032	$4,032	$4,032	$0
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$37,226,788	$37,226,788	$37,226,788	$37,226,788	$37,226,788	$37,226,788	$0
Depreciation		$6,531,667	$6,531,667	$6,531,667	$6,531,667	$6,531,667	$6,531,667	$0
CAPEX	$47,190,000							
Investment Costs	$40,000,000	-	-	-	-	-	-	-
Start-up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Table 65. Capital and annual costs for 9 AHS trucks.

9 AHS Trucks	Year							
	0	1	2	3	4	5	6	7
OPEX		$57,081,314	$57,081,314	$57,081,314	$57,081,314	$57,081,314	$18,763,809	$0
Total fuel		$12,549,278	$12,549,278	$12,549,278	$12,549,278	$12,549,278	$4,125,207	$0
Tire		$1,643,425	$1,643,425	$1,643,425	$1,643,425	$1,643,425	$540,228	$0
Maintenance		$502,211	$502,211	$502,211	$502,211	$502,211	$165,087	$0
Labour costs		$621,776	$621,776	$621,776	$621,776	$621,776	$204,391	$0
Turnover costs		$4,536	$4,536	$4,536	$4,536	$4,536	$1,491	$0
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$41,760,088	$41,760,088	$41,760,088	$41,760,088	$41,760,088	$13,727,405	$0
Depreciation		$8,103,189	$8,103,189	$8,103,189	$8,103,189	$8,103,189	$2,674,053	$0
CAPEX	$52,190,000							
Investment Costs	$45,000,000	-	-	-	-	-	-	-
Start-up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Appendix 19: Economic Analysis – Manual Operating at Same Production as 9 AHS Trucks

Table 66. Capital and annual costs for 10 manual trucks.

10 manual trucks - baseline case	Year							
	0	1	2	3	4	5	6	7
OPEX		$62,504,870	$62,504,870	$62,504,870	$62,504,870	$62,504,870	$62,504,870	$0
Total fuel		$12,294,310	$12,294,310	$12,294,310	$12,294,310	$12,294,310	$12,294,310	$0
Tire		$2,125,739.25	$2,125,739.25	$2,125,739.25	$2,125,739.25	$2,125,739.25	$2,125,739.25	$0
Maintenance		$444,132	$444,132	$444,132	$444,132	$444,132	$444,132	$0
Labour costs		$6,342,499	$6,342,499	$6,342,499	$6,342,499	$6,342,499	$6,342,499	$0
Turnover costs		$47,040	$47,040	$47,040	$47,040	$47,040	$47,040	$0
Training		$367,500	$367,500	$367,500	$367,500	$367,500	$367,500	$0
Extra Mining costs		$40,883,650	$40,883,650	$40,883,650	$40,883,650	$40,883,650	$40,883,650	$0
Depreciation		$7,504,690	$7,504,690	$7,504,690	$7,504,690	$7,504,690	$7,504,690	$0
CAPEX	$40,000,000							
Investment Costs	$40,000,000	-	-	-	-	-	-	-
Start-up Issues	-	-						
Infrastructure	-	-	-	-	-	-	-	-

Table 67. Capital and annual costs for 9 AHS trucks.

9 AHS Trucks	Year							
	0	1	2	3	4	5	6	7
OPEX		$57,081,314	$57,081,314	$57,081,314	$57,081,314	$57,081,314	$18,763,809	$0
Total fuel		$12,549,278	$12,549,278	$12,549,278	$12,549,278	$12,549,278	$4,125,207	$0
Tire		$1,643,425	$1,643,425	$1,643,425	$1,643,425	$1,643,425	$540,228	$0
Maintenance		$502,211	$502,211	$502,211	$502,211	$502,211	$165,087	$0
Labour costs		$621,776	$621,776	$621,776	$621,776	$621,776	$204,391	$0
Turnover costs		$4,536	$4,536	$4,536	$4,536	$4,536	$1,491	$0
Training		$0	$0	$0	$0	$0	$0	$0
Extra Mining costs		$41,760,088	$41,760,088	$41,760,088	$41,760,088	$41,760,088	$13,727,405	$0
Depreciation		$8,103,189	$8,103,189	$8,103,189	$8,103,189	$8,103,189	$2,674,053	$0
CAPEX	$52,190,000							
Investment Costs	$45,000,000	-	-	-	-	-	-	-
Start-up Issues		$500,000						
Infrastructure	$6,690,000	-	-	-	-	-	-	-

Appendix 20: Communication Model

Current AHS systems are being developed with two major approaches to the communications network. First, the extent to which each truck is fully-autonomous with on-board computing equipment to make decisions on movement and direction is an important distinction. Secondly, the centralized supervisory system that informs each truck about its schedule and task is also important. The distribution of hardware and software resources between the centralized computer system and the distributed ones on each truck is central to the types of studies that can be done using simulation.

As the number of pieces of automated equipment increases within the overall haulage system, two major problems will begin to build that may limit continued expansion of these system. These elements are bandwidth and latency. All communication networks have bottlenecks that constrain the rate of data-transfer. As the amount of data approaches this limitation, individual equipment behaviours may be delayed such that significant impact on the operation of each truck and/or the overall system will occur. Process control demands that feedback between outputs and control variables must take place in a timely fashion to ensure the truck responds to environmental and operational changes in an efficient and safe manner. Temporal effects can be complex – too rapid a response and the system may overshoot its desired target, leading to oscillations that may prove unstable. Conversely, too slow a response may lead to system failure due to poor coordination of steering and speed causing accidents or a requirement for shutdown.

Automating a single haulage truck isn't a major problem with respect to bandwidth and latency with existing computer hardware and wireless systems. It is also likely that two or three trucks can also be dealt with adequately by a properly-designed system. But each new piece of equipment will introduce significant complexity with respect to communication and interactions. For example, the potential number of inter-truck communication channels increases at an exponential rate as follows:

Number of Trucks	Communication Channels
1	1
2	3
3	6
4	10
5	15
10	55
20	210
40	820
50	1,275
55	1,540
100	5,050
150	11,325

Obviously, it is infeasible and impractical to continue to add new channels to provide secure independent communication between each pair of trucks in the system. Instead, sharing of the resource channels can reduce the ultimate size of the network as more trucks (and other automated equipment) are added into the system. As such, a hierarchical software structure is useful together with a communication module to prioritize each message and/or data packet. Packet delays will increase as more and more messages interact on the same channel. Eventually, the size of these delays will become intolerable under certain situations that may lead to system failure or significant slowdown. It is possible to estimate the onset of such limitations by analyzing the frequency of occurrence of different disturbances.

It would be useful to develop a COM feature in this simulation tool in the future to evaluate how increased fleet size impacts on bandwidth and latency issues for a particular network. Such knowledge can predict when a step change in the expansion of the network hardware is needed and what steps, if any, in software might be taken to improve system efficiency.

