

University of Southern Queensland  
Faculty of Health, Engineering and Sciences

# **Optimisation of off-highway truck fuel consumption through mine haul road design**

A dissertation submitted by

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# Abstract

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This study aims to optimise the fuel consumption of Caterpillar 785D off-highway trucks as used by the project sponsor at an open cut coal mining operation in Queensland, Australia.

This was achieved by:

- Researching mine design and operational factors influencing fuel consumption of off-highway trucks
- Identifying variables and haul road design scenarios relevant to the project sponsor's particular operation
- Creating a data collection program to obtain and combine relevant condition monitoring data from multiple sources
- Analysing the data for variations in fuel consumption
- Quantifying fuel consumption in different haul road scenarios

Fuel consumption rates were found for three scenarios, ascending ramps, stop-start driving and idling. Mining engineers can use these quantities to predict fuel costs incurred by various ramp grades and lengths, truck queuing, intersections and other similar road features. Fuel costs can be compared to construction and production costs to determine optimal road designs. An additional tool was created to assist with the calculation of fuel costs over the life of a ramp. This tool demonstrates how these costs are affected by ramp grade.

The methodology could be expanded to other truck models or operations in the future. In addition to optimising fuel consumption, condition monitoring data could also be used to optimise other production, design or maintenance tasks.

**University of Southern Queensland**  
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## Chapter 1

# Introduction

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### 1.1 Problem Statement

In the open cut mining environment, off-highway trucks (also called 'haul trucks') are used to carry material along haul roads to different locations within the mine. Haul roads can change rapidly as mining progresses and access to different areas is required.

Diesel is a key consumable for mining operations. For some sites fuel can constitute as much as 30% of operating costs (Bellamy & Pravica 2011). As a result, it is imperative to understand the relationship between haul road design and fuel consumption.

### 1.2 Project Initiation

This research opportunity was identified through discussion with Trent Knack, Maintenance Manager at New Hope Group. New Hope Group operates several open cut coal mines in South East Queensland. These assets produced 6.29 million tonnes of thermal coal in 2012 (*Coal Operations* 2015). The mine chosen for this study (henceforth referred to as the 'study site') has a particularly steep profile meaning haul road designs often includes short haul runs over ramps with high grades.

The price of Australian thermal coal has been in decline for several years. In October 2014, the price per metric tonne was sitting at almost half of its late 2010/early 2011 value (Tasker 2014). This puts pressure on operational efficiency as coal miners endeavour to reduce their cost per tonne. As a result, New Hope has been reviewing procedures and practices with the aim of identifying potential savings and efficiency improvements.

An example of this work was a very general investigation into haul road design and equipment operation practices, conducted by a New Hope vacation student over the summer of 2013/2014. This research indicated that there might be opportunities to optimise off-highway truck fuel consumption through control of mine design or equipment operation factors, particularly with respect to ramp design. As diesel is a key consumable across its operations, the company would like to take the research further by investigating and quantifying the effects of controlling specific factors within these areas.

While general research into the fuel consumption of various mining equipment has been published, the company would like to understand what actions should be taken to lower fuel consumption with regard to their specific set of circumstances and environmental conditions. It was anticipated that developing a student project to address these issues would identify optimisation opportunities. Ideally the project findings will be used to improve haul road design and equipment operation practices, resulting in lower fuel costs.

### **1.3 Objectives and Benefits**

- Research mine design and operational factors that impact the fuel consumption of Caterpillar 785D off-highway trucks as they are used by the company at the study site.
- Design a data collection programme to record fuel consumption rates, vehicle operating data and environmental conditions as appropriate.
- Analyse and compare variations in fuel consumption and the factors contributing to these variations.
- Quantify fuel consumption in different haul road scenarios.

Expected benefits include:

- Reducing fuel usage represents a significant economic benefit for the company.
- This study could form the basis for further optimisation of fuel consumption in different vehicles in different environments.
- An increase in fuel economy also provides an environmental benefit through decreased diesel consumption and emissions.

## **1.4 Consequential Effects**

Care was taken during the research planning phase to identify and manage the following consequential effects:

### **1.4.1 Health and Safety**

This research involves the modification of a truck through the installation of fuel meters. This will affect people who work with this vehicle including operators, diesel fitters and other tradespeople. In order to minimise the potential for negative impacts, this work was carried out in accordance with the company's "Change Management" Policy. As a result, all changes were reviewed by multiple qualified people before works were undertaken. Work was carried out by qualified tradespeople and all changes were communicated to affected personnel.

### **1.4.2 Environmental**

Experimental runs (if required) would contribute to site fuel consumption and potentially produce additional diesel, noise and dust emissions. This was considered before planning these activities and unnecessary truck use was kept to an absolute minimum.

### **1.4.3 Social**

This research would potentially examine driving characteristics, identifying driver behaviour that both positively and negatively affects fuel consumption. While collecting data and reporting on these findings, it would be counterproductive to make operators feel their behaviour is being unfairly scrutinised.

For this reason, all data collected was anonymous and was not linked back to any individual operators. Where driver behaviour was examined, it was the specific behaviours that were investigated and critiqued, rather than the person driving.

Any findings from this project that impact truck operators will need to be communicated effectively and, if necessary, appropriate guidance and training will be provided to educate drivers on optimal driving technique.

## Chapter 2

# Background Information

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### 2.1 Operational Context

The relationship between cost of production and profit is a key consideration for any business. As a producer of basic resources including metals and coal, the mining industry is subject to fluctuating commodity prices. This means minimising production costs per tonne is critical in order to maintain profitability should commodity prices fall.

The focus of this project is to optimise the fuel consumption of off-highway trucks by identifying the effect of road design on fuel consumption. The specific environment being considered is a small open cut coal mining operation in Queensland, Australia.

Within an open cut mine, the product is regularly transported from the point of extraction to stockpiles or processing plants using off-highway haul trucks. These trucks are also used to transport overburden and interburden (waste rock) to dumps within the mine. At the study site trucks are generally loaded by excavators or wheel loaders. The haulage cycle is illustrated in Figure 1 below. Diesel is a key cost associated with operating haul trucks and one that is subject to market fluctuations. Given the number of trucks, the 24 hour 365 day per year nature of mining and the cost of diesel, any reduction in fuel consumption can result in significant operational cost savings over the mine's life.

Off-highway trucks are highly instrumented, allowing fuel consumption to be compared to other operating conditions and more broadly to environmental conditions. Many of these variables can be controlled by vehicle operators or



appropriate mine design. Identification and control of applicable variables will reduce diesel usage, thus reducing the overall cost of production.

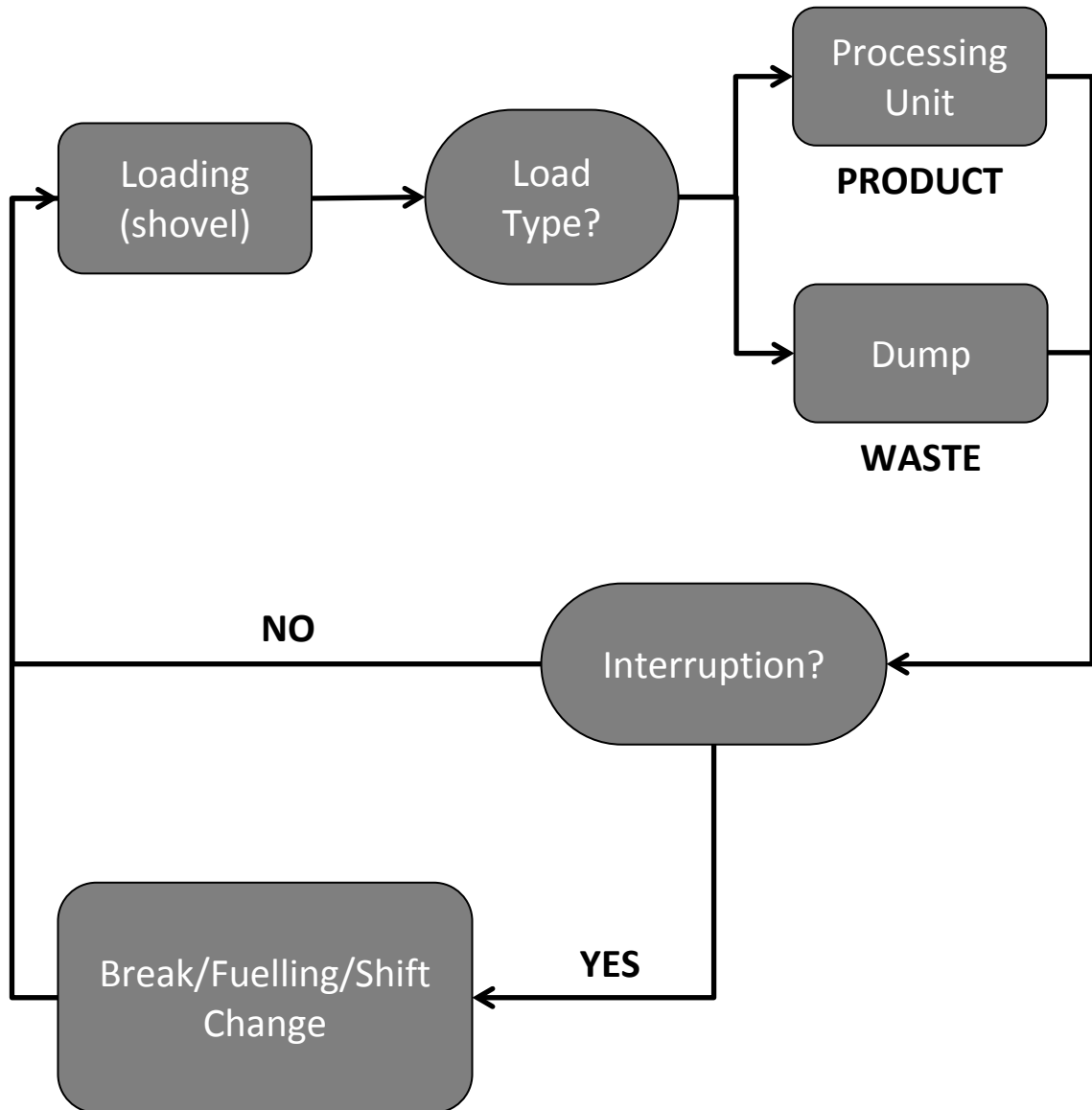


Figure 1: Haulage Cycle (Stahl, Donmez & Jamieson 2011)

### 2.1.1 Haul Roads at the study site

Haul roads at the study site can change regularly to suit production requirements. It is a relatively small site featuring several pits with very steep profiles. New roads are often needed to access hard to reach areas and switchbacks are often required to gain height in restricted areas. Commercial concerns can also play a role as

particular grades of coal are sometimes called for, prompting a change to the mining schedule. This in turn requires roads to be quickly built to allow access to the required coal in different sections of the mine.

At the same time, there are several well-established roads leading to frequently accessed areas such as the wash plant, frequently used dumps, mobile plant workshop and in-pit break area. These may remain in use for extended periods of several months or years. Short term roads may be used for as little as a few days and need to join onto the main roads to access mine infrastructure.

In these situations, mining engineers may be faced with a number of options for road placement and will consider many factors including safety, time and cost of construction, the shortest route to the intended destination and the mining schedule. The mining engineers at the study site aim to limit ramp grades to 10% with 8% considered preferable, however this is not always practical and steeper grades can be found.



Figure 2: Grader conducting road maintenance (Caterpillar 2015)

Crushed waste rock and clay (both from site) are used for road construction. The roads are regularly maintained with graders (Figure 2) and water trucks working to condition the road throughout each shift. This prevents the roads breaking up and reduces dust.

Figure 3 below shows an example of some mine haul roads. Trucks may take different routes depending on whether they are hauling coal or waste rock. The upper section is likely to remain unchanged for some time, while the lower sections may be changed as mining progresses across a block. Figure 4 shows a system of ramps leading from a shovel to other areas within the mine. Open cut pits can dramatically vary in depth in different areas over time.



Figure 3: Haul Roads in an Open Cut Coal Mine (Kubler 2015)



Figure 4: Another Open Cut Coal Mine (*Coal mines in Australia* n.d.)

## 2.2 Literature Review

A literature review was conducted to find information on the following:

- General description of the trucks to be investigated
- Off-highway truck operation and fuel consumption
- Condition monitoring possibilities
- Analysis methods that could be used to find optimal operation and design guidelines

### 2.2.1 General Description of Caterpillar 785D Off-highway truck

The vehicle in question is a 785D off-highway truck manufactured by Caterpillar (often abbreviated to Cat). These vehicles are classed as ‘off-highway trucks’ to distinguish them from the types of truck used on public roads. Off-highway trucks are suitable for use in demanding off-road environments and are commonly found in the mining, forestry and construction industries (HastingsDeering n.d.). The truck is pictured below in Figure 5.



Figure 5 Caterpillar 785D Truck (Caterpillar n.d.)

The 785D uses a 12-cylinder Cat 3512C HD engine with a six-speed planetary transmission. It makes use of a lock up torque converter which acts as a fluid coupling at low speeds when in first gear before engaging direct drive first gear at approximately 8 km/h. (Caterpillar n.d.)

According to Caterpillar (n.d.), this vehicle has a mass of approximately 116.5 metric tonnes when empty. The payload capacity is 143 metric tonnes. New Hope aims for a payload of approximately 136 metric tonnes. Net power output of 1005 kW is measured at the flywheel at the rated speed of 1750 rpm.

Due to Australian standards, regulations and commercial needs, these trucks have been slightly modified from the standard models sold in the United States. New Hope and the local Caterpillar dealer have modified or changed out some accessories to suit specific site requirements. Any difference in mass between the Australian and United States models would be negligible when compared to mass variation due to payload and fuel fluctuation. In addition, all aftermarket

accessories have been selected to conform with Caterpillar’s recommended target gross machine mass.

### 2.2.2 Manufacturer’s Performance Specifications

The *Caterpillar Performance Handbook* (2013, p. 24-22) specifies the following hourly fuel consumption rates for the 785D:

Table 1: Caterpillar 785D Hourly Fuel Consumption Rates (*Caterpillar Performance Handbook* 2013)

<b>Application*</b>	<b>Low</b>	<b>Medium</b>	<b>High</b>
<b>Engine Load Factor</b>	20%-30%	30%-40%	40%-50%
<b>Fuel Consumption (L/hour)</b>	54.2-81.4	81.4-108.5	108.5-135.6

\*Applications are defined as follows:

- Low - Continuous operation at an average gross weight less than recommended. Excellent haul roads. No overloading, low load factor.
- Medium - Continuous operation at an average gross weight approaching recommended. Minimal overloading, good haul roads, moderate load factor.
- High - Continuous operation at or above maximum recommended gross weight. Overloading, poor haul roads, high load factor.

The *Caterpillar Performance Handbook* (2013, p. 9-62) also specifies operating speeds at various grades via the Rimpull-Speed-Gradeability chart (Figure 6) shown below. This chart is primarily used by mining engineers to find travel speeds on various grades. The speed is then used to determine travel time on the ramp, total cycle times and so on.