Communication and Telemetry System

A good telemetry service uses a communication system that enables data traffic between trucks and the control room without unexpected delay. Among several requirements for a proper functioning of the whole process, the telemetry system must be designed with the following requirements in mind:

- Security
- Reliability
- Operation for 100% of up-time
- Comply with legislation
- Comply with industrial best-practices

The telemetry and communication system is complex and new standards and technologies are emerging in the market place on a monthly basis.

Telemetry is a technique to gather, process, monitor, and transmit data from a distant location. A good telemetry system has a communication system that ensures "perfect" communication between trucks and control room to ensure safe operation all the time. In these investigations, it appears that most telemetry services used today employ a mobile communications network for data transmission from trucks to the central room. Several cellular network technologies are currently under development, but the most common in use today are GSM and CDMA. GSM is the predominant system in the world and several of the mobile phone companies in Australia (Australian Virgin Mobile and Telstra) use GSM. GSM could be a telecommunications system that it can be used in the AHS project.

GSM technology, also called second generation, or 2G, has the ability to evolve at low cost. This concept allowed evolution to 2.5G, with development of GPRS (General Packet Radio Service) allowing good data transmission to allow growth of various services including telemetry. Most telemetry applications use this system because of:

- Permanent connection (always on) between the mobile device and network;
- Good transmission rate of ~40 kbit/s can quadruple in optimal conditions;

- Data packets follow the standard IP and X.25 protocols (fixed data networks).

The telemetry system available at the mine is another point to consider. The Lucy mine uses Modular Mining's dispatch system, a Komatsu technology; and this is an important point with respect to using CAT's AHS system which may require replacement with Caterpillar's MineStar system.

With respect to topography, COMS systems must handle both local and central supervision; all trucks have on-board local supervision to protect themselves and others by deciding in real time what to do next (microsecond feedback), but they are also connected to the central supervisor which attempts to optimize the overall network and ensure safe operation throughout the mine. For example, if a rock is on the road, a particular truck may stop and then drive around it, i.e., the truck has the autonomy to make a pre-determined decision at the same time that the information about the activity is forwarded to the control centre. When the message is sent to the central supervisor, the onboard hard drive of the truck is refreshed. In addition to the added processing time, the on-board server must be configured to ensure information is handled in real time in order avoid a wrong decision.

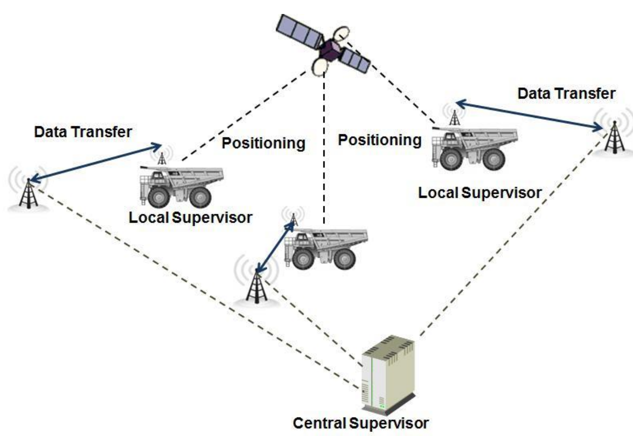


Figure 54. Schematic diagram of an AHS data and communication network.

In other situations, each truck receives information about other vehicles on the same road segment. These data include location, speed, truck ID, current distance, and direction of movement. This information is received in real time through the central supervisor. If the distance between trucks is less than the minimum safe distance set by the mine, a following truck must assume the speed of the forward truck in order to maintain the safe distance. This distance is 50 m which can be assessed by on-board instruments and server. However, if line-of-sight is lost, then the central system must provide surrogate information. With a centralized system, bandwidth is saved while processing time, cost of maintenance and infrastructure, and system latency is decreased. With a distributed system, the infrastructure is more complex resulting in high maintenance costs and a greater number of points of failure (each independent process). Table 68 shows an example of a packet that might be a priority for a truck to send to the central supervisor; this message packet has 225 characters.

Table 68. Example of a truck data package.

Data Transfer	Data
Distance travelled	Dt=0,000.00 km/t
Speed of the truck	St=00.00 km
Driver Acceleration	Ad=0.00 m/s^2
Truck Acceleration	At=0.00 m/s^3
Braking	B=0
Tire Temperature	Tt=000 C
Tire Pressure	Tp=000 psi
Time idling	Ti=000 hours
Time Movement	Tm=000 hours
Time loading	Tl=000 hours
Time Unloading	Tu=000 hours
Time Queuing	Tq=000 hours
Gears	G=0
Power	P=0000 kw
Speed of the motor	Vm=0000rpm
Level of fuel	L=000L
Fuel consumption	F=000L
Position (GPS)	X=000;Y=000;Z=000
Engine Temperature	Et=000C
Distance near another equipment	Dn=000m
Distance near object	Dn=000m
Pressure engine oil	Ep = 000psi
Tire Temperature	Tt=000C
Tire Pressure	Tp=000psi

Since one character in ASCII format occupies one byte of data, the size of this packet is ~2 kb. Suppose the total fleet in an AHS system is scaled to increase to 150 trucks. Each truck must transmit 2 kb within its own channel to the central supervisor. Since the message size is small in this case, GPRS technology provides enough bandwidth to deal with the traffic between this number of trucks and the central supervisor.

Note that if the specific bandwidth required between each truck and an antenna is ~2 kb, a specific project must determine the average number of trucks per tower, to establish total bandwidth required between the tower and control centre. This is essential to correctly dimension the network infrastructure. An appropriate network project should provide redundancy (parallel systems) to guarantee 100% operation.

Example of Traffic Data Simulation

There are tools available that can verify that network performance is satisfactory in order to ensure safety, continuity of service, and scalability as a system grows over time. For reliable simulation of network traffic within an AHS, it is necessary to know the network topology, and its assets (routers, transmission systems, servers and switches), security policies, and applications (software types and operating characteristics). It is suggested that the simulation of reaction time between an AHS compared to a manual system can be a good measure of the latency and bandwidth issues within the system. By assuming a time tolerance of a delay within the network that meets safety standards, the maximum number of trucks in the overall decision-making process can be determined. Changing the topology of the system in a hierarchical manner can be used to increase packet-transfer efficiency together with establishing the priority of different packets. For example, the most important message that might be sent out at the same time to all trucks would be a command to stop. If that message occupies 2 kb, then the system bandwidth with 5 trucks would be 10 kb. With 50 trucks, it would be 100 kb, while 150 trucks would require 300 kb. For a truck moving at 40 kph, if safe operation demands a distance tolerance of 0.04 m (4 cm) between where a truck actually is and where the system thinks it is, the required packet latency is 3.6 microseconds requiring a total bandwidth speed of 83,333 kb/second which is orders of magnitude above current telemetry speeds (144 kb/second) - ~580 times too slow.

Even 5 trucks do not have the necessary tolerance – the COMS system will be about 17 times too slow. So a 5-truck system is only safe if we accept a tolerance of about 0.7 m. One can easily see that as you scale up, this number increases quickly requiring parallel processors and a hierarchical approach to Message Transfer. For the same tolerance at 150 trucks, 30 parallel systems would be necessary. That level becomes far too expensive and excessive very quickly.

COM features can provide data on how system latency and bandwidth requirements will increase as the fleet size increases. As well, attempts can also be made to demonstrate how the supervisory software can prioritize messages and be organized into a hierarchy to reduce latency and increase the safe operation of the overall system.

Appendix 21: Stability of the Model

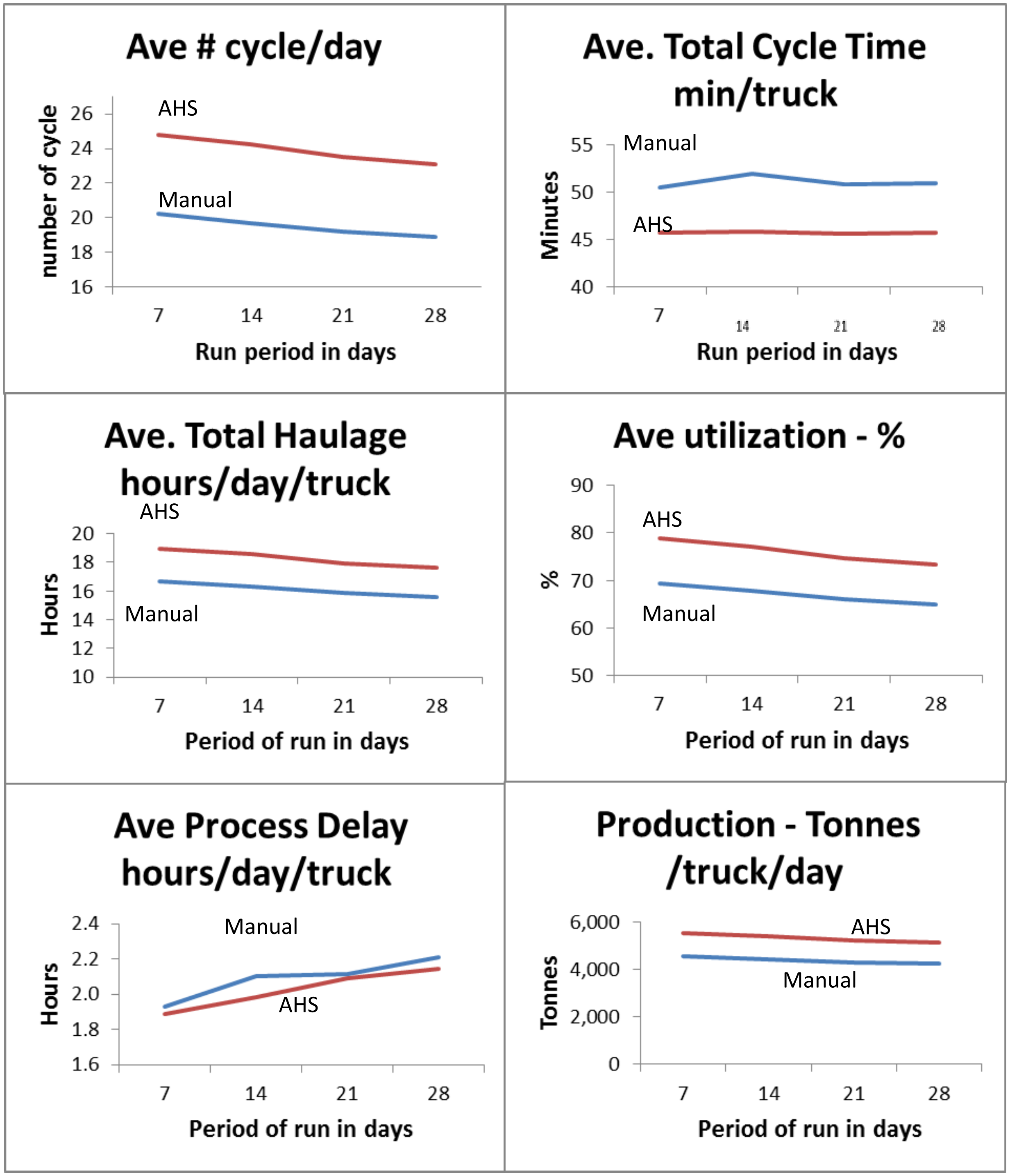


Figure 55. Simulation period – red is autonomous and blue is manual. The model was run for 7, 14, 21 and 28 days to check the stabilitity of the system.

In Figure 55, different outputs are examined to analyze the stability of the model. Table 69 compares a 7-day run with a 28-day run period. The cycles per day KPI for manual is 20.2 while for 28 days it is 18.2. The manual mode gives an average of 51 minutes cycle time at 28 days while AHS gives 45.7 minutes. The haulage time for manual at 28 days is 15.6 hours per day while for AHS it is 18.94 hours per day.. Utilization for 7 days of manual is 69.4% and for autonomous is 78.9%; while for 28 days it is 65.0% and 73.4% respectively. The delays due to preventive maintenance, process delays, and unplanned maintenance also have a small variance when comparing 7 days to 28 days. Since the difference in the results of the 7-day and 28-day of simulation time is small, all of the reported case studies were run for 7 days to reduce the time required per test.

Table 69. Stability of the model

	AHS		Manual		AHS-Manual		
Element	**7 days**	**28 days**	**7 days**	**28 days**	**7 days**	**28 days**	**% Diff.**
Ave. Number of Cycle/day	24.80	23.10	20.20	18.20	4.6	4.9	6.5
Ave. Total Cycle Time (min)/truck	45.70	45.70	50.50	51.00	-4.8	-5.3	-5.8
Ave. Total Haulage Time/day/truck	18.94	17.60	16.70	15.60	2.24	2.0	10.7
Percent Utilization(%)	78.90	73.40	69.40	65.00	8.5	8.4	0.1
Total Production (tonnes)/day/truck	5,527	5,130	4,574	4,231	953	999	-4.8

The model was run for 168, 336, 504 and 672 operating hours which represents 7, 14, 21 and 28 operational days of Lucy mine. The stochastic model generates random data according to the distribution set at the beginning of the run. Table 70 show the frequency of the generated random data when the average number of cycles per day is 22. In this example, the model generates 154 samples for 7 days of mine operation and 616 samples for 28 days of mine operation.

Table 70. Frequency of the generated random data

Variable	Generation frequency	# random samples			
		7 days	14days	21 days	28 days
Unloading Time	Every cycle	154	308	462	616
Loading Time					
Production					

Limitations

For each period of time chosen to run the model, i.e. 168, 336, 504 and 672 hours, the model was run three times to find the steady state of the model. As a result, 12 simulations took place in total (3 runs of 7 days, 3 runs of 14 days, 3 runs of 21 days, 3 runs of 28 days). The results show only a small output variation comparing 7 to 28 days of simulation time. As a result, all of the following case studies of the thesis were run for 7 days to reduce the time required per test.