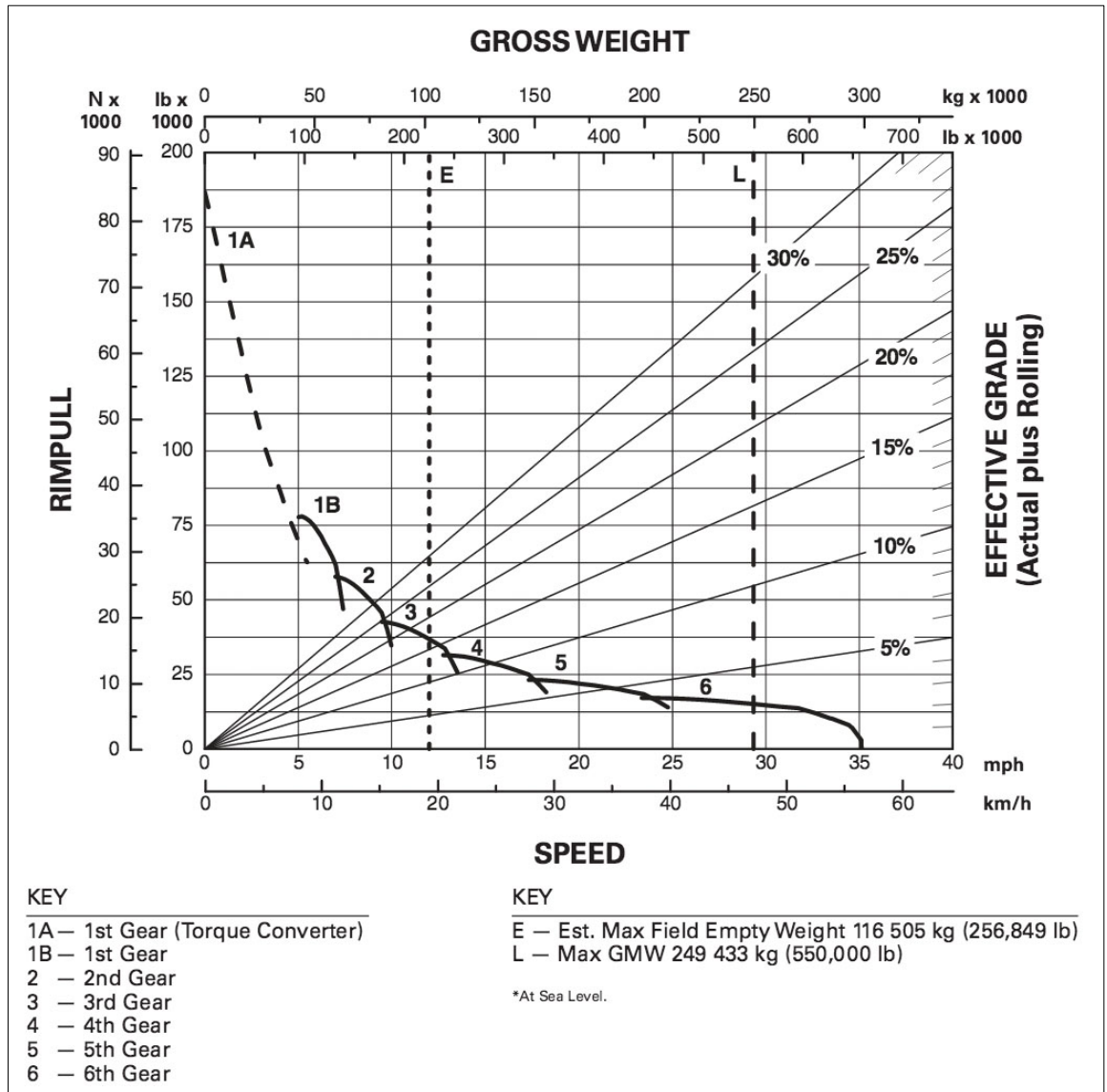


Figure 6: Rimpull-Speed-Gradeability Chart (*Caterpillar Performance Handbook* 2013, p. 9-62)

The handbook explains that the chart should be read by identifying the Maximum Gross Machine Weight (GMV) then reading vertically down the chart until this line intersects the desired effective grade line. From here, read to the left horizontally until intersecting a curve corresponding to the optimal gear for that scenario. Finally, read vertically down from this point to find the expected speed.

To determine the speed on a ramp of known grade, first the 'effective grade' must be determined. This is defined as follows:

$$\text{Effective Grade \%} = \text{Rolling Resistance \%} + \text{Grade \%}$$

Page 29-1 of the Caterpillar Performance Handbook (2013) provides typical rolling resistance percentages for various surfaces. A 'firm, smooth, rolling roadway with dirt or light surfacing, flexing slightly under load or undulating, maintained fairly regularly, watered' is specified as having a 3.0% rolling resistance. This assumes good tyre maintenance practices.

Using the specified (GMV) of 249 433 kg, the following Grade-Speed combinations for a loaded truck can be read from the chart:

Table 2: Caterpillar 785D Expected Grade-Speed Combinations

<b>Grade %</b> (Effective Grade % - Rolling Resistance 3.0%)	<b>Expected Speed</b> (km/h)	<b>Recommended Gear</b>
27	2.5	1 <sup>st</sup> (Torque Converter)
22	4	1 <sup>st</sup> (Torque Converter)
17	5	1 <sup>st</sup> (Torque Converter)
12	8	1 <sup>st</sup>
7	14	2 <sup>nd</sup>
2	22	4 <sup>th</sup>

### 2.2.3 Off-highway truck operation and fuel consumption

Historically, haul truck operation has been a major contributor to operating costs in a typical Australian open cut mine (Ghojel 1993). Fuel consumption is a key aspect of these costs and reducing fuel usage will result in significant savings for mine operators. In order to maximise the fuel efficiency of off-highway trucks, it is first necessary to understand the factors that influence consumption.



Sahoo, Bandyopadhyay and Banerjee (2014) investigated and modelled the fuel consumption of off-highway trucks in open cut coal mines. This was then compared to data from the field. Their work summarises previous research conducted in this area and brings together several general mine design and equipment operational factors that influence fuel economy.

At the mine level, these included truck allocation, mine layout, time spent travelling to and waiting at dump or loading point, and loading/unloading practices. These variables are further influenced by other mining equipment, for example crusher and excavator capacities. At the vehicle level, they also examined speed, payload, front area of truck and its drag coefficient, engine power and engine speed. This paper provided a good starting point and further research verified the importance of these factors in controlling fuel consumption.

Another paper that gave a good introduction to this topic was Ghojel's 1993 conference paper detailing a computer model he created to explore the impact of various variables on fuel consumption. The input data used in the model reflects many of the above findings, and through simulation he was able to obtain a theoretical fuel consumption reduction of 23%. Variables considered include:

- Vehicle mass
- Payload mass
- Aerodynamic drag
- Lengths and grades of haul roads
- Engine accessory load
- Cooling fan load
- Rolling resistance
- Engine operating speeds
- Driving speeds, acceleration and deceleration

Fu and Bortolin (2014) investigated the effect of gear shift sequence and timing on fuel consumption by off-highway trucks as used in the construction industry. They

found that optimising these factors in conditions where variable road grades exist can increase fuel efficiency. A similar link between gear selection and fuel economy was also found by Ahmed et al. (2012) who used a statistical analysis to determine optimal gear selection and shifting behaviour under different vehicle loading scenarios. Rylander, Axelsson and Wallin (2014) and Parreira and Meech (2011) also suggest that optimal gear selection should be used to control fuel consumption.

The influence of gear selection is a result of engine speed. Driving at the most efficient engine RPM for each gear can be used to increase fuel economy. Parreira and Meech (2011) give detailed explanations showing how the optimum engine speed will in turn determine the optimum ground speed for that gear. This is supported by Rylander, Axelsson and Wallin (2014) who also stress the importance of finding vehicle specific optimal driving speed. Both papers suggest this could be used to better train equipment operators and draw a link between driver skill and fuel consumption. It logically follows that acceleration and deceleration behaviour play a part in fuel burn. Chang and Morlok (2005) investigated land transport more generally and, as expected they found that travelling at a constant speed is preferable in regards to fuel economy.

Motlogelwa and Minnitt (2013) looked at vehicle mass and payload influence in further detail. Their study was conducted in a South African iron ore mine and reviewed the fuel consumption under different payloads to identify an optimum tonnage. Carmichael, Bartlett and Kaboli (2014) also demonstrated that payloads influence fuel consumption. They used field data to verify and refine their model, allowing them to find optimum payloads for different vehicles. This is further supported by Rylander, Axelsson and Wallin (2014).

Steepness and length of roads are regularly identified in the literature as contributing to increased fuel burn, with other sources including Fu and Bortolin (2014), Carmichael, Bartlett and Kaboli (2014), Pontt et al. (2010) and Rylander, Axelsson and Wallin (2014) providing support for the conclusions of Sahoo et al.

and Ghojel. Writing about equipment management in a mining context, Tomlison (2009) further explains the impact of haul road design of fuel economy. As the open cut operation moves deeper into the pit, haul roads will need to become steeper or significantly longer. Both of these changes will lead to increased fuel usage.

Queuing is another mine design factor that was repeatedly identified in the literature (Motlogelwa & Minnitt 2013; Sahoo, Bandyopadhyay & Banerjee 2014). Time spent idling while queuing at dumps and loaders is very costly in terms of fuel consumption. Ideally this would be eliminated, but there may be limiting factors such as the number of shovels or entrances to stockpiles so in those cases it may prove more cost effective to turn off engines while waiting.

Many of the factors that influence fuel consumption are not possible or very difficult to control. These mainly include environmental factors such as air density, wind speed, temperature, humidity, topography of the mining lease and characteristics of the product/waste being hauled (Ghojel 1993; Sahoo, Bandyopadhyay & Banerjee 2014). Although these factors cannot be controlled, it is important to be aware of their influence on fuel consumption when analysing the data. It should also be noted that any fuel consumption quantities found at the study site will not necessarily be applicable at other mine sites due to environmental variation.

To summarise, the major variables influencing fuel consumption are categorised in Figure 7.

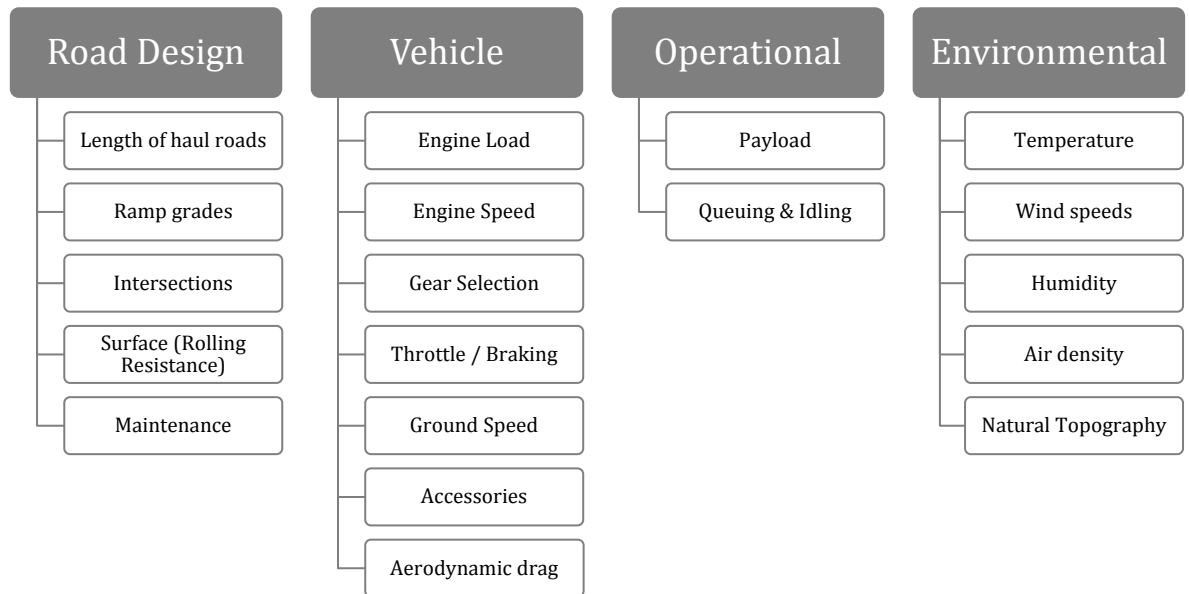


Figure 7: Summary of Variables

As this study is focussing on one particular site, some of these variables can be eliminated as they are either not relevant or can be expected to remain constant for the duration of the research. For example, the length of haul roads is limited by site infrastructure and the site is relatively small, so there are not many opportunities to shorten haul distances. Road maintenance and surface condition can also be expected to remain relatively consistent as roads are regularly graded and watered throughout the day.

With respect to the vehicle, fuel consumption due to accessories and aerodynamic drag will be the same for all 785D trucks. This would apply to other vehicle-based variables not mentioned above, for example engine tuning and weight distribution.

Environmental variables are most difficult to control and measure in real time. Fortunately their influence is thought to be relatively minor compared to the other variables mentioned. Drastic changes in weather should not skew any results as the mine does not operate in inclement weather. This means rain and fog are not

an issue as mining operations do not resume until the roads are dry. Smaller variations in temperature, air density and humidity can be 'smoothed out' by collecting data across both night and day shifts for several days. Climactic data (1941 to 2015) from the study site's local weather observatory has been included in Figure 8 for reference.

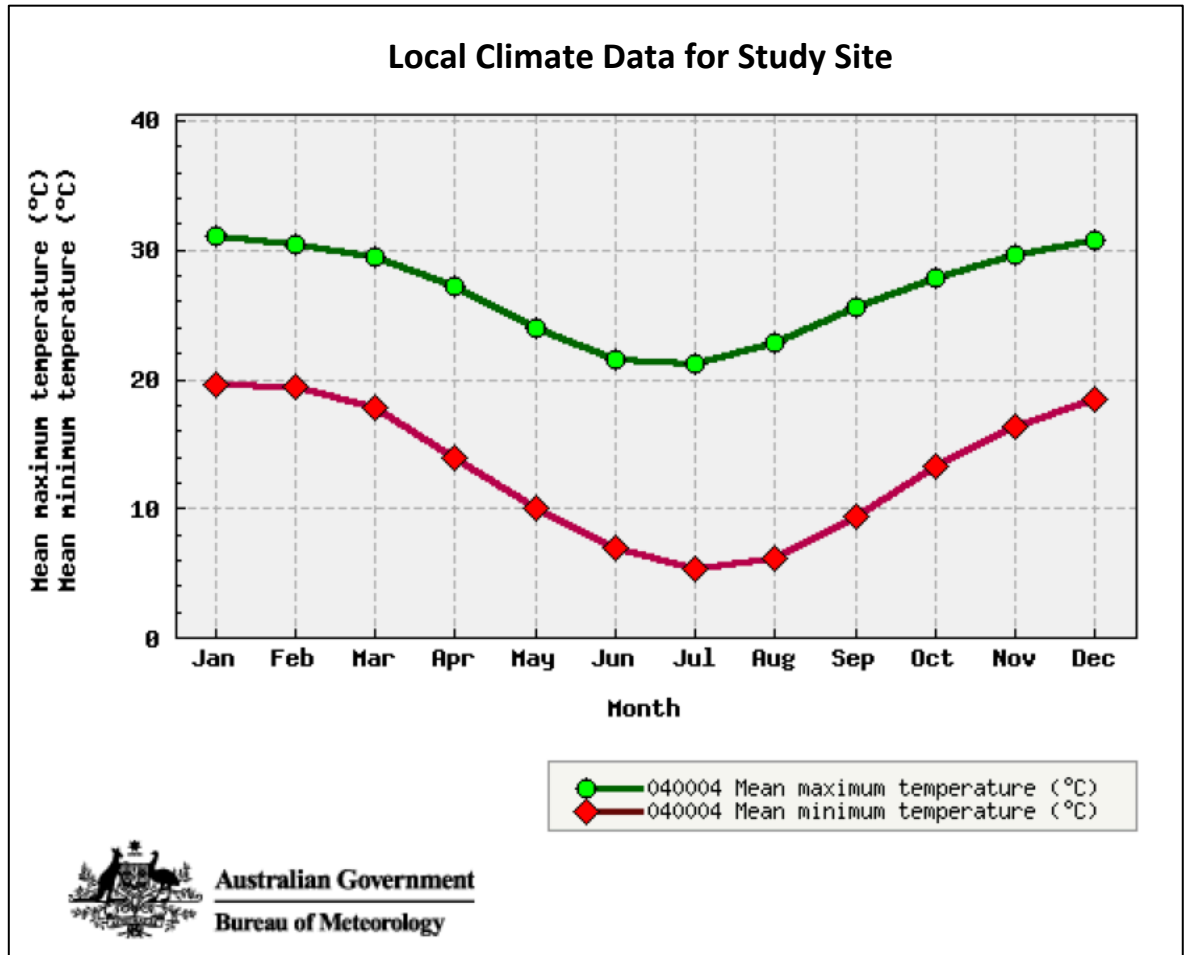


Figure 8: Climate Data from the Study Site's Local Observatory (*Graphical Climate Statistics - Amberley AMO 2015*)

#### **2.2.4 Fuel Costing and Cost Reduction Strategies in Mining**

According to Runge (1998, p. 112), mining operations calculate fuel costs with three inputs:

- The cost of fuel
- The vehicle's consumption rate
- Working conditions / intensity

The vehicle's consumption rate may be based on company records or obtained from the manufacturer (Caterpillar's specifications for the 785D are included in Section 2.2.2). Working conditions and intensity are defined by 'load factors', which are also obtained from the manufacturer or textbooks (Runge 1998, p. 112). Engineers at the study site use this general approach described by Runge.