The deterministic calculation slows down the model routine. This happens because the model is accessing several databases over a simulated period of 0.1 seconds. Storing travel distance data for the trucks and applying the rolling resistance/traction coefficient model are processes that slow the simulation in a very significant way since, for every simulated 100 milliseconds, the model must read and write variables in and out of the internal database. The tire wear calculations and fuel consumption model also slow the simulation considerably.

The road resistance and traction coefficient processes can be turned off, if faster and more studies are necessary in future work with the model, however road condition changes are considered important in understanding the dynamic behaviour of haulage trucks.

If the time to complete the study is more important than accuracy, the deterministic models can be turned off completely and the model can run in a fully-stochastic mode. In this case the model takes about 10 minutes to simulate one day of mining. With the deterministic components included, one day of mining takes about 35 minutes to simulate. The deterministic models slow the system by about 3.5 times compared to the fully stochastic mode which means for a 42-day test, the time to obtain a result is just over 25 hours. A simulation period of this length was not found necessary to provide additional accuracy.

The time to carry out a test run is also hardware dependent. The studies done in this research used two laptops and one desktop equipped with high-speed chips (i7-2677M, chi26700M, and i7-2650 respectively). These CPUs are rated at about 50% of the fastest current Intel chip on the market.

Appendix 22: Probabilistic Distributions Used in the Model

The model uses lognormal, normal and triangular distribution to generate random values; some variables are just set constant. The choice of using these distribuitions was based on analysing and plotting the data from the Lucy mine. The constant values were based on information of the mine. Table 71 shows the variables of the model that use probabilistic distributions to set their values and others that use constant numbers.

Table 71. Probabilistic distribution and constant values used in the model

<table>
<tr><th>Variable</th><th>Time until downtime</th><th>Downtime</th></tr>
<tr><td>Major Maintenance</td><td rowspan="2">Triangular distribution - set by Lucy mine</td><td rowspan="2">Triangular distribution - set by Lucy mine</td></tr>
<tr><td>Minor Maintenance</td></tr>
<tr><td>Refueling</td><td>Constant - 10% of tank level</td><td>Triangular distribution - set by Lucy mine</td></tr>
<tr><td>Lunch</td><td>Based on the Lucy mine lunch time</td><td rowspan="3">Constant - based on Lucy mine data</td></tr>
<tr><td>Driver's break</td><td>Two breaks, but depends on other breaks</td></tr>
<tr><td>Shift Change</td><td>Based on the Lucy mine shift change time</td></tr>
<tr><td>Mine Delays</td><td>Constant - based on the different Lucy mine delays</td><td>Triangular distribution - set by Lucy mine</td></tr>
<tr><th colspan="3">Other variables</th></tr>
<tr><th>Variable</th><th colspan="2">Event</th></tr>
<tr><td>Unload Time</td><td colspan="2" rowspan="2">Lognormal Distribution - based on VIMS© data of the Lucy mine</td></tr>
<tr><td>Load Time</td></tr>
<tr><td>Productivity</td><td colspan="2">Normal Distribution - based on VIMS© data of the Lucy mine</td></tr>
<tr><td>Precipation – Intensity</td><td colspan="2" rowspan="2">Triangular distribution - based on Lucy mine weather</td></tr>
<tr><td>Precipation – Duration</td></tr>
<tr><td>Wind – Direction</td><td colspan="2" rowspan="2">Triangular distribution - by segment based on Lucy mine weather</td></tr>
<tr><td>Wind – Speed</td></tr>
<tr><td>Ambient Temperatute</td><td colspan="2">look table or constant value - based on Lucy mine weather</td></tr>
</table>

Unloading and loading time, and productivity data were obtained from the VIMS© (vehicle information monitoring system) from 12-Feb-10 to 15-Feb-10. According to the Lucy data, the unplanned maintenance is divided in two kinds: minor where the problem can be solved quickly and major where the maintenance can take days. The maximum, minimum and average values of the unplanned maintenance distribution were set by Lucy mine.

The definition of how these probabilistic are used in ExtendSim is described below:

- Normal: Gaussian or bell curve with the given (1) Mean and (2) Std Dev (standard deviation). The Mean is specified as a real number and the standard deviation is specified as a non-negative real number. INPUT: Mean and Std Dev.
- Lognormal: Natural log of the variable that follows the Gaussian or bell curve with the given (1) Mean and (2) Std Dev (standard deviation). This distribution outputs a value > 0, skewed so that most of the values occur near the minimum value (positive skew). INPUT: Mean, Std Dev, Location (the value to skew the distribution).
- Triangular: Outputs a value N, where N is a real (decimal) number greater than or equal to the real number selected for argument 1 (the minimum) and less than or equal to the real number selected for argument 2 (the maximum) with the added provision that N tends towards its most likely, or modal value. INPUT: Minimum, maximum and most likely.

Appendix 23: Tire Construction and Nomenclature

Radial Tire Construction

Two types of tires are in use today – bias ply and radial ply. Caterpillar recommends the 40.00R57 tire to be used with the 793D trucks. "R" represents the radial construction. The main features of a radial tire are as follows (see Figure 56):

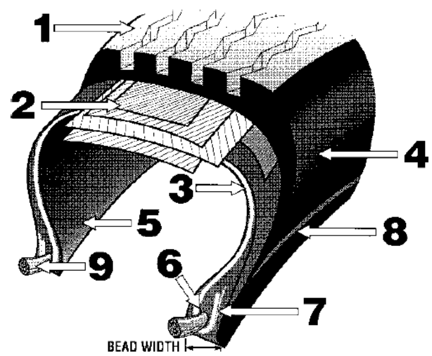


Figure 56. Tire components (from Goodyear radial truck tire retread service manual, 2003)

1. Tread:	Provides the interface between the tire structure and the road; Purpose is to provide traction and wear
2. Belts:	Steel cord belt plies give the tire strength, stabilize the tread, and protect the air chamber from punctures
3. Radial Ply:	Radial ply together with belt plies withstands burst loading of the tire under operating pressure; must transmit all loads, braking, and steering forces between wheel and tread
4. Sidewall:	Sidewalls must withstand flexure and weathering while protecting the ply.
5. Liner:	Layers of rubber in tubeless tires compounded to resist air diffusion. Liner replaces the inner tube of the tube-type tire
6. Apexes:	Rubber pieces used to fill in the bead and lower sidewalls Provide smooth transition from stiff bead to flexible sidewall
7. Stabilizer Ply:	Laid over radial ply, turned-up outside of the bead and under the rubber chafer to reinforce and stabilize the bead-to-sidewall transition zone.
8. GG Ring:	Reference for proper seating of bead on rim
9. Bead Core:	Continuous high-tensile wound wire to provide high-strength; Major structural element in plane of rotation to maintain tire on rim diameter.

Tire Nomenclature

The tire industry divides off-the-road tires into six categories:

C — Compactor Service
E — Earthmover Service
G — Grader Service
L — Loader & Dozer Service
LS — Log-Skidder Service

Sub-categories are designated by numerals. For example, the 793D uses an E4 tire type.

Table 72. Sub-categories of tires for earthmoving equipment (Caterpillar 3, 2007).

Earthmover		
Code	Type	% Tread Depth
E-1	Rib	100
E-2	Traction	100
E-3	Rock	100
E-4	Rock Deep Tread	150

Tire size nomenclature designates tire cross-sectional width and rim diameter. As an example, a 40.00R57 tire is a radial ply standard base tire having a width of about 1.01 m (40 in.) between the sidewalls, and a rim diameter of 1.44 m (57 in). Figure 57 shows a few of these terms.

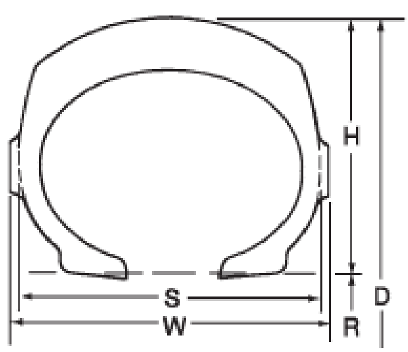


Figure 57. Tire cross-section (from caterpillar handbook 38th edition).

where:

D = the tire overall diameter
R = nominal rim diameter
H = tire section height
W = tire width (includes ornamental ribs)
H/S = aspect ratio

Appendix 24: Model Input

Table 73. Truck input

Truck	
GWV	165749
Vinitial	0
tank Level (L)	4354
Major_break_T (h) *	108
Minor_break_T (h) *	6
TTRefuel_T (min) *	0.22
TTR_Major_T (min) *	5
TTR_Minor_T (min) *	0.32
TTR_prevent_T (min) *	0.1
total_tire (thread)	75
Shift_14days (hours)	12

** Random- each run gives a different value*

Table 74. Driver behavior input

Driver Behaviour Input			
	Aggressiveness Factor	Variance	Stability Factor
Drive1	-1	0	0.8
Drive2	0	0	0.05
Drive3	-1	0	0.9
Drive4	-1	0	0.8
Drive5	1	0	1.2
Drive6	0	0	0.1
Drive7	0	0	0.07
Drive8	0	0	0.05
Drive9	-1	0	0.9
Drive10	1	0	1.1
Drive11	0	0	0.1
Drive12	-1	0	0.8
Drive13	-1	0	0.9
Drive14	-1	0	0.9
Drive15	0	0	0.05
Drive16	0	0	0.1
Drive17	0	0	0.03
Drive18	1	0	1.2

Table 75. Route input

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
1	1	Ore Shovel / Crusher	450	40	0	5	0	0.21	-0.42	1
1	2	Ore Shovel / Crusher	430	40	0	7	0	0.21	-0.42	1
1	3	Ore Shovel / Crusher	296	40	1	7	30	0.21	-0.42	1
1	4	Ore Shovel / Crusher	182	40	1	7	30	0.21	-0.42	1
1	5	Ore Shovel / Crusher	130	40	1	7	30	0.21	-0.42	1
1	6	Ore Shovel / Crusher	442	40	1	7	30	0.21	-0.42	1
1	7	Ore Shovel / Crusher	235	40	1	7	30	0.21	-0.42	1
1	8	Ore Shovel / Crusher	149	40	1	7	30	0.21	-0.42	1
1	9	Ore Shovel / Crusher	114	40	1	7	30	0.21	-0.42	1
1	10	Ore Shovel / Crusher	127	40	1	7	30	0.21	-0.42	1
1	11	Ore Shovel / Crusher	298	40	1	7	30	0.21	-0.42	1
1	12	Ore Shovel / Crusher	235	40	0	7	0	0.21	-0.42	1
1	13	Ore Shovel / Crusher	492	40	1	7	30	0.21	-0.42	1
1	14	Ore Shovel / Crusher	114	40	1	7	30	0.21	-0.42	1
1	15	Ore Shovel / Crusher	445	40	0	7	0	0.21	-0.42	1
1	16	Ore Shovel / Crusher	124	40	1	7	30	0.21	-0.42	1
1	17	Ore Shovel / Crusher	266	40	0	7	0	0.21	-0.42	1
1	18	Ore Shovel / Crusher	314	40	1	5	30	0.21	-0.42	1
1	19	Ore Shovel / Crusher	314	40	1	5	30	0.21	-0.42	1
1	20	Ore Shovel / Crusher	128	40	1	1	30	0.21	-0.42	1
1	21	Ore Shovel / Crusher	410	40	0	1	0	0.21	-0.42	1
2	1	Ore Shovel/Parking	250	40	0	5	0	0.42	-0.42	1
2	2	Ore Shovel/Parking	230	40	0	5	0	0.42	-0.42	1
2	3	Ore Shovel/Parking	296	40	0	7	0	0.21	-0.42	1
2	4	Ore Shovel/Parking	182	40	1	7	30	0.21	-0.42	1
2	5	Ore Shovel/Parking	130	40	1	7	30	0.21	-0.42	1
2	6	Ore Shovel/Parking	442	40	1	5	30	0.42	-0.42	1
2	7	Ore Shovel/Parking	235	40	0	7	0	0.21	-0.42	1
2	8	Ore Shovel/Parking	149	40	1	7	30	0.21	-0.42	1
2	9	Ore Shovel/Parking	114	40	1	7	30	0.21	-0.42	1
2	10	Ore Shovel/Parking	127	40	1	7	30	0.21	-0.42	1
2	11	Ore Shovel/Parking	298	40	1	7	30	0.21	-0.42	1
2	22	Ore Shovel/Parking	391	40	0	-1	0	0.62	-0.42	1
2	23	Ore Shovel/Parking	294	40	0	5	0	0.42	-0.42	1
2	24	Ore Shovel/Parking	424	40	0	-5	0	0.62	-0.42	1