Mining operations aim to use the shortest haul route possible. This is primarily aimed at increasing production, but also reduces fuel consumption by off-highway trucks. Choi and Nieto (2011) explain the use of specialised algorithms and geographic information systems (GIS) to automatically identify optimal haul routes within large construction and mining operations. They have built a model that allows operations to use either fuel consumption rates (fuel volume per unit length at three different intensities) or time per trip to evaluate routing options, depending on management requirements. Similar systems are in use at mining operations around the world. These models require detailed and frequent aerial photography, which may be cost prohibitive for many operations.

Fuel economy can also be improved through vehicle modification. Global mining companies including BHP Billiton and Rio Tinto have implemented driverless trucks at some of their operations. While a reduction in fuel consumption is not the primary motivation for using autonomous vehicles, their use can reduce consumption by 10 to 15 percent. Notwithstanding the advantages of this technology, it has thus far been largely limited to the world's biggest miners and implementation requires continuing long-term investment. For example, Rio Tinto has been developing this technology since the mid 2000's and reportedly spent

AUD\$370 million on technology and innovation in 2013 alone (Bellamy & Pravica 2011; Spence 2014).

Other vehicle modifications include 'smart' cruise control systems (Hellström et al. 2009), improving aerodynamics (Wei, Wang & Feng 2008), battery powered accessories or even switching to hybrid or fully electric trucks (Koellner et al. 2004).

All of these options, while promising, require capital expenditure to implement. As a result, this project aims to improve and optimise existing practices in order to produce better outcomes with minimal up front expense.

### **2.2.5 Analysis methods**

Given the amount of data to be analysed, effective strategies must be employed to deal with this volume. Automated computer analysis should be used wherever possible, but there are also certain scenarios that will require more manual analysis. The literature review has provided some starting points for dealing with this large amount of data and using it to optimise fuel consumption.

A common theme found throughout the papers using real world data for optimisation was the grouping of 'like' scenarios to allow comparison. In effect this amounts to controlling certain variables in order to determine the influence of others. In the context of this project, this could involve isolating trips along a certain section of road of a consistent grade, then examining variations in fuel consumption depending on other variables, for example engine speeds. Results can then be compared against those from other ramp grades, hopefully leading to the identification of fuel consumption rates for different grades.

The examples found in the literature review also showed how condition monitoring parameters can be used to identify environmental or mine design issues, for example, looking at the frequency of idling and matching this to position data can be used to find and possibly eliminate haul road bottlenecks. GPS data can

also be used to find the steepness and length of roads (Ribeiro, Rodrigues & Aguiar 2013).

Another aspect to be considered is the impact of weather and climate effects when comparing data across time periods. Depending on the time span of the data considered (days versus months versus years) it might be necessary to control for differences due to time of day or seasonal variation. For the purposes of this study, obtaining as much data as possible across a wide time period would be ideal as this would result in an 'all purpose' model that can be used to estimate fuel costs year round.

Once the influence of the major variables has been determined, this information can be used to identify improvement opportunities in terms of design or operational controls. Field testing of these controls and review of data produced can be used to validate the analysis. If successful, this data can be used to inform mine design and vehicle operation guidelines in order to reduce fuel used across site. It can also be used to conduct cost-benefit analyses to understand the commercial impact of haul road design decisions.



## Chapter 3

# Data Availability, Equipment and Collection

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As outlined above, there are many variables influencing fuel consumption. It is clear from the literature review that increased fuel consumption occurs where steep ramp grades, stop-start operation and queuing exist. As these conditions are known to exist at the study site, this research focussed on those key aspects of road design. The goal of the analysis is to quantify fuel consumption in these scenarios so mining engineers are better able to estimate the fuel costs associated with newly designed haul roads before construction begins.

Other variables that must be examined include payload mass, engine speed, engine load, ground speed, gear selection and throttle position.

Extensive condition monitoring is conducted on modern mining equipment including off-highway trucks. In particular, real time condition monitoring sensors and electronic control modules are included as standard on Caterpillar 785D trucks. Condition monitoring data has already been successfully collected and analysed to optimise equipment performance for site-specific conditions and requirements across the mining, forestry and agricultural industries, so this research builds upon these precedents.

Based on the study site's off-highway truck fleet and available resources, three data sources were identified that would allow the relevant variables to be monitored. These sources are Caterpillar VIMS (on board condition monitoring system), SAFEmine Collision Avoidance System, and Kral fuel flow meters. These systems will be described in greater detail below. The variables selected for monitoring were informed by the Literature Review and equipment capability. These are summarised in Figure 9.

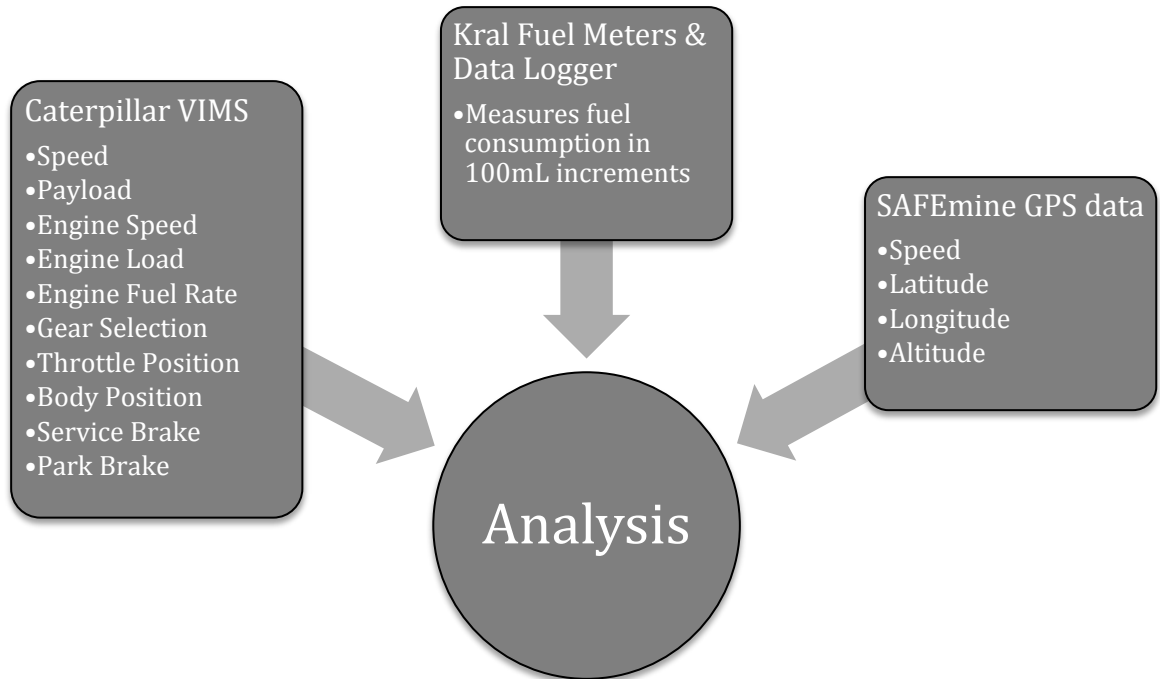


Figure 9: Data Sources and their Variables

As mentioned, there are many factors that influence fuel consumption but are difficult or impossible to measure during this study. These mainly include weather and climate conditions identified in the literature review including air density, wind speed, temperature and humidity. Fuel consumption may also be influenced by characteristics of the road surface via rolling resistance. These variables were not considered as the effect on individual vehicles (of the same model) will be identical. Due to the slippery conditions caused by moisture, the mine does not operate in inclement weather. As a result, all data collected is from driving in dry conditions.

Using this data along with analysis techniques based on those identified in the literature review allows the quantification of fuel consumption rates, future trials in real world conditions, evaluation of the commercial value of any changes and validation of design and vehicle operation guidelines.

### **3.1.1 Caterpillar ‘Vital Information Management System’ Condition Monitoring**

The vehicle investigated is outfitted with condition monitoring equipment as standard. The Caterpillar Vital Information Management System (VIMS) makes vehicle data available for download both manually at the vehicle and wirelessly.

VIMS has several features but this study will only use the so called ‘Data Logger’ feature. The particular set up at the study site means that data is logged until the vehicle’s data storage capacity is reached and is then transferred wirelessly to the Caterpillar dealership. This equates to approximately 30 minutes worth of data. Once the data has been successfully transferred, the data logger is reset and the collection process repeats indefinitely. Occasionally, the data transfer connection may be lost or does not work as it should. This can result in periods where data is not collected. Collection is also affected by extended periods of inactivity that cause the data logger to switch off. This results in data loss when trucks return from meal breaks, it may take up to half an hour of activity before the data logger is reactivated.

VIMS monitors over 30 conditions using sensors and electronic control modules. The monitoring is done in real time and conditions include gear selection, fuel level, ground speed, fluid pressures and temperatures, component loading, park/service brake use and payload. When combined with positioning data, VIMS data can be used to understand the influence of the road design variables on fuel consumption.

This ability to access this comprehensive data greatly aids in analysis as data can be collected across a range of time periods. This is helpful as haul road routes and characteristics change over time, so a greater range of road features will be compared.

### **3.1.2 Global Positioning Data from SAFEmine Anti-Collision System**

All vehicles at the study site are equipped with the SAFEmine collision avoidance system. The system consists of a Global Positioning System (GPS) unit and a user

interface (pictured below) fitted to each vehicle. The GPS unit collects latitude, longitude, altitude, speed, heading angle and vibration data. The system uses various algorithms to identify where vehicles are on a collision path, following too closely or speeding. (*Our Products - SAFEmine CAS* n.d.; *SAFEmine Company Brochure* n.d.)



Figure 10: SAFEmine user interface shown in in vehicle cabin (*Our Products - SAFEmine CAS* n.d.)

The user interface (shown above in Figure 10) is mounted in the vehicle cabin and uses alarms and flashing lights to alert the driver to potential collision risks. GPS data can be downloaded through this unit. The unit's storage capacity accomodates approximately four days of data. A single data file generally contains 10 – 12 hours of data but shorter and longer time spans have also been found.

Proprietary SAFEmine software can be used to export the data to Microsoft Excel and Google Earth formats. The Google Earth file can be used to review the location

data against satellite imagery of the mine site, giving a quick visual understanding of the truck's haul route.

The sampling frequency is approximately one second, however if the truck does not move for an extended period, the sampling frequency will change to 60 seconds until the truck starts moving again.

### **3.1.3 Fuel Consumption Data from Kral Volumeters via Hobo Data Logger**

Kral OME series volumeters have been fitted to one Caterpillar 785D truck to collect fuel consumption data for the duration of this research project. Two volumeters are fitted, one measuring fuel flow out of the fuel tank, and one fitted to the return fuel line. These sensor outputs go to a BEM 500 Electronic Unit where a precise volume measurement is calculated. Temperature is measured and this data is incorporated into the calculation if the medium properties are entered during calibration. Kral states the volumeters are accurate up to 0.1%. (*KraL Volumeter®. Flowmeter Overview. 2011; KRAL Flowmeters Series OME Compact n.d.*)

A schematic of the volumeter is shown below in Figure 11. The Volumeter data is recorded using an Onset Hobo UX90-001 Data Logger connected to the Kral BEM 500 Electronic Unit. A pulse is recorded every time 100mL of fuel is consumed. More than 14 days worth of data can be stored and downloaded via USB from the truck cab.

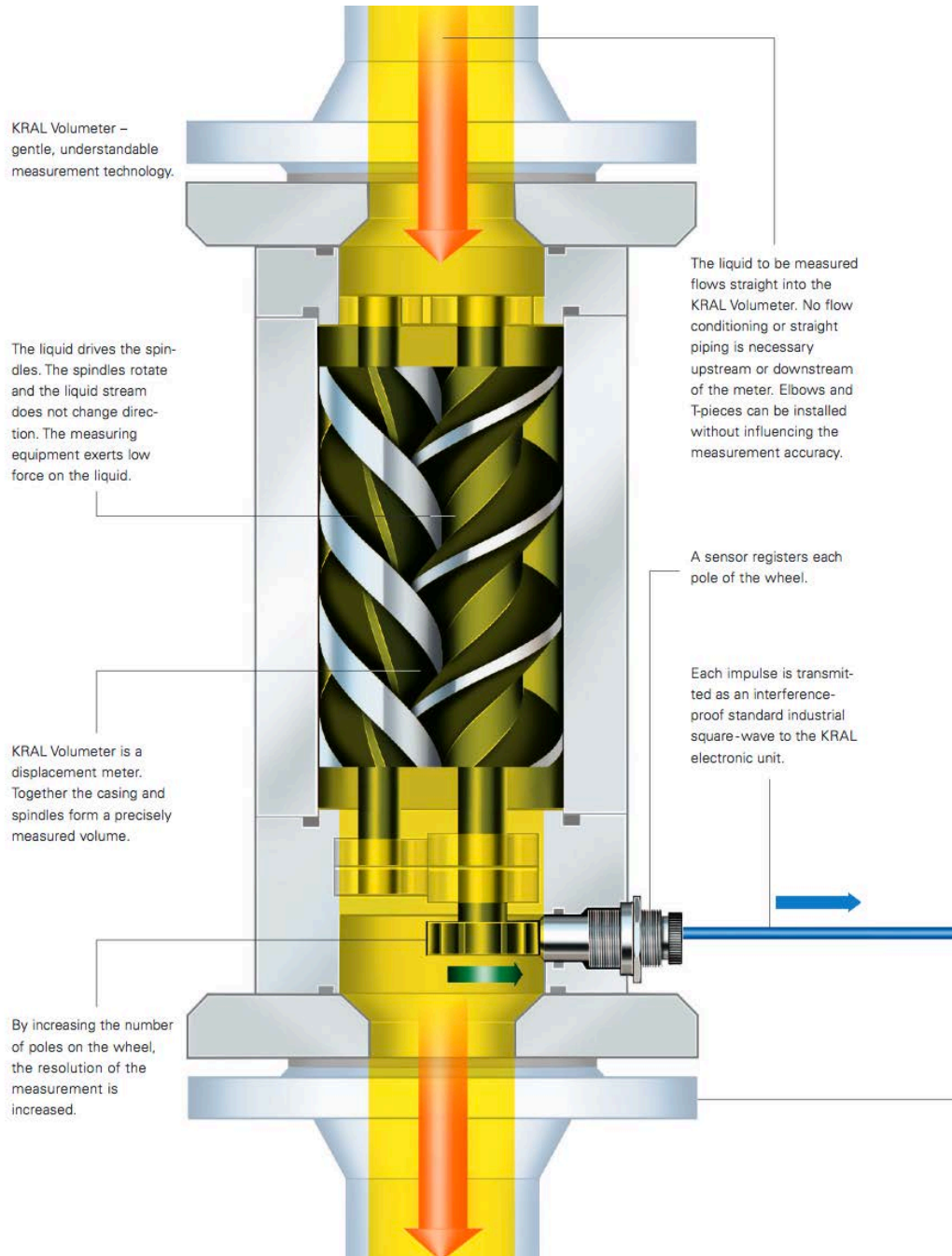


Figure 11: Volumeter Schematic (*Kral Volumeter®. Flowmeter Overview. 2011*)

## Chapter 4

# Methodology

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The methodology encompassed five main stages summarised below.

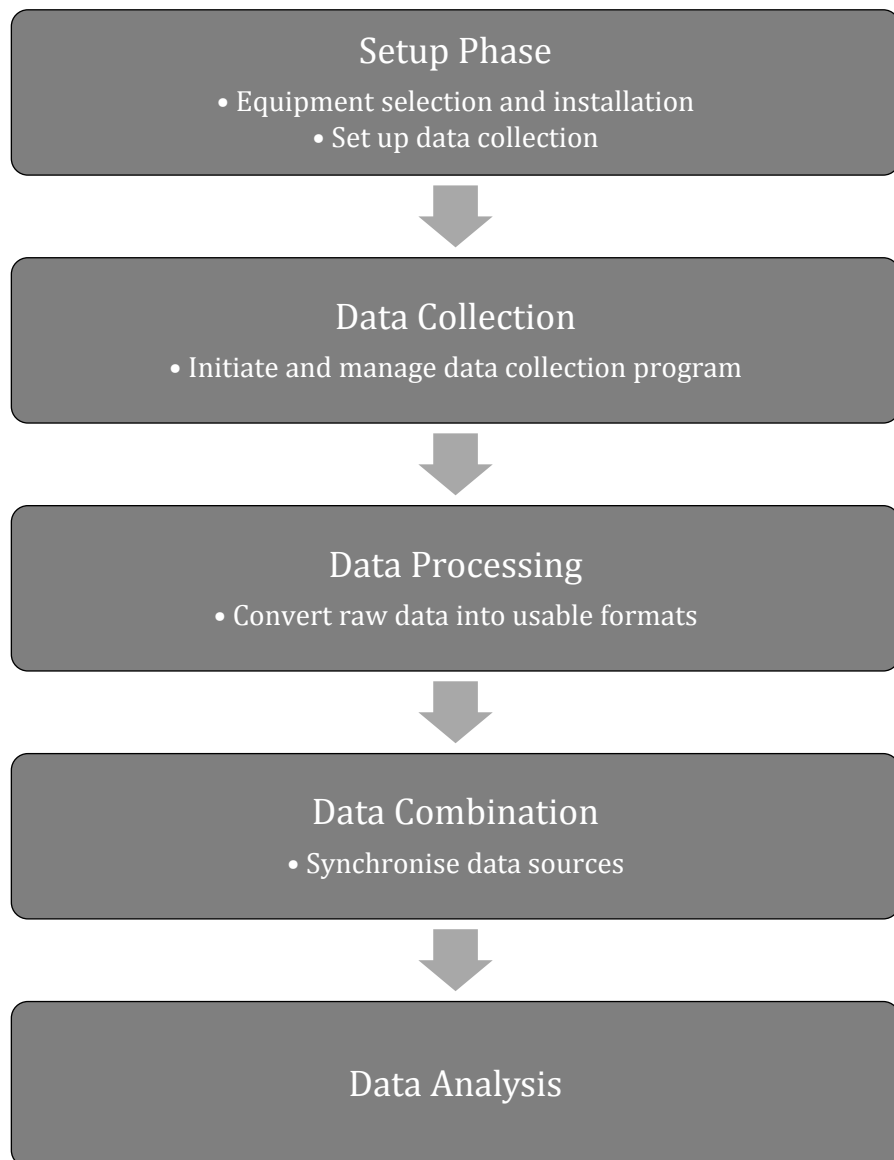


Figure 12: Methodology Phases

## **4.1 Setup Phase**

### **4.1.1 Vehicle Selection**

Only one Volumeter was available for this study and downloading data from multiple vehicles would be onerous for the study site. As a result, a single vehicle was chosen to be monitored for the duration of this study. The particular vehicle was selected as it was already set up with the highest level of round the clock condition monitoring through VIMS, with data automatically transferred to the local Caterpillar dealership. Additionally, it was manufactured and purchased at the same time as the company's other 785D trucks. Therefore, this truck provides a good starting point for this research as any findings are likely to be representative of the rest of the fleet. Where the research identifies any opportunities for fuel consumption improvement, it would be a straightforward process to repeat this methodology across the rest of the fleet.

### **4.1.2 Installation and Calibration of Volumeters, Electronic Unit and Data Logger**

The Kral Volumeters, Electronic Unit and Hobo Data Logger were installed on the selected vehicle in March 2015. Qualified technicians performed the installation and calibration. The Volumeters are located under the tray body at the fuel tank outlet and return inlet. The location of the fuel tank on a 785D truck is circled on Figure 13 below.





Figure 13: Location of Fuel Tank (Caterpillar n.d.)

The Volumeters are connected to the BEM 500 Electronic Unit which was secured in the cab behind the passenger seat. Once these components were connected the truck was turned on to test the installation. The fuel flow rate appeared on the BEM 500 display indicating the Volumeters were working correctly. The Hobo Data Logger was connected to the BEM 500 and began recording immediately. This system is illustrated below in Figure 14.

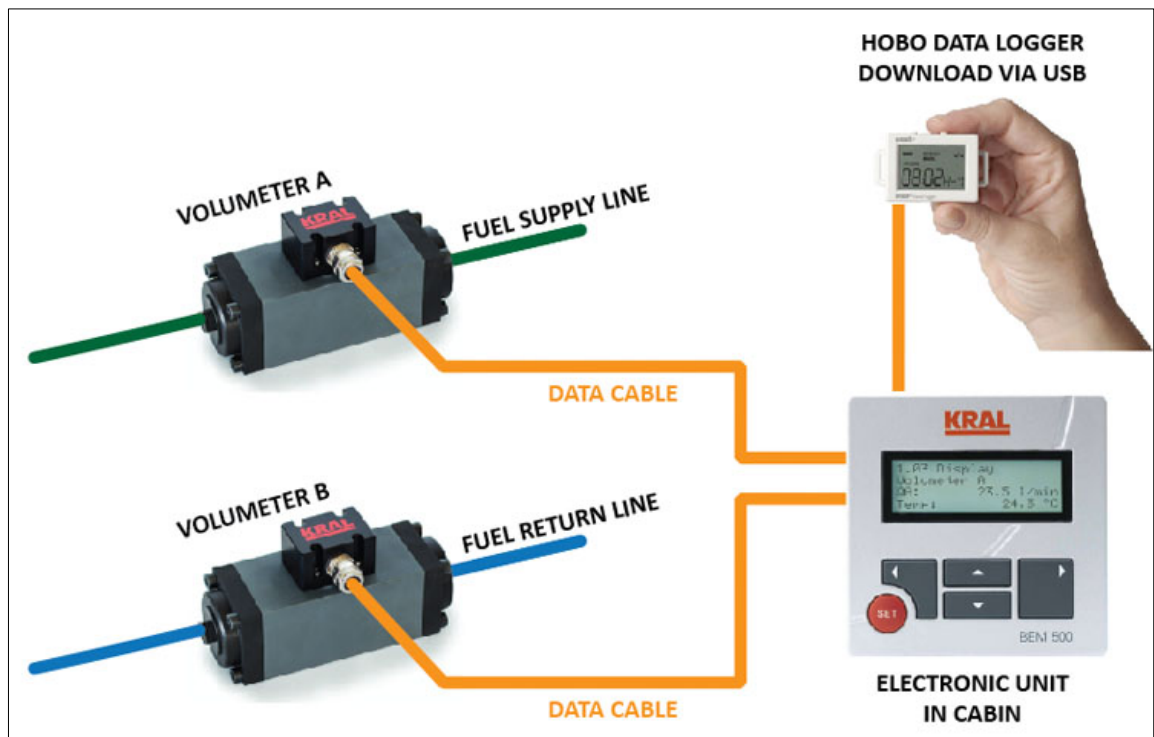


Figure 14: Volumeter, Electronic Unit and Data Logger Setup

Figure 15 shows the physical installation on the fuel tank when standing under the truck. Both the inlet and outlet meters can be seen. At this stage the cables connecting the meters to the cabin had not been installed.



Figure 15: Installation of Kral Volumeters to fuel tank of Caterpillar 785D truck (Kubler 2015)

The Electronic Unit and Hobo Data Logger were secured in the truck cabin for the duration of the study. Cables were run alongside other existing cables to connect to the Volumeters. They were securely fastened and protected to ensure continuous operation in harsh mining conditions. The system was calibrated to send a pulse to the data logger every time 100mL of fuel is consumed. The sampling frequency for the data logger is 2 seconds.

#### **4.2 Data Collection**

As VIMS and SAFEmine were already installed on the vehicle, the data collection phase could begin immediately after the Volumeters, Electronic Unit and Data Logger were installed.

As mentioned above, VIMS data is collected automatically. Product support representatives from the local Caterpillar dealership periodically sent the latest raw data via email.

The SAFEmine GPS data is downloaded using propriety software from the user interface unit in the truck cabin. This is then exported in Excel and Google Earth formats for processing.

The fuel consumption data is downloaded from the Hobo Data Logger in the vehicle cabin at the same time as the SAFEmine data. This is exported to a Comma Separated Values (csv) file for processing.

### **4.3 Data Processing**

#### **4.3.1 VIMS Data**

The local Caterpillar dealership periodically supplies the latest data in a proprietary format. This raw data must be 'merged' using a Caterpillar software package. 'VIMSpC 2009' was used for this study. Merged data can be viewed graphically using the VIMS software or exported in csv format. The variables that are being considered in this analysis are:

- Engine Fuel Burn – recorded in litres per hour
- Engine Speed – revolutions per minute
- Engine Load – percentage
- Gear Selection – current gear, the truck uses automatic transmission but the operator can lock the transmission into a lower gear when required
- Park Brake Status – on/off
- Service Brake Status – on/off
- Throttle Position – 0% closed to 100% fully open
- Payload – mass of load in tray, measured in tonnes
- Body Position – tray lowered/raised

Each export covers one data logging session of approximately 30 minutes as described in Section 3.1.1. Once all data has been exported for a particular date,

these were assembled in chronological order, with timestamps, into a single csv file.

#### **4.3.2 SAFEmine GPS Data**

As described in Section 3.1.2, the SAFEmine data is exported in Google Earth (kmz) and Microsoft Excel formats. This is reviewed in Google Earth to check the truck's path and the period of time covered by that file. In Google Earth, the file is resaved in kml format. This file format can be opened in Microsoft Excel or a text-editing package and reveals extra data not present in the Excel file exported using the SAFEmine software, namely altitude.

The data in the kml file consists of

- Time (UTC +00:00),
- Longitude (degrees),
- Latitude (degrees),
- Altitude (metres),
- Speed (kilometres per hour)
- Vibration (Hz)
- Number of Satellites.

A Matlab program was written to convert the data for analysis. This has been included in Appendix 1. Firstly, the GPS coordinates are converted from degrees to metres using a function built into Matlab for this purpose. Generally this function uses zero degrees latitude/longitude as an origin, but also allows a custom origin to be set. An arbitrary origin slightly outside the mining lease was chosen to reduce the size of the coordinates from many thousands of kilometres to a few thousand metres.

Linear interpolation was used to map the truck's path in the X, Y and Z directions to a new time scale with a constant time step of one second. The latitude, longitude and time data is mapped against the new time scale. The interpolated X, Y and Z coordinates are plotted in three dimensions along with the original coordinates to

give a visual comparison. Figure 16 shows an example of a three dimensional plot and Figure 17 shows the Altitude versus Time for this sample.

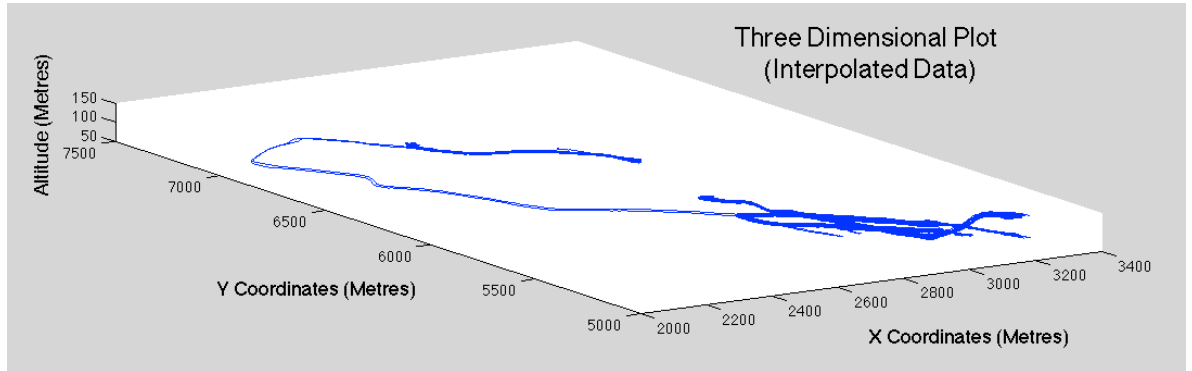


Figure 16: Three Dimensional Plot of Interpolated SAFEmine Data

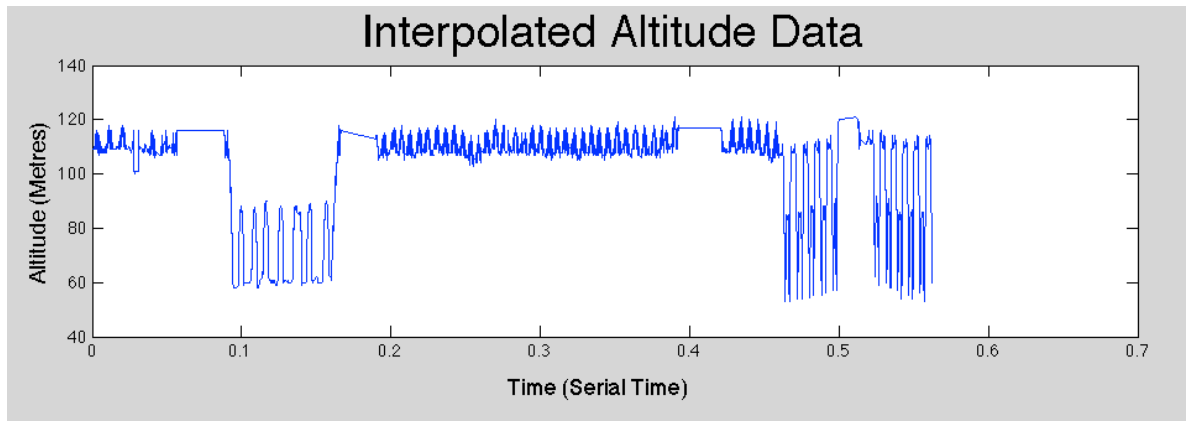


Figure 17: Altitude data obtained from SAFEmine

Figure 18(a) and (b) shows the same data (viewed in the XY plane) before and after interpolation. Performing this check ensures interpolation has been successful.