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
3	21	Crusher/Parking	410	40	0	-1	0	0.62	-0.42	0
3	20	Crusher/Parking	128	40	1	-1	30	0.62	-0.42	0
3	19	Crusher/Parking	314	40	1	-5	30	0.62	-0.42	0
3	18	Crusher/Parking	314	40	1	-5	30	0.62	-0.42	0
3	17	Crusher/Parking	266	40	1	-2	30	0.62	-0.42	0
3	16	Crusher/Parking	124	40	1	-5	30	0.62	-0.42	0
3	15	Crusher/Parking	445	40	1	-7	30	0.62	-0.42	0
3	14	Crusher/Parking	114	40	1	-7	30	0.62	-0.42	0
3	13	Crusher/Parking	492	40	0	-5	0	0.62	-0.42	0
3	12	Crusher/Parking	235	40	1	-5	30	0.62	-0.42	0
3	22	Crusher/Parking	391	40	1	-1	30	0.62	-0.42	1
3	23	Crusher/Parking	294	40	0	-5	0	0.62	-0.42	1
3	24	Crusher/Parking	424	40	0	5	0	0.42	-0.42	1
4	21	Crusher / waste shovel	410	40	1	-1	30	0.62	-0.42	0
4	20	Crusher / waste shovel	128	40	1	-1	30	0.62	-0.42	0
4	19	Crusher / waste shovel	314	40	1	-5	30	0.62	-0.42	0
4	18	Crusher / waste shovel	314	40	1	-5	30	0.62	-0.42	0
4	17	Crusher / waste shovel	266	40	10	-2	0	0.62	-0.42	0
4	16	Crusher / waste shovel	124	40	1	-5	30	0.62	-0.42	0
4	15	Crusher / waste shovel	445	40	0	-7	0	0.62	-0.42	0
4	14	Crusher / waste shovel	114	40	1	-7	30	0.62	-0.42	0
4	13	Crusher / waste shovel	492	40	0	-5	0	0.62	-0.42	0
4	12	Crusher / waste shovel	235	40	1	-7	30	0.62	-0.42	0
4	11	Crusher / waste shovel	298	40	0	-7	0	0.62	-0.42	0
4	10	Crusher / waste shovel	127	40	1	-7	30	0.62	-0.42	0
4	9	Crusher / waste shovel	114	40	1	-7	30	0.62	-0.42	0
4	8	Crusher / waste shovel	149	40	1	-7	30	0.62	-0.42	0
4	7	Crusher / waste shovel	235	40	0	-7	0	0.62	-0.42	0
4	6	Crusher / waste shovel	442	40	1	-5	30	0.62	-0.42	0
4	5	Crusher / waste shovel	130	40	1	-7	30	0.62	-0.42	0
4	25	Crusher / waste shovel	151	40	1	-5	30	0.62	-0.42	0
4	26	Crusher / waste shovel	160	40	1	-5	30	0.62	-0.42	0
4	27	Crusher / waste shovel	102	40	1	-7	30	0.62	-0.42	0
4	28	Crusher / waste shovel	118	40	1	-5	30	0.62	-0.42	0
4	29	Crusher / waste shovel	118	40	1	-5	30	0.62	-0.42	0
4	30	Crusher / waste shovel	250	40	0	-5	0	0.62	-0.42	0
4	31	Crusher / waste shovel	244	40	1	-5	30	0.62	-0.42	0

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
4	32	Crusher / waste shovel	260	40	1	-5	30	0.62	-0.42	0
4	33	Crusher / waste shovel	260	40	1	-5	30	0.62	-0.42	0
4	34	Crusher / waste shovel	240	40	0	-1	0	0.62	-0.42	0
5	24	Parking /waste shovel	424	40	1	-5	30	0.62	-0.42	0
5	23	Parking /waste shovel	294	40	0	-5	0	0.62	-0.42	0
5	22	Parking /waste shovel	391	40	1	1	30	0.62	-0.42	0
5	11	Parking /waste shovel	298	40	0	-7	0	0.62	-0.42	0
5	10	Parking /waste shovel	127	40	1	-7	30	0.62	-0.42	0
5	9	Parking /waste shovel	114	40	1	-7	30	0.62	-0.42	0
5	8	Parking /waste shovel	149	40	1	-7	30	0.62	-0.42	0
5	7	Parking /waste shovel	235	40	0	-7	0	0.62	-0.42	0
5	6	Parking /waste shovel	442	40	0	-5	0	0.62	-0.42	0
5	5	Parking /waste shovel	130	40	1	-7	30	0.62	-0.42	0
5	25	Parking /waste shovel	151	40	1	-5	30	0.62	-0.42	0
5	26	Parking /waste shovel	160	40	1	-5	30	0.62	-0.42	0
5	27	Parking /waste shovel	102	40	1	-7	30	0.62	-0.42	0
5	28	Parking /waste shovel	118	40	1	-5	30	0.62	-0.42	0
5	29	Parking /waste shovel	118	40	1	-5	30	0.62	-0.42	0
5	30	Parking /waste shovel	421	40	1	-5	30	0.62	-0.42	0
5	31	Parking /waste shovel	244	40	1	-5	30	0.62	-0.42	0
5	32	Parking /waste shovel	450	40	1	-5	30	0.62	-0.42	0
5	33	Parking /waste shovel	527	40	1	-5	30	0.62	-0.42	0
5	34	Parking /waste shovel	509	40	0	-1	0	0.62	-0.42	0
6	45	Dump/waste shovel	349	40	1	-5	30	0.62	-0.42	0
6	44	Dump/waste shovel	295	40	0	-7	0	0.62	-0.42	0
6	43	Dump/waste shovel	285	40	1	-7	30	0.62	-0.42	0
6	42	Dump/waste shovel	300	40	0	-7	0	0.62	-0.42	0
6	41	Dump/waste shovel	330	40	1	-7	30	0.62	-0.42	0
6	40	Dump/waste shovel	339	40	1	-7	30	0.62	-0.42	0
6	39	Dump/waste shovel	326	40	0	-7	0	0.62	-0.42	0
6	38	Dump/waste shovel	228	40	1	-7	30	0.62	-0.42	0
6	37	Dump/waste shovel	241	40	1	-7	30	0.62	-0.42	0
6	36	Dump/waste shovel	347	40	0	-7	0	0.62	-0.42	0
6	35	Dump/waste shovel	343	40	1	-7	30	0.62	-0.42	0
6	31	Dump/waste shovel	244	40	1	-7	30	0.62	-0.42	0
6	32	Dump/waste shovel	450	40	1	-7	30	0.62	-0.42	0
6	33	Dump/waste shovel	250	40	1	-7	30	0.62	-0.42	0

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
6	34	Dump/waste shovel	509	40	0	-1	0	0.62	-0.42	0
7	45	Dump/parking	649	40	1	-5	30	0.62	-0.42	1
7	44	Dump/parking	295	40	0	0	0	0.62	-0.42	1
7	43	Dump/parking	285	40	1	-3	30	0.62	-0.42	1
7	42	Dump/parking	300	40	0	-5	0	0.62	-0.42	1
7	46	Dump/parking	106	40	1	-5	30	0.62	-0.42	1
7	47	Dump/parking	397	40	1	-1	30	0.62	-0.42	1
7	48	Dump/parking	171	40	1	-1	30	0.62	-0.42	1
7	49	Dump/parking	309	40	1	-1	30	0.62	-0.42	1
7	50	Dump/parking	309	40	1	0	30	0.62	-0.42	1
7	51	Dump/parking	177	40	1	1	30	0.62	-0.42	1
7	52	Dump/parking	349	40	1	1	30	0.62	-0.42	1
7	53	Dump/parking	179	40	1	5	30	0.42	-0.42	1
7	24	Dump/parking	424	40	0	5	0	0.42	-0.42	1
8	45	Dump/ore shovel	649	40	1	-5	30	0.62	-0.42	0
8	44	Dump/ore shovel	295	40	0	0	0	0.62	-0.42	0
8	43	Dump/ore shovel	285	40	1	-3	30	0.62	-0.42	0
8	42	Dump/ore shovel	300	40	0	-5	0	0.62	-0.42	0
8	41	Dump/ore shovel	330	40	1	-5	30	0.62	-0.42	0
8	40	Dump/ore shovel	839	40	1	-7	30	0.62	-0.42	0
8	39	Dump/ore shovel	326	40	1	-7	30	0.62	-0.42	0
8	38	Dump/ore shovel	428	40	0	-7	0	0.62	-0.42	0
8	37	Dump/ore shovel	241	40	1	-7	30	0.62	-0.42	0
8	36	Dump/ore shovel	347	40	0	-7	0	0.62	-0.42	0
8	35	Dump/ore shovel	343	40	1	-5	30	0.62	-0.42	0
8	30	Dump/ore shovel	250	40	1	-5	30	0.62	-0.42	0
8	29	Dump/ore shovel	118	40	1	-5	30	0.62	-0.42	0
8	28	Dump/ore shovel	118	40	1	-5	30	0.62	-0.42	0
8	27	Dump/ore shovel	102	40	1	-7	30	0.62	-0.42	0
8	26	Dump/ore shovel	160	40	1	-5	30	0.62	-0.42	0
8	25	Dump/ore shovel	151	40	1	-5	30	0.62	-0.42	0
8	4	Dump/ore shovel	182	40	1	-7	30	0.62	-0.42	0
8	3	Dump/ore shovel	296	40	1	-7	30	0.62	-0.42	0
8	2	Dump/ore shovel	230	40	0	-5	0	0.62	-0.42	0
8	1	Dump/ore shovel	250	40	0	-5	0	0.62	-0.42	0
9	21	Crusher/Ore shovel	410	40	0	-1	0	0.62	-0.42	0
9	20	Crusher/Ore shovel	128	40	1	-7	30	0.62	-0.42	0