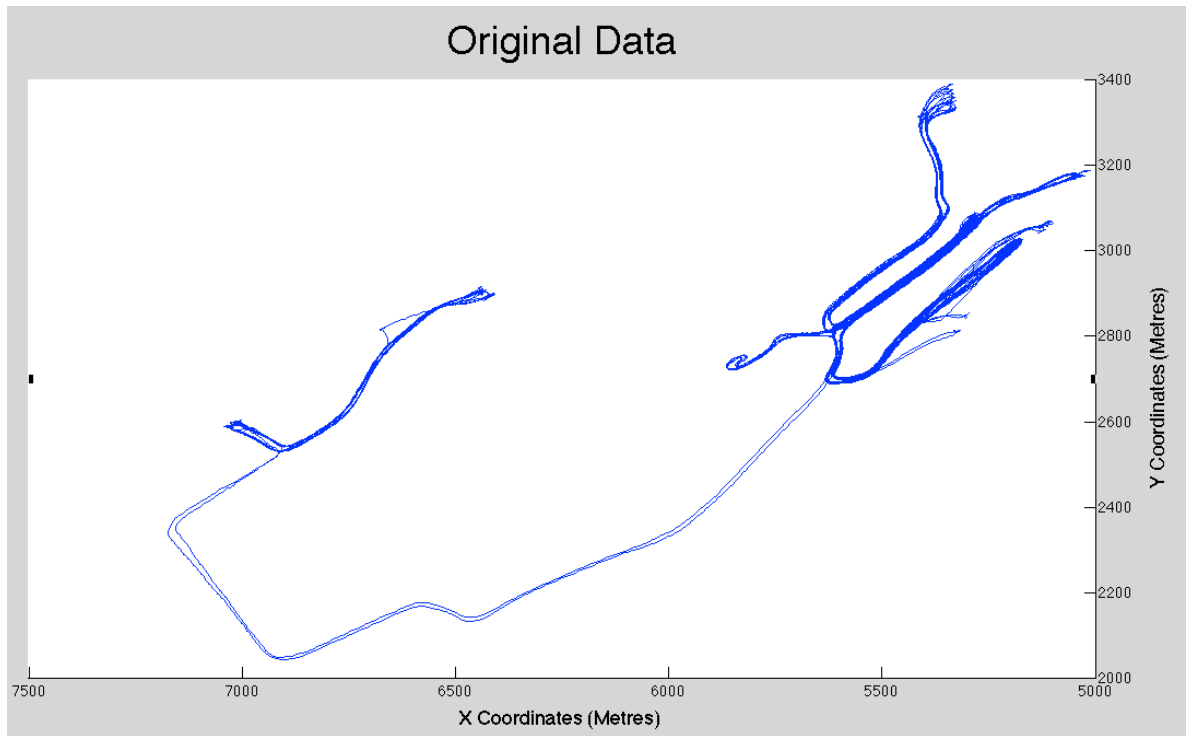
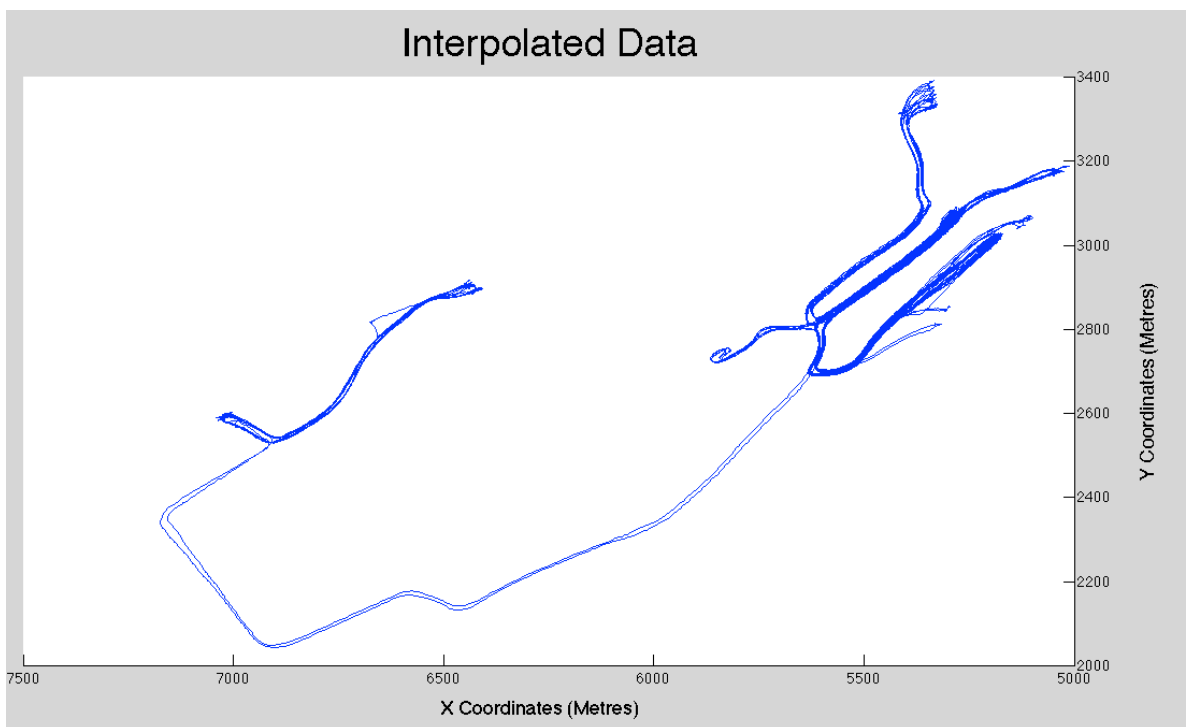


Figure 18: (a) GPS Data plot before interpolation



(b) GPS Data plot after interpolation

The interpolated plot is also compared to the Google Earth render to ensure the conversion and interpolation has been successful. This also gives an idea of the type of work that was being performed during the sample, for example, hauling coal from deep within the pit or transporting waste rock closer to the surface. Google Earth also provides an elevation profile that is compared to the altitude plot from Matlab and acts as another check to ensure the data has been converted correctly. An example from Google Earth corresponding to the plots above is illustrated below in Figure 19.



Figure 19: Screenshot from Google Earth showing a sample of SAFEMine data

It is clear that the paths are identical between the Matlab and Google Earth renders, however the Google Earth image is somewhat distorted suggesting a different aspect ratio. The 'ruler' function in Google Earth was used to confirm the distances match up. A screenshot is shown below in Figure 20. When the



measurement is compared to the Matlab scale the values correspond. The yellow line is the distance being measured.



Figure 20: Screenshot showing use of Google Earth's 'ruler' function to check scale matches Matlab plot

Matlab's 'findpeaks' function is then used to find the turning points in the Z coordinates. These indicate rough starting and finishing points for ramps. A new array is created to capture this information, troughs are marked with a 1 and peaks are marked with a 2. A separate array is created and tallies the cumulative horizontal distance travelled between each peak and trough by taking the difference between the X and Y coordinates at each step. This will be used in the slope analysis.

The data is exported in csv format. This consists of Time (UTC +00:00), X coordinate, Y coordinate, Z coordinate, Speed, Ramp Start/Finish and Cumulative horizontal distance. Since exported files are grouped according to the UTC +00:00 time they must be converted to Queensland time. The exported csv files are reviewed and new files are created with the data grouped into days according to local time.

This process is summarised in Figure 21.

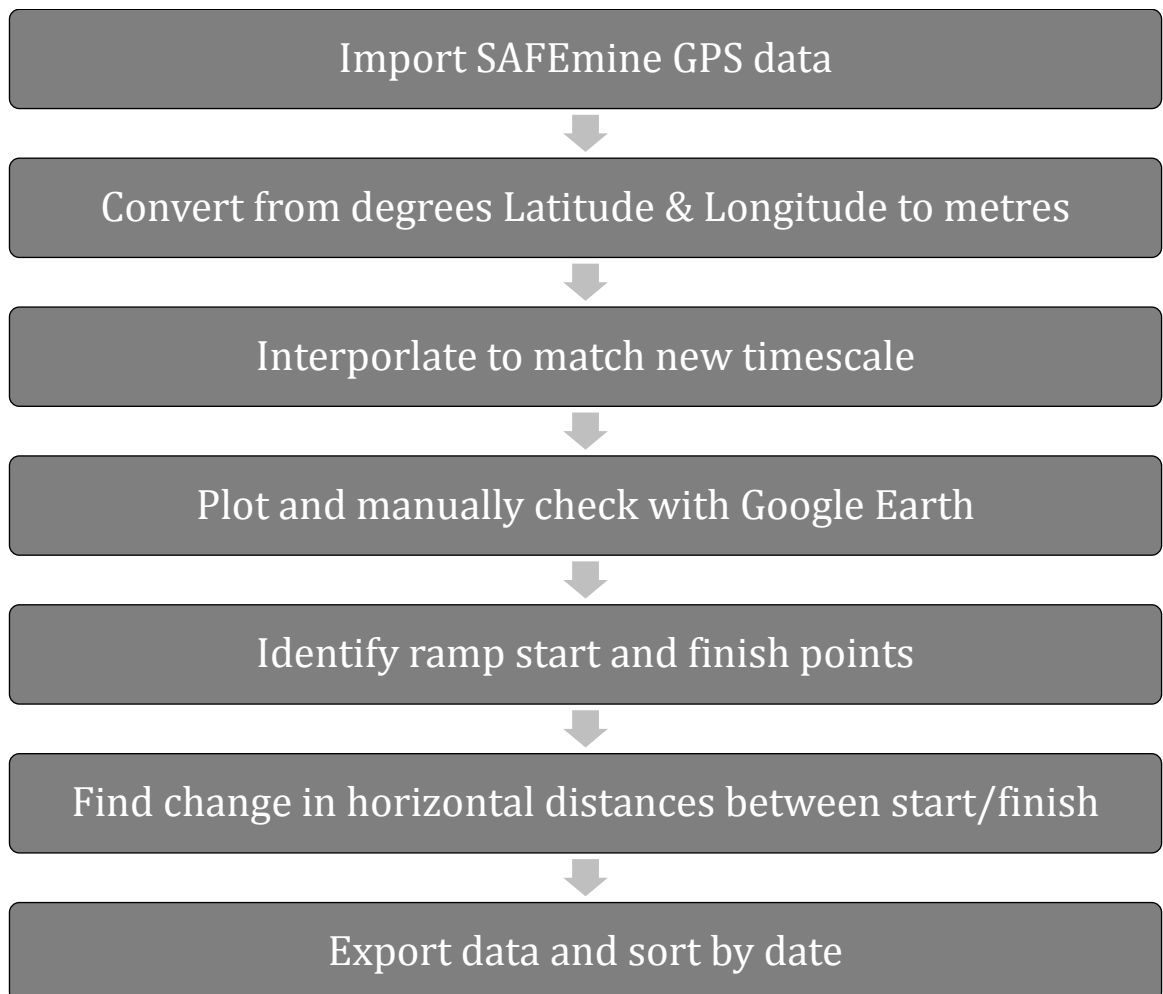


Figure 21: SAFEmine data conversion and processing

#### 4.3.3 Kral Volumeters and Hobo Data Logger

A Matlab script has been written to convert the 100mL pulses to mL/sec and L/hr fuel consumption rates at an interval of one second. The raw data from the exported csv file is read into Matlab. The program reads through the data and

deletes repeated zero entries where the time interval is less than three seconds (based on two second sampling frequency while the truck is moving). The remaining data points and corresponding time points are used to calculate the fuel consumption in mL/sec (fuel used / time elapsed).

A new time scale with one-second intervals is set up and the calculated values are inserted at the corresponding timestamps. The script then 'backfills' the calculated mL/sec values across the applicable time interval to create an array of fuel burn values that corresponds to the new one second time scale array. This is also converted to L/hr for easy comparison to the VIMS data. An example has been included below in Table 3 for clarity. The second row shows the imported values, the third row shows the converted values. Note the two-second sampling frequency for the 100 mL pulses.

Table 3: Example Fuel Consumption Conversion

<b>Seconds</b>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
<b>Pulse</b>		100		0		100		100		200		100		300
<b>mL/sec</b>	50	50	25	25	25	25	50	50	100	100	50	50	150	150

Although in reality the fuel consumption may not follow a linear distribution, this method was chosen to reduce the influence of the chosen start and finish points over the volume of fuel included in future calculations. For example, if measuring between 4 and 13 seconds using the data above, the pulse data would give 500 mL and the converted data would give 625 mL.

At the end of the script, a average fuel consumption rate in litres per hour is displayed as a check against any conversion errors or unusual results.

#### 4.4 Combining Data

As stated above, the sample frequency, duration, start/end times and time codes vary with each data source. The previous data processing stage converted all data to one-second time steps. With that task completed, a Matlab script was created to 'match up' the various time stamps from each source and export the data with

separate files created for each calendar day. This script can be found in Appendix A.

#### **4.4.1 Synchronising Time Stamps**

The first step in combining the data was to determine the discrepancy between time stamps from each source. This ensures the data from 09:30:01 as recorded by the Hobo Data Logger corresponds to 09:30:01 on the same day as recorded by VIMS and SAFEmine. It was decided use SAFEmine time as the global time for this research. This would make it easier to check truck performance and location against the Google Earth map as Google Earth displays the SAFEmine data and therefore time stamps.

There are several scheduled breaks for truck operators in a 24-hour period. The SAFEmine data was examined around this time and the exact second where the truck operator had parked for a 30-minute break was recorded. This precise point in time is easily identified using the velocity (0 km/h for over 30 minutes) and the physical location within the mine (a closed loop of road near a demountable lunch room).

Once this break time was identified, the VIMS data was examined around this time. By examining Park Brake Status, Ground Speed and Engine Fuel Rate, the exact parking time is easily found. It was determined that VIMS time is equal to SAFEmine time +00:10:15. Due to this large time difference, this was manually checked each time the synchronisation process is performed with new data.

Finally, the fuel consumption data is compared to the other two data sources. The 785D truck is equipped with a 'turbo timer' to keep the engine running for a length of time that allows the turbocharger to cool slowly rather than stopping suddenly. The fuel data shows a steep decline in fuel consumption once the truck stops moving, followed by a few minutes of very low fuel consumption while the turbo timer is activated. Finally, the fuel consumption ceases for the remainder of the operator's break. As an extra check, this was compared to the SAFEmine vibration

data. Low-level vibration corresponded to the turbo timer operation and then ceased when the engine stopped running. It was determined that the fuel data time corresponds to SAFEmine time +00:00:06.

#### **4.4.2 Export of Combined Data**

Once the time stamps are adjusted appropriately, the Matlab script creates a global time array from 00:00:01 to 00:00:00. This equates to 86400 time steps per day (one for each second). The script then creates new arrays for all variables to be matched. By default these are set to 'Not a Number' (NaN) so it is easy to see time periods where no data exists. The script examines the time stamps for each data source's variables and inserts data into the correct 'matched' array where the index corresponds to the new global time scale. These new 'matched' arrays are assembled into a single csv file.

The exported data consists of

- Time
- X coordinate
- Y coordinate
- Z coordinate (Altitude)
- Ramp Start/Finish (1 for start, 2 for finish, else NaN)
- Cumulative Horizontal Distance (between Start/Finish points)
- SAFEmine speed
- Kral fuel mL/sec
- Kral Fuel L/hr
- VIMS engine fuel rate
- VIMS ground speed
- Engine speed
- Engine load
- Gear selection
- Park Brake status
- Service Brake status
- Throttle position

- Payload
- Body position

The csv file is opened in Microsoft Excel and conditional formatting is used to highlight ramp turning points by colouring the start/finish cells. Time periods without data (that is, cells displaying NaN) are greyed out. The following columns are added:

- Change in Altitude (needed to calculate slope)
- Total Fuel (for fuel to be totalled once samples are identified)
- Codes (for numerical codes to be added indicating whether samples meet certain criteria outlined below)

Some data has been included in Appendix 3 to better illustrate the exported format.

#### **4.5 Data Analysis**

The analysis aims to quantify fuel consumption in the following three scenarios:

- Driving up various ramp grades
- Stop-start driving due to intersections or queuing
- Idling due to queuing

These haul road design features have been chosen as the literature review indicated that controlling ramp grades and eliminating unnecessary stopping are effective methods for reducing fuel consumption. Targeting these elements of road design is also pragmatic, as these elements are relatively easy to control when compared with other elements, such as road length, which are somewhat more constrained by existing infrastructure, geology and topology of the site.

In a 24 hour period, data from all three data sources may exist for as many as 66,000 time stamps. With data collected over several days, this resulted in a large amount of data to be analysed.

The literature review showed that one method for dealing with large amounts of data is to break the data into 'chunks' where similar conditions exist. For example, isolating data where the truck was driving up a ramp while loaded with full throttle and with full engine load.

#### 4.5.1 Road Design Scenarios

Accordingly, the data was broken into major design scenarios and coding was used within the spread sheet to identify samples conforming to more specific criteria. This is summarised in Figure 22 and the criteria are defined in greater detail below.

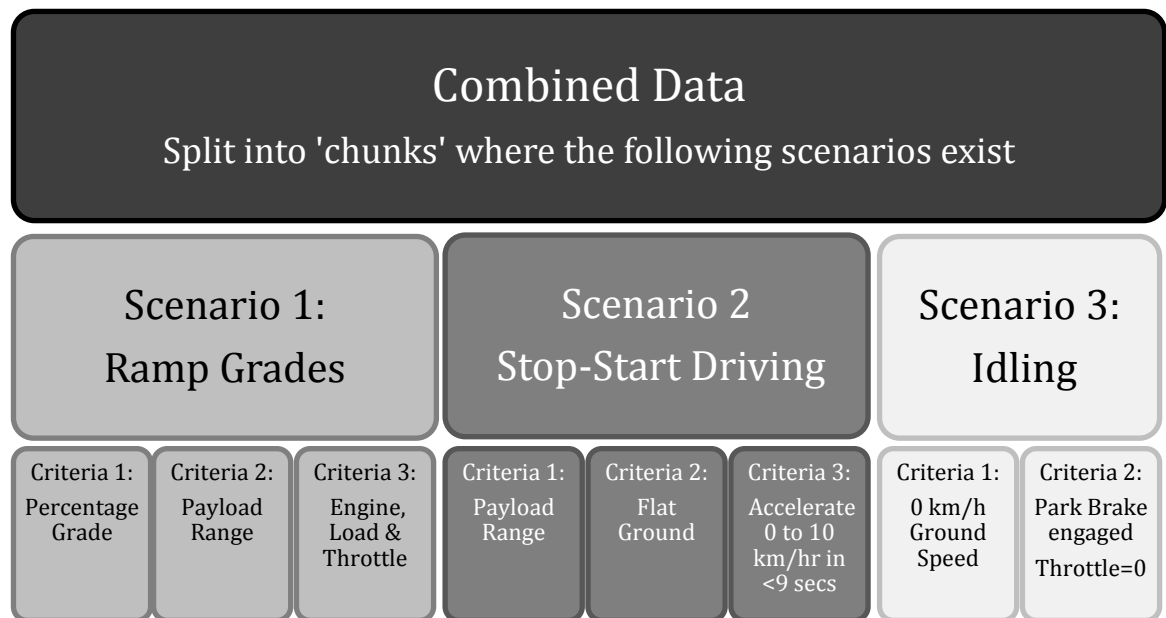


Figure 22: Breakdown of Data

For Scenario 1: Ramp Grades, time periods where the truck was ascending a ramp were identified. These were further filtered according to the following criteria:

- Percentage Grade – This is simply the grade of the ramp the truck is ascending. Only positive grades will be included as downhill runs consume minimal fuel.
- Payload Range – The target payload is 136 tons however trucks can sometimes be overloaded or under loaded. Payload data was reviewed and

a summary can be seen in Figure 23. A range of 112 to 143 tons was selected to reflect the most common real world loading conditions.

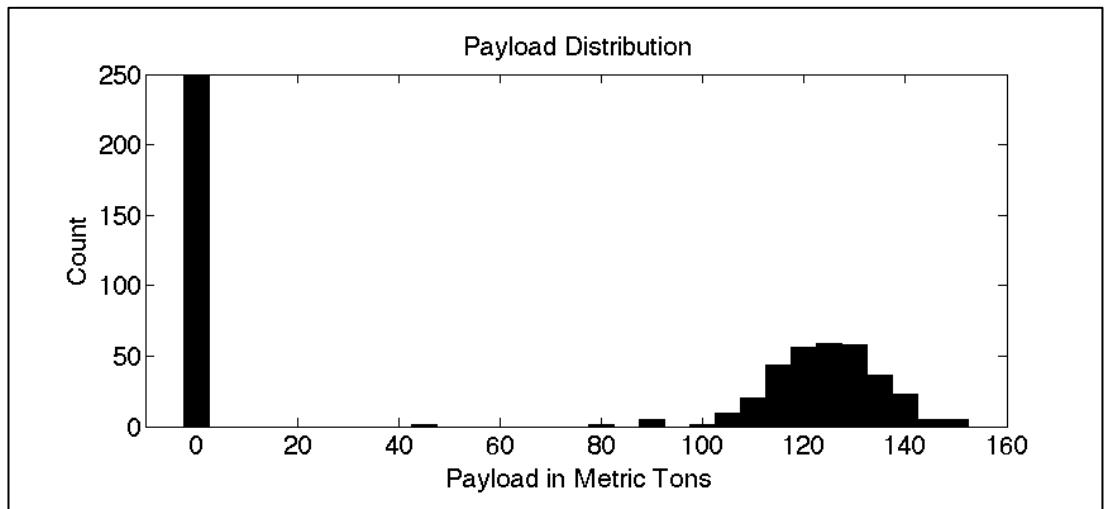


Figure 23: Distribution of Payloads

- Engine Load and Throttle Position – The truck uses less fuel when coasting so it is necessary to exclude such samples from the analysis. This was achieved by examining engine load and throttle position and coding examples where both of these parameters were greater than 90%.

For Scenario 2: Stop-Start Driving the following criteria were used:

- Payload Range – As defined in Scenario 1.
- Flat Ground – The sample should be on a grade of less than 1%.
- Acceleration from 0 to 10 km/h in less than 10 seconds – This range was chosen as it captures most cases of stop-start driving including queuing. Had a higher cut-off (for example 20 km/h) been chosen it would have excluded many samples. A time cut off was also implemented to restrict the analysis to typical operations. The sample durations were plotted and can be seen in Figure 24 below. These results indicated 9 seconds duration was a reasonable cut off.



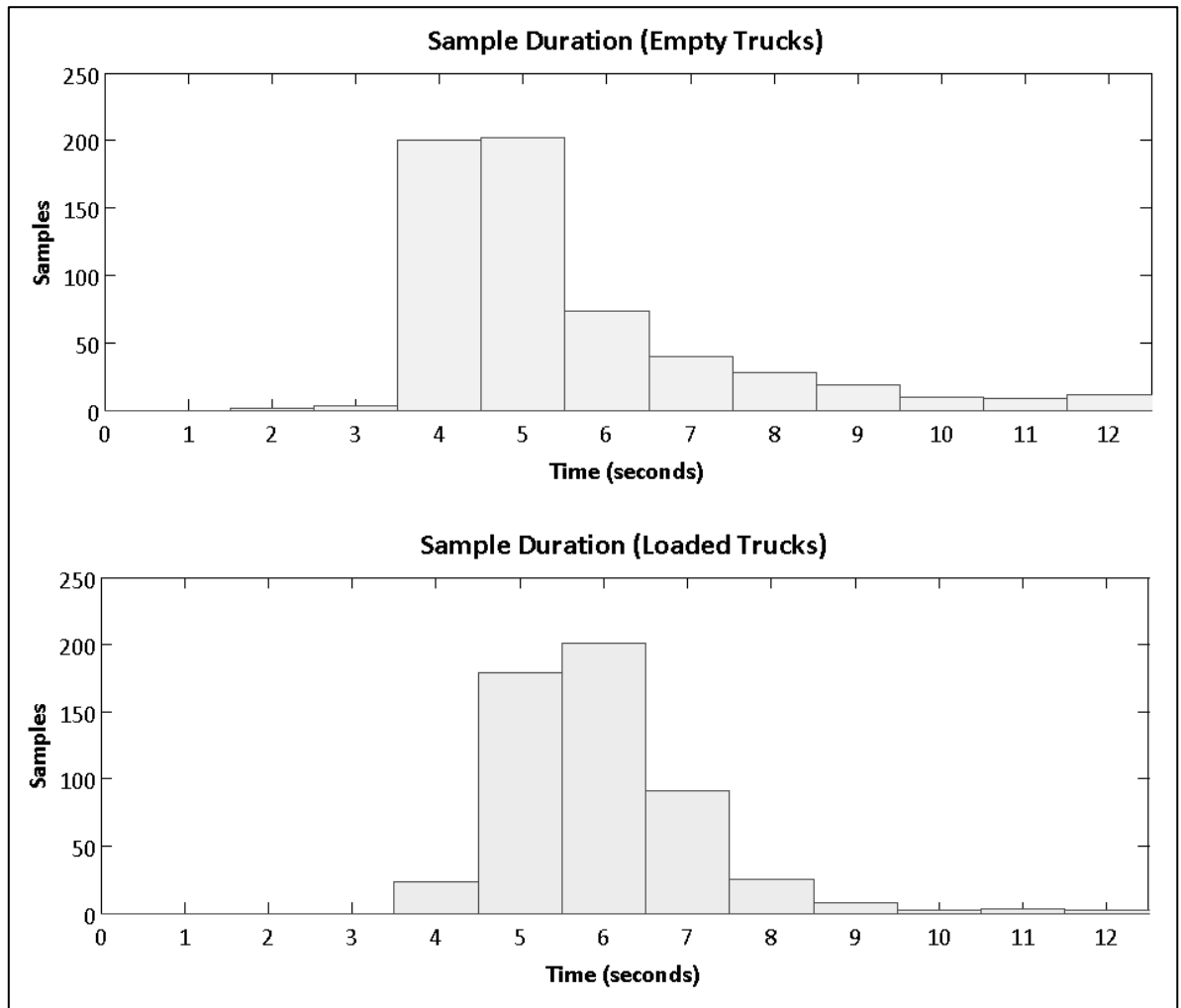


Figure 24 Sample Duration for Stop-Start Driving Analysis

For Scenario 3: Idling the following criteria were used:

- Ground Speed 0 km/h – The truck should be stationary.
- Park Brake engaged – Confirms the truck is stationary and generally indicates the operator expects to remain stationary for some time.
- No Throttle – This criterion adds an extra level of assurance that only idling samples are being isolated for analysis.

#### 4.5.2 Scenario 1 - Calculating Ramp Grade

As outlined above, turning points in the altitude versus time array were used to identify the approximate start and finish points of ramps. While this does successfully highlight periods of time where the truck is ascending a ramp, it cannot identify sections of ramp with a constant grade. Therefore, more accurate

ramp start and finish points were identified via manual inspection of the combined data files for each day.

The first step was to locate the start of a ramp, indicated by a 1 in the spread sheet column labelled 'Ramp S/F'. From here, the altitude and speed data was inspected and used to identify sections suspected to have a constant grade. The original 1 in the 'Ramp S/F' column is changed to a 3 to prevent confusion and the new suspected start and finish points are marked with a 1 and 2 respectively. An example is shown in Table 4 below. This shows how the 1, 2 and 3 labels are used in the 'Ramp S/F' column.

Table 4: Ramp Grade Labelling Example

X Coord	Y Coord	Altitude	Speed	Ramp S/F	Ramp Height	Ramp Length	Slope
3109.4	5348.9	54.439	37.07	3	0	0	NaN
3106.2	5346.8	55.438	36.616	0	0	3.7894	NaN
3102.7	5345.4	56.437	36.323	0	0	7.5539	NaN
3098.9	5345	57.436	35.376	0	0	11.39	NaN
3094.9	5345.5	58.435	34.487	0	0	15.47	NaN
3090.6	5347	59.434	33.663	0	0	20.01	NaN
3086.4	5348.7	60.433	32.769	0	0	24.576	NaN
3081.9	5350.6	61	31.657	0	0	29.432	NaN
3077.3	5352.8	61.431	30.922	0	0	34.503	NaN
3073.3	5355.3	62.43	30.133	1	0	39.242	NaN
3069.3	5358.1	63.429	29.279	0	0	44.097	NaN
3065.4	5361	64.428	28.789	0	0	48.988	NaN
3061.1	5363.9	65	28.536	0	0	54.187	NaN
3056.7	5366.9	65.426	28.284	0	0	59.487	NaN
3052.3	5370.1	66	28.306	0	0	64.953	NaN

DATA TRIMMED

2932.8	5528.8	83.396	27.36	0	0	264.16	NaN
2929	5533.9	84.395	27.153	0	0	270.59	NaN
2925.3	5539.1	85.394	26.762	0	0	276.92	NaN
2921.2	5544	86	26.7	0	0	283.27	NaN
2917	5548.8	86.392	26.6	0	0	289.67	NaN
2913	5553.5	87	26.443	0	0	295.85	NaN
2908.8	5558	87.39	26.241	0	0	302	NaN
2905.2	5562.6	88.389	25.92	0	0	307.88	NaN
2901.6	5567.3	89.388	25.73	0	0	313.82	NaN
2897.7	5572	90	25.73	0	0	319.89	NaN
2893.7	5576.2	90.386	25.499	0	0	325.72	NaN
2890.2	5580.8	91.385	25.122	0	0	331.45	NaN
2886.7	5585.5	92.384	25.095	0	0	337.34	NaN
2882.9	5590	93	25.059	0	0	343.22	NaN
2879	5594.1	93.382	24.967	0	0	348.88	NaN
2875.6	5598.3	94.381	24.705	0	0	354.28	NaN
2871.9	5602	95	24.341	0	0	359.5	NaN
2868.1	5605.5	95.379	24.281	0	0	364.7	NaN
2864.9	5609.2	96.378	24.039	0	0	369.6	NaN
2861.9	5612.6	97.377	22.748	0	0	374.04	NaN
2859.1	5615.5	98.376	21.788	0	0	378.19	NaN
2856.3	5617.9	99.375	21.445	0	0	381.82	NaN
2853.4	5619.6	100	20.965	2	37.57	345.91	0.108612

The changes in vertical (Altitude) and horizontal (X and Y coordinates) distance are calculated between the new start and finish points. This is also shown in the Table 4 example. A simple slope calculation is performed where:

$$\text{Slope} = \frac{\text{Vertical Distance Travelled}}{\text{Horizontal Distance Travelled}}$$

This slope is checked by performing another slope calculation somewhere between these start and finish points. If the second slope calculation matches the first, this was considered to be a successful ramp grade identification.

After the grade of the ramp has been successfully checked using the above method for two or more runs, it was possible to perform a single slope calculation and compare the result to the previous samples from the same ramp. By checking the truck's location and work path on Google Earth, it was possible to use time stamps to determine whether the truck was travelling over the same ramps repeatedly.