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
9	19	Crusher/Ore shovel	314	40	1	-7	30	0.62	-0.42	0
9	18	Crusher/Ore shovel	314	40	1	-7	30	0.62	-0.42	0
9	17	Crusher/Ore shovel	266	40	1	-7	30	0.62	-0.42	0
9	16	Crusher/Ore shovel	124	40	1	-7	30	0.62	-0.42	0
9	15	Crusher/Ore shovel	245	40	0	-7	0	0.62	-0.42	0
9	14	Crusher/Ore shovel	114	40	1	-7	30	0.62	-0.42	0
9	13	Crusher/Ore shovel	250	40	0	-7	0	0.62	-0.42	0
9	12	Crusher/Ore shovel	235	40	1	-7	30	0.62	-0.42	0
9	11	Crusher/Ore shovel	298	40	1	-7	30	0.62	-0.42	0
9	10	Crusher/Ore shovel	127	40	1	-7	30	0.62	-0.42	0
9	9	Crusher/Ore shovel	114	40	1	-7	30	0.62	-0.42	0
9	8	Crusher/Ore shovel	149	40	1	-7	30	0.62	-0.42	0
9	7	Crusher/Ore shovel	235	40	1	-7	30	0.62	-0.42	0
9	6	Crusher/Ore shovel	200	40	0	-7	0	0.62	-0.42	0
9	5	Crusher/Ore shovel	130	40	1	-7	30	0.62	-0.42	0
9	4	Crusher/Ore shovel	182	40	1	-7	30	0.62	-0.42	0
9	3	Crusher/Ore shovel	296	40	1	-7	30	0.62	-0.42	0
9	2	Crusher/Ore shovel	230	40	0	-5	0	0.62	-0.42	0
9	1	Crusher/Ore shovel	250	40	0	-5	0	0.62	-0.42	0
10	24	Parking/Ore Shovel	424	40	1	-5	30	0.62	-0.42	0
10	23	Parking/Ore Shovel	294	40	0	-5	0	0.62	-0.42	0
10	22	Parking/Ore Shovel	391	40	1	1	30	0.62	-0.42	0
10	11	Parking/Ore Shovel	298	40	0	-7	0	0.62	-0.42	0
10	10	Parking/Ore Shovel	127	40	1	-7	30	0.62	-0.42	0
10	9	Parking/Ore Shovel	114	40	1	-7	30	0.62	-0.42	0
10	8	Parking/Ore Shovel	149	40	1	-7	30	0.62	-0.42	0
10	7	Parking/Ore Shovel	235	40	1	-7	30	0.62	-0.42	0
10	6	Parking/Ore Shovel	442	40	0	-5	0	0.62	-0.42	0
10	5	Parking/Ore Shovel	130	40	1	-7	30	0.62	-0.42	0
10	4	Parking/Ore Shovel	182	40	0	-7	0	0.62	-0.42	0
10	3	Parking/Ore Shovel	296	40	0	-7	0	0.62	-0.42	0
10	2	Parking/Ore Shovel	230	40	0	-5	0	0.62	-0.42	0
10	1	Parking/Ore Shovel	250	40	0	-5	0	0.62	-0.42	0
11	24	Parking/Crusher	424	40	1	-5	30	0.62	-0.42	0
11	23	Parking/Crusher	294	40	0	-5	0	0.62	-0.42	0
11	22	Parking/Crusher	391	40	0	1	0	0.62	-0.42	0
11	12	Parking/Crusher	235	40	0	5	0	0.42	-0.42	1

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
11	13	Parking/Crusher	492	40	1	5	30	0.62	-0.42	1
11	14	Parking/Crusher	114	40	1	-7	30	0.21	-0.42	1
11	15	Parking/Crusher	445	40	1	-7	30	0.21	-0.42	1
11	16	Parking/Crusher	124	40	1	5	30	0.42	-0.42	1
11	17	Parking/Crusher	266	40	1	2	30	0.62	-0.42	1
11	18	Parking/Crusher	314	40	1	5	30	0.62	-0.42	1
11	19	Parking/Crusher	314	40	1	5	30	0.62	-0.42	1
11	20	Parking/Crusher	128	40	1	1	30	0.62	-0.42	1
11	21	Parking/Crusher	410	40	0	1	0	0.62	-0.42	1
12	34	waste shovel /Crusher	509	40	1	1	30	0.62	-0.42	1
12	33	waste shovel /Crusher	527	40	1	5	30	0.21	-0.42	1
12	32	waste shovel /Crusher	150	40	1	5	30	0.42	-0.42	1
12	31	waste shovel /Crusher	244	40	0	5	0	0.42	-0.42	1
12	30	waste shovel /Crusher	421	40	1	5	30	0.42	-0.42	1
12	29	waste shovel /Crusher	118	40	1	5	30	0.42	-0.42	1
12	28	waste shovel /Crusher	118	40	1	5	30	0.42	-0.42	1
12	27	waste shovel /Crusher	102	40	1	7	30	0.21	-0.42	1
12	26	waste shovel /Crusher	160	40	1	5	30	0.42	-0.42	1
12	25	waste shovel /Crusher	151	40	1	5	30	0.42	-0.42	1
12	5	waste shovel /Crusher	130	40	1	7	30	0.21	-0.42	1
12	6	waste shovel /Crusher	442	40	1	5	30	0.42	-0.42	1
12	7	waste shovel /Crusher	235	40	1	7	30	0.21	-0.42	1
12	8	waste shovel /Crusher	149	40	1	7	30	0.21	-0.42	1
12	9	waste shovel /Crusher	114	40	1	1	30	0.21	-0.42	1
12	10	waste shovel /Crusher	127	40	1	7	30	0.21	-0.42	1
12	11	waste shovel /Crusher	298	40	1	7	30	0.21	-0.42	1
12	12	waste shovel /Crusher	235	40	0	7	0	0.21	-0.42	1
12	13	waste shovel /Crusher	492	40	1	5	30	0.62	-0.42	1
12	14	waste shovel /Crusher	114	40	1	7	30	0.21	-0.42	1
12	15	waste shovel /Crusher	445	40	1	7	30	0.21	-0.42	1
12	16	waste shovel /Crusher	124	40	1	5	30	0.42	-0.42	1
12	17	waste shovel /Crusher	266	40	1	2	30	0.62	-0.42	1
12	18	waste shovel /Crusher	314	40	1	5	30	0.62	-0.42	1
12	19	waste shovel /Crusher	314	40	1	5	30	0.62	-0.42	1
12	20	waste shovel /Crusher	128	40	1	1	30	0.62	-0.42	1
12	21	waste shovel /Crusher	410	40	0	1	0	0.62	-0.42	1
13	34	waste shovel/parking	509	40	1	1	30	0.62	-0.42	1