#### **4.5.3 Scenario 1 – Calculating Fuel Consumption Rate**

The volume of fuel used on a ramp is determined by summing the Kral Fuel Meter mL/sec data between the ramp start and finish points. This is then divided by the horizontal distance travelled to get a mL/m rate of consumption. This is displayed as L/km as those units are more intuitive for mining engineers to use in calculations and estimating

#### **4.5.4 Scenario 1 – Coding and Quantifying Fuel Consumption**

As the ramp grades and fuel consumption rates are being calculated, the individual samples are coded with a 1 for runs meeting the engine load and throttle criteria described previously. Runs that do not meet these criteria are coded with a 2. Empty and loaded runs are also coded 0 and 1 respectively.

This data was imported into Matlab and runs that did not meet the engine load and throttle criteria were eliminated. Data was then isolated according to payload. This

resulted in two separate data sets for loaded and unloaded trucks. The Matlab curve-fitting tool was used to compare fits using different polynomial curves.

#### **4.5.5 Scenario 2 – Identifying Stop and Start Behaviour**

For this scenario, the combined data from a range of dates was read into Matlab and the ground speed data was examined to find instances of stop-start driving. The ground speed at each timestamp (n) was compared to the (n + 1) timestamp and instances where (n) = 0 and (n + 1) > 0 were labelled with a 1 to indicate the start of a potential sample. The script then progresses through the ground speed data until a speed equal to or greater than 10 km/h is found and labelled with a 2 to indicate the end of the sample. Samples with deceleration were excluded.

#### **4.5.6 Scenario 2 – Determining Fuel Consumption and Controlling for Sample Duration, Payload, Slope and Body Position**

Fuel consumption was tallied between the sample start and finish points with a result obtained in millilitres. After separating out samples taken on flat ground and meeting duration requirements, the results were divided according to payload into empty and loaded groups.

After manually checking a random selection of the results, it was found that a specific driving behaviour occurs at waste dumps, where the operator will often raise the truck body so the payload begins to fall, before slowly moving forward. This is done to distribute waste rock across the ground, rather than forming stockpiles. The data for body position was used to exclude samples where the body was raised. Excluding these samples produced a population that better reflects usual operations.

The results from several days were combined and the distributions for both empty and loaded trucks were found.

#### **4.5.7 Scenario 3 – Determining Fuel Consumption while Truck Idles**

Instances of idling were extracted from the daily combined data by checking each time step for samples meeting the criteria outlined previously. The samples

collected from each day were then compiled and a mean fuel consumption rate in L/hour was calculated.

#### **4.6 Assumptions**

These results and any subsequent recommendations are based on the following assumptions:

- Roads are consistently graded and watered throughout each shift such that any difference in road surface properties between samples is negligible.
- All roads are constructed using the same materials and methods so road surface properties are consistent across site.
- The 785D truck used for this research is well maintained. There is no variation in performance due to poor maintenance. This includes tyre maintenance.
- The truck is identical in performance to other 785D trucks in the company's off-highway truck fleet. It has not been modified in any way that would improve or worsen its performance relative to the rest of the fleet.

## Chapter 5

# Results and Discussion

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After combining several days' worth of data from all three data sources, the assembled data was reviewed. There was a high level of agreement between the data from different sources. For example the SAFEmine speed matches the VIMS ground speed; while the Kral fuel data matches the VIMS fuel data and both correspond to known average hourly consumption rates.

The data covers 21 shifts and therefore up to 21 different operators.

## 5.1 Ramp Grades

### 5.1.1 Raw Data

584 samples were identified where the truck was ascending various ramps. Figure 25 shows a scatter plot of this data. The data seems to split into two separate trend lines. The data is set out in Appendix C.

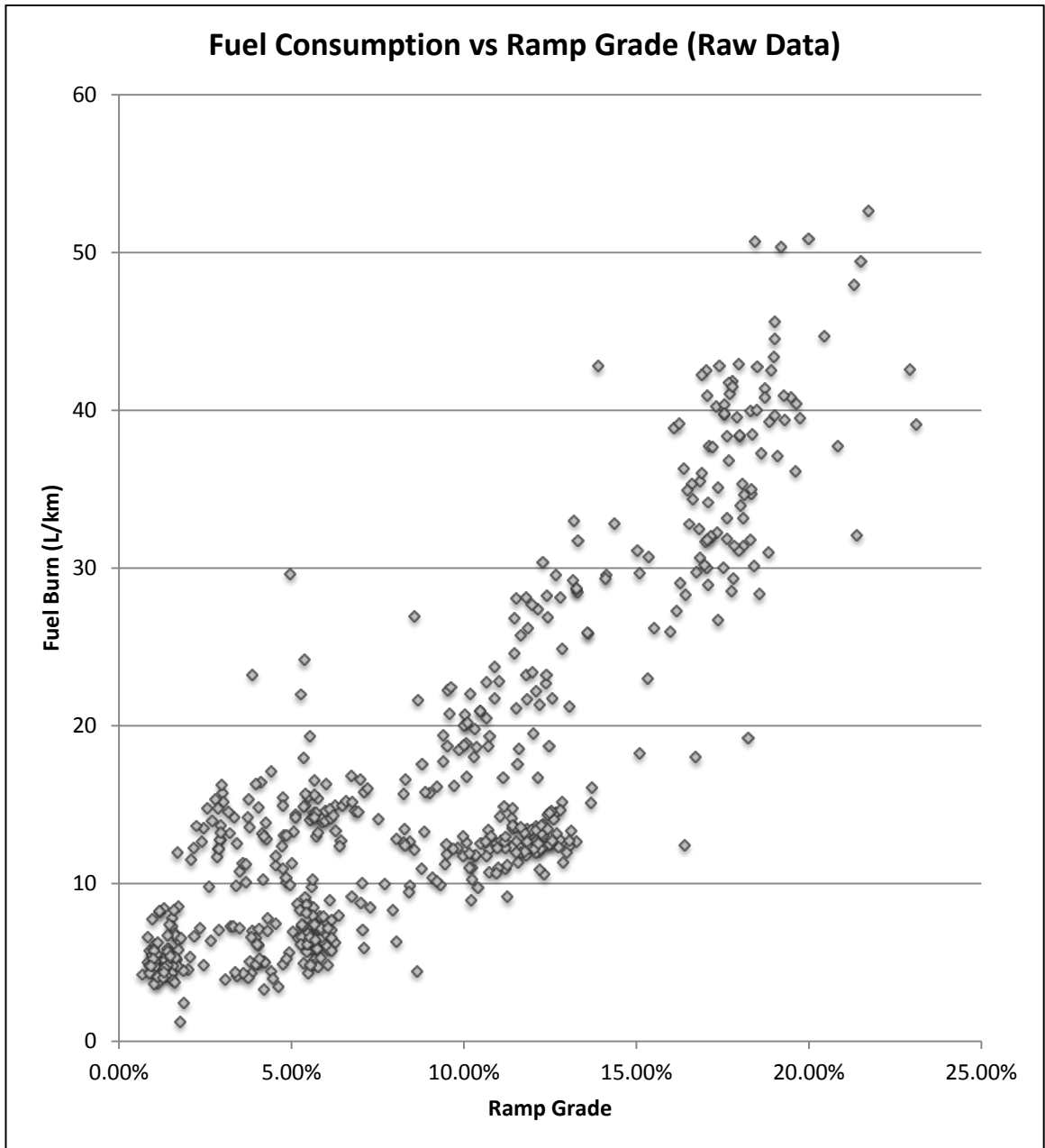


Figure 25: Scatter plot of all ramp grade data

It should be noted again that the units for fuel consumption, litres per kilometre, are derived from the horizontal distance covered by the ramp, not the actual ramp length. This is to allow easier comparison between ramps of different grades.



After eliminating unacceptable samples according to the engine load and throttle conditions described above, the data was split according to payload. With these conditions, a clearer trend emerged as shown in Figure 26. These data sets were then used for curve fitting.

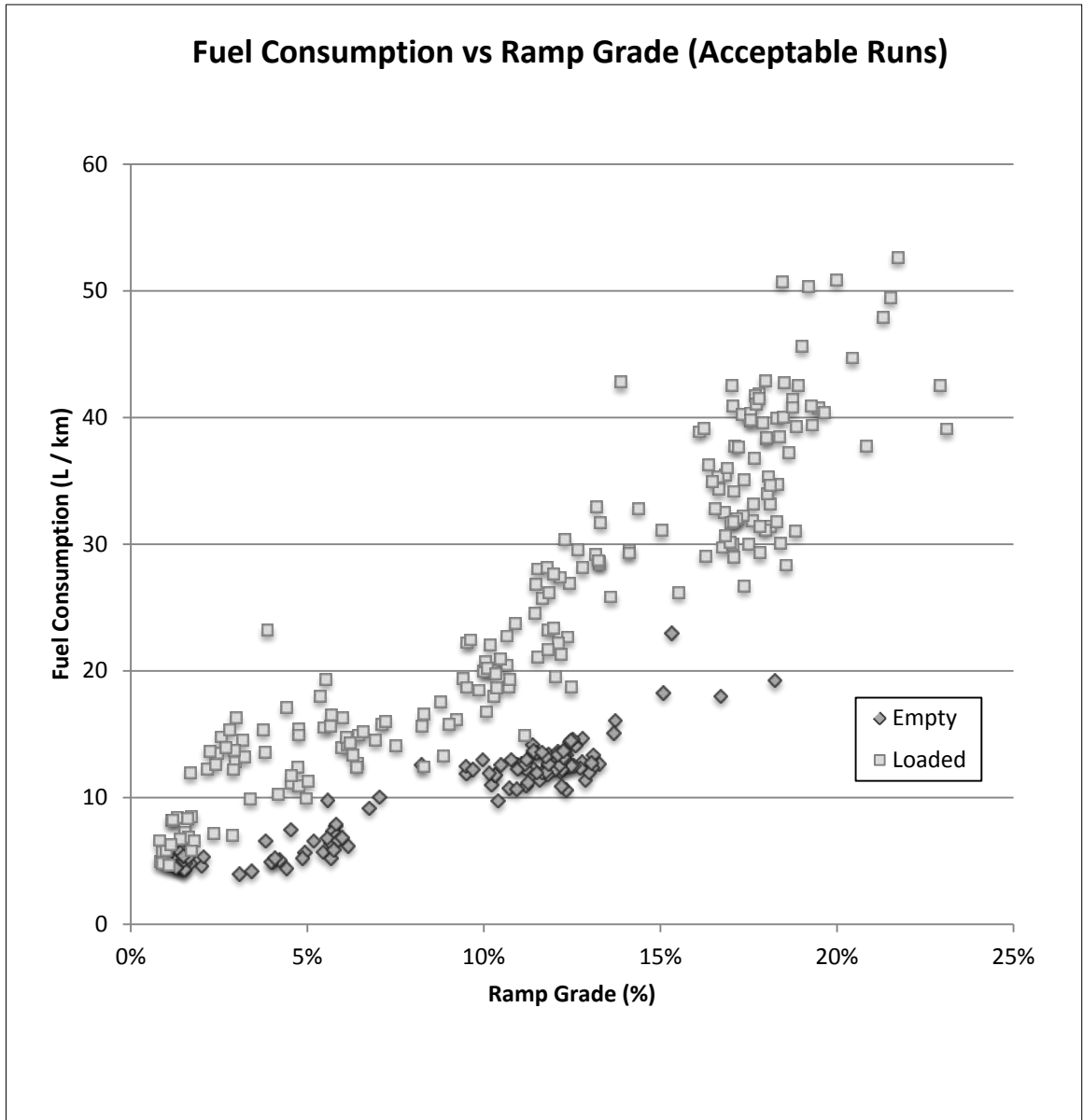


Figure 26: Scatter plot showing acceptable runs, empty and loaded

### 5.1.2 Curve Fitting

Cubic and 5<sup>th</sup> degree polynomials provided the best matches both visually and numerically (based on  $R^2$  values). Although the 5<sup>th</sup> degree functions had slightly higher  $R^2$  values, the extrapolated regions of the 5<sup>th</sup> degree polynomials tended away from the trend for both cases. These results are summarised in Table 5.

Table 5:  $R^2$  Values for Curve Fitting

<b><math>R^2</math> values</b>	<b>3rd Degree</b>	<b>5th Degree</b>
<b>Loaded</b>	0.8890	0.8948
<b>Unloaded</b>	0.9086	0.9233

The graphical results of curve fitting are shown below in Figure 27 and Figure 28.