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
13	33	waste shovel/parking	527	40	1	5	30	0.21	-0.42	1
13	32	waste shovel/parking	450	40	1	5	30	0.42	-0.42	1
13	31	waste shovel/parking	244	40	1	5	30	0.42	-0.42	1
13	30	waste shovel/parking	421	40	1	5	30	0.42	-0.42	1
13	29	waste shovel/parking	118	40	1	5	30	0.42	-0.42	1
13	28	waste shovel/parking	118	40	1	5	30	0.42	-0.42	1
13	27	waste shovel/parking	102	40	1	7	30	0.21	-0.42	1
13	26	waste shovel/parking	160	40	1	5	30	0.42	-0.42	1
13	25	waste shovel/parking	151	40	1	5	30	0.42	-0.42	1
13	5	waste shovel/parking	130	40	1	7	30	0.21	-0.42	1
13	6	waste shovel/parking	442	40	1	5	30	0.42	-0.42	1
13	7	waste shovel/parking	235	40	0	7	0	0.21	-0.42	1
13	8	waste shovel/parking	149	40	1	7	30	0.21	-0.42	1
13	9	waste shovel/parking	114	40	1	7	30	0.21	-0.42	1
13	10	waste shovel/parking	127	40	1	7	30	0.21	-0.42	1
13	11	waste shovel/parking	298	40	1	7	30	0.21	-0.42	1
13	22	waste shovel/parking	391	40	0	-1	0	0.62	-0.42	1
13	23	waste shovel/parking	294	40	0	5	0	0.42	-0.42	1
13	24	waste shovel/parking	424	40	0	5	0	0.42	-0.42	1
14	34	waste shovel /dump	509	40	1	1	30	0.21	-0.42	1
14	33	waste shovel /dump	527	40	0	5	0	0.21	-0.42	1
14	32	waste shovel /dump	450	40	1	7	30	0.21	-0.42	1
14	31	waste shovel /dump	444	40	1	7	30	0.21	-0.42	1
14	35	waste shovel /dump	343	40	1	7	30	0.21	-0.42	1
14	36	waste shovel /dump	347	40	1	7	30	0.21	-0.42	1
14	37	waste shovel /dump	241	40	1	7	30	0.21	-0.42	1
14	38	waste shovel /dump	428	40	1	7	30	0.21	-0.42	1
14	39	waste shovel /dump	326	40	0	7	0	0.21	-0.42	1
14	40	waste shovel /dump	339	40	0	7	0	0.21	-0.42	1
14	41	waste shovel /dump	330	40	1	7	30	0.21	-0.42	1
14	42	waste shovel /dump	300	40	1	7	30	0.21	-0.42	1
14	43	waste shovel /dump	285	40	0	7	0	0.21	-0.42	1
14	44	waste shovel /dump	295	40	0	7	0	0.21	-0.42	1
14	45	waste shovel /dump	649	40	0	5	0	0.21	-0.42	1
15	24	parking/dump	424	40	1	-5	30	0.62	-0.42	0
15	53	parking/dump	179	40	1	-5	30	0.62	-0.42	0
15	52	parking/dump	349	40	0	-1	0	0.62	-0.42	0

Route	Sub seg.	From	Length	Speed limit	Stop at ending	Grade	Next Speed	Acce. max	Deac. max	Direction
15	51	parking/dump	177	40	1	-1	30	0.62	-0.42	0
15	50	parking/dump	309	40	1	0	30	0.62	-0.42	0
15	49	parking/dump	309	40	0	1	0	0.62	-0.42	0
15	48	parking/dump	171	40	1	1	30	0.62	-0.42	0
15	47	parking/dump	397	40	0	1	0	0.62	-0.42	0
15	46	parking/dump	106	40	1	5	30	0.42	-0.42	0
15	42	parking/dump	300	40	1	5	30	0.42	-0.42	0
15	43	parking/dump	285	40	0	3	0	0.62	-0.42	0
15	44	parking/dump	295	40	0	0	0	0.62	-0.42	0
15	45	parking/dump	649	40	0	5	0	0.42	-0.42	0
16	1	ore shovel/Dump	250	40	0	5	0	0.42	-0.42	1
16	2	ore shovel/Dump	230	40	0	5	0	0.42	-0.42	1
16	3	ore shovel/Dump	296	40	1	7	30	0.21	-0.42	1
16	4	ore shovel/Dump	182	40	0	7	0	0.21	-0.42	1
16	25	ore shovel/Dump	151	40	1	5	30	0.42	-0.42	1
16	26	ore shovel/Dump	160	40	1	5	30	0.42	-0.42	1
16	27	ore shovel/Dump	102	40	1	7	30	0.21	-0.42	1
16	28	ore shovel/Dump	118	40	1	5	30	0.42	-0.42	1
16	29	ore shovel/Dump	118	40	1	5	30	0.42	-0.42	1
16	30	ore shovel/Dump	421	40	1	5	30	0.42	-0.42	1
16	35	ore shovel/Dump	343	40	1	5	30	0.42	-0.42	1
16	36	ore shovel/Dump	347	40	0	7	0	0.21	-0.42	1
16	37	ore shovel/Dump	241	40	1	7	30	0.21	-0.42	1
16	38	ore shovel/Dump	428	40	1	7	30	0.21	-0.42	1
16	39	ore shovel/Dump	326	40	0	7	0	0.21	-0.42	1
16	40	ore shovel/Dump	339	40	1	7	30	0.21	-0.42	1
16	41	ore shovel/Dump	330	40	1	5	30	0.42	-0.42	1
16	42	ore shovel/Dump	300	40	1	5	30	0.42	-0.42	1
16	43	ore shovel/Dump	285	40	1	3	30	0.62	-0.42	1
16	44	ore shovel/Dump	295	40	1	0	30	0.62	-0.42	1
16	45	ore shovel/Dump	649	40	0	5	0	0.42	-0.42	1