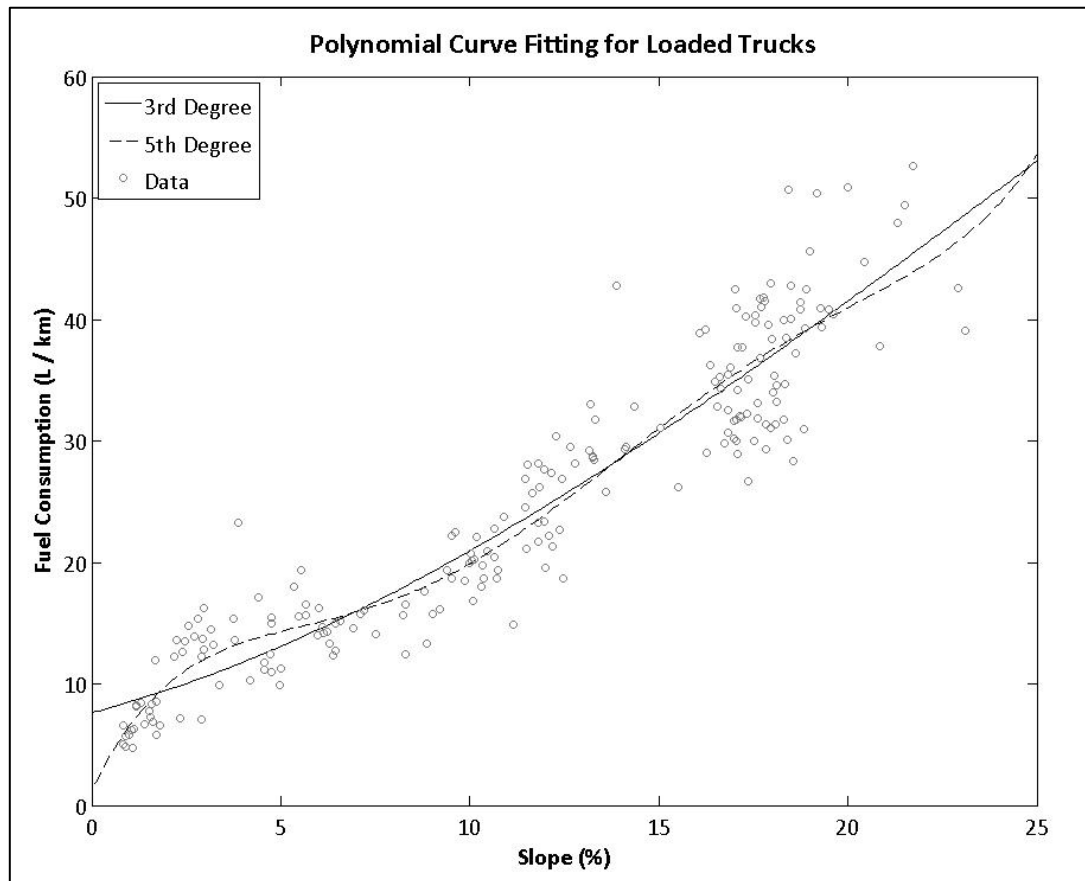


Figure 27: Polynomial Curve Fitting for Loaded Trucks

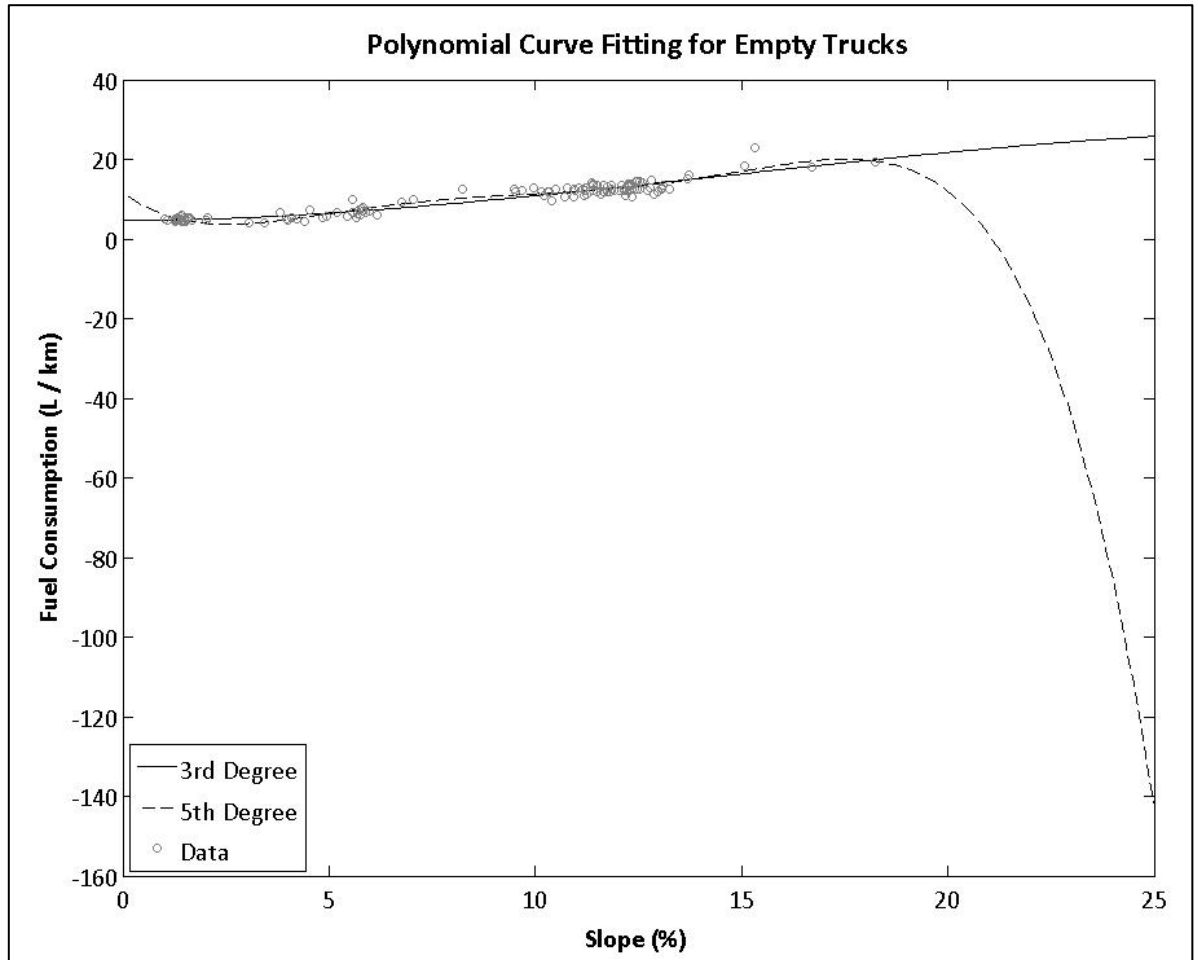


Figure 28: Polynomial Curve Fitting for Empty Trucks

The polynomial coefficients are summarised in Table 6.

Table 6: Polynomial Coefficients

<b>Coefficients</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Loaded 3<sup>rd</sup> Deg</b>	-803.80	603.87	80.825	7.6380		
<b>Loaded 5<sup>th</sup> Deg</b>	8.064e+05	-5.343e+05	-1.271e+05	-1.272e+04	640.1	1.287
<b>Empty 3<sup>rd</sup> Deg</b>	-1661	727.7	6.809	4.562		
<b>Empty 5<sup>th</sup> Deg</b>	-3.343e+06	1.66e+06	-3.017e+05	2.454e+04	-764.7	11.61

### 5.1.3 Ramp Grade Summary and Discussion

Based on the above results, the cubic functions provide the best approximation of fuel consumption with respect to ramp grade. Despite the 5<sup>th</sup> degree polynomials having marginally higher R<sup>2</sup> values, the extrapolated regions do not make sense and are not useful in estimating fuel consumption.

Therefore, the functions to be used to determine fuel consumption are:

$$f_{empty} = -1661x^3 + 727.7x^2 + 6.809x + 4.562$$

and

$$f_{loaded} = -803.8x^3 + 603.87x^2 + 80.825x + 7.638$$

These are graphed in Figure 29 and Figure 30 below with the scattered data and observation bounds (95% of data) for the function.

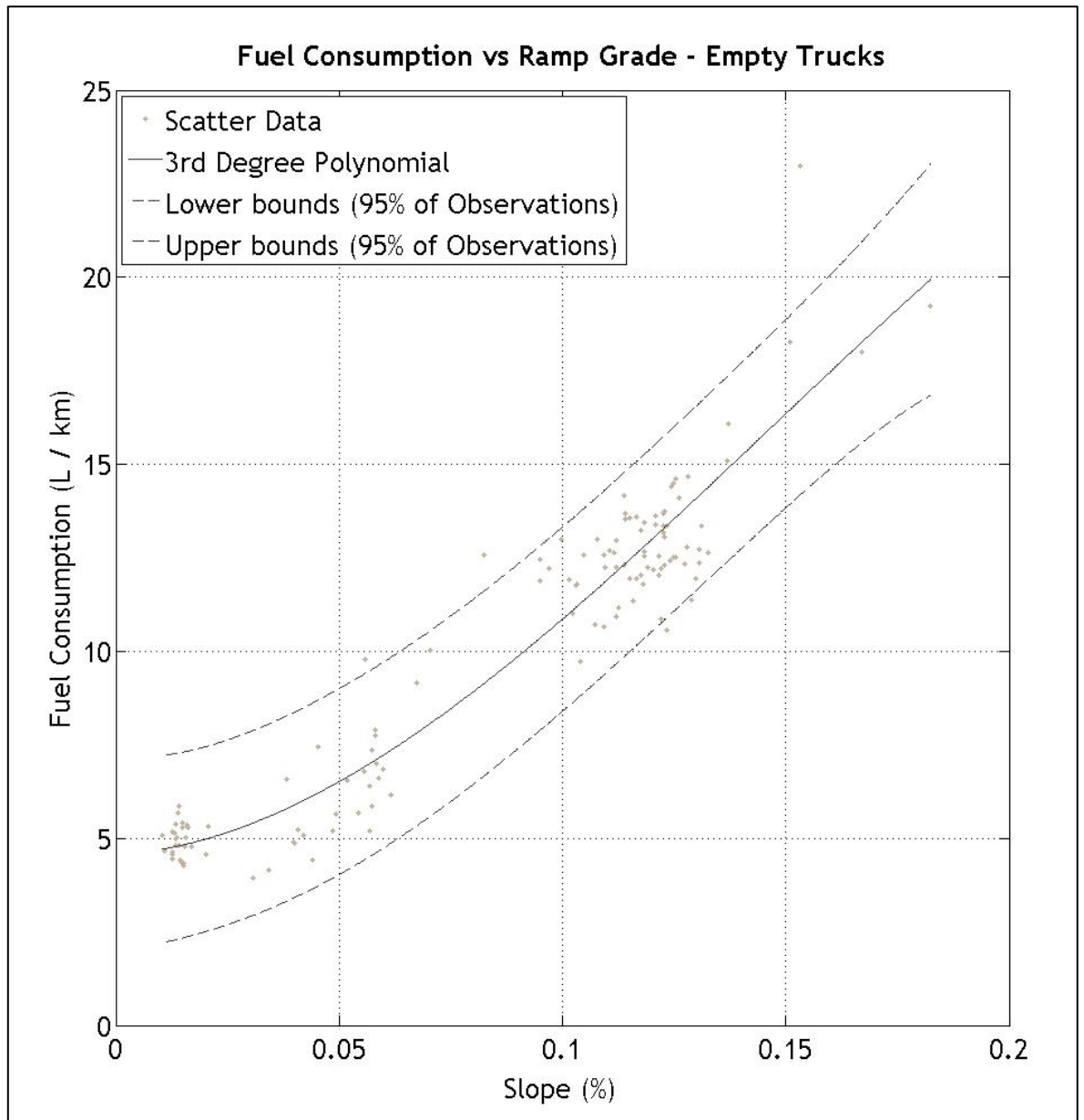


Figure 29: Fuel Consumption versus Ramp Grade for Empty Trucks

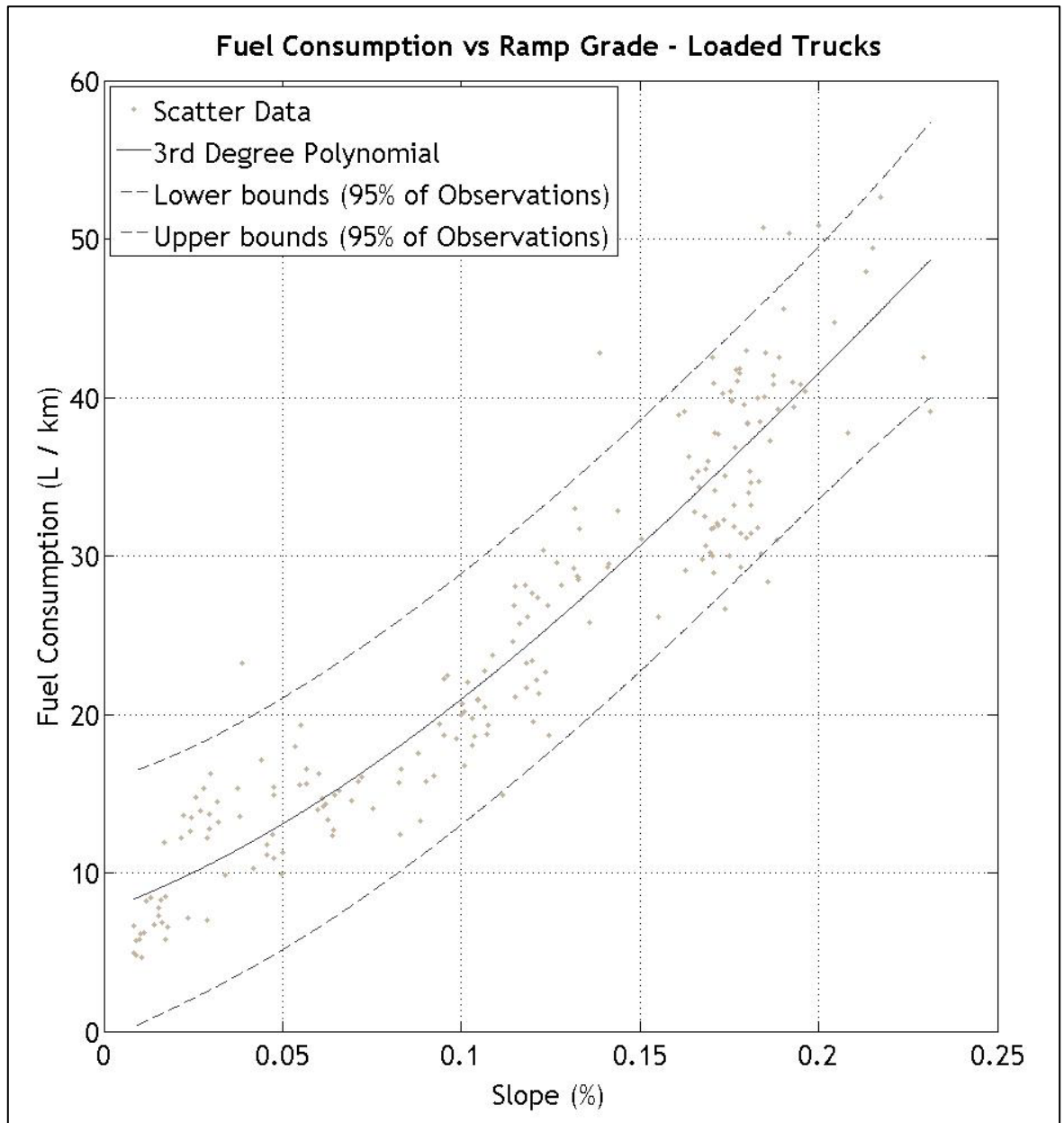


Figure 30: Fuel Consumption versus Ramp Grade for Loaded Trucks

Overall, the data matches expectations in that fuel consumption increases with ramp grade. The grouping of individual samples was fairly consistent with a relatively small number of outlying data points, especially after controlling for driving style using throttle position and engine load to exclude coasting and braking.

With regard to the slope calculation, the use of Google Earth allowed identification of particular ramps within the mine by looking at the time stamp and truck location. This allowed slope calculations for the same ramp to be checked against each other making it possible to identify any unexpected results. Throughout the data analysis, slopes calculated for the same ramp were very consistent. This suggests that the methodology used did not produce any random errors due to incorrect measurements, however it is still possible systemic errors may exist due to errors in the conversion of coordinates from degrees to metres. These results rely on the accuracy of the Matlab function used for this process.

Another issue is the accuracy of the SAFEmine GPS data. Unfortunately the altitude has a precision of 1 m, making it difficult to determine sections of ramp with consistent gradients and introducing error into slope calculations. The lack of precision means that each measured change in altitude has an accuracy of  $\pm 1$  m. This limitation was dealt with by treating the first instance of each altitude as the 'true' measurement and using only these points for ramp starts and finishes. A simplified example is given in Table 7 to better explain this point, however real ramps are much longer than shown in this example.

The impact of this issue would be limited for ramps covering longer horizontal distances. Conversely, the accuracy of slope calculation for ramps covering shorter horizontal distances or with lower grades could be affected by the uncertainty of the change in altitude. If this methodology was to be repeated, it would be preferable to use a different GPS device capable of providing greater accuracy in altitude measurement. The literature review found examples where mobile phones had been used for this purpose, so that may be one low cost alternative to consider.

Table 7: Example of Altitude Problem

<b>Altitude (metres)</b>	<b>Ramp Start (1) and Finish (2)</b>
100	
100	
100	
100	
101	1
101	
102	
102	
103	
103	
104	2
104	
104	
104	

Another key aspect of the analysis is driving style. As described above, engine load and throttle position were key variables considered in order to eliminate driving styles that may skew the data. As a result of the truck’s engine and transmission characteristics, the truck will quickly reach maximum engine load and speed when accelerating up a ramp. As such, full throttle and engine load is the normal driving style used when ascending a ramp so most samples met this criterion. However, as highlighted by the literature review, gear selection is the other major aspect of driving style that could influence these results.

As the 785D truck uses automatic transmission, gear selection is not generally an issue on ramps as the operator will almost always be using 100 % throttle and the truck will quickly downshift to 1<sup>st</sup> or 2<sup>nd</sup> gear. However it is possible for operators



to lock the transmission into a lower gear when required and such samples are likely to be included in the data. This would come into play most often on lower grades where the operator may lock the transmission in a lower gear to prevent continual shifting (for example, locking the truck into 1<sup>st</sup> gear to prevent shifting from 1<sup>st</sup> to 2<sup>nd</sup> gear, then back to 1<sup>st</sup> in quick succession). The effect this behaviour may have on fuel consumption was not examined, but it is expected that the results reflect real world fuel usage as the data was obtained from several different operators. Although it is a small sample size, the operators should provide a mix of typical, above average and below average driving styles with respect to efficiency.

Initial ground speed as the truck enters the ramp also affects fuel consumption, especially if the truck was descending a ramp immediately prior to beginning an ascent. Although care was taken to select ramp start points that were not affected by entry characteristics, the manual nature of this process means that this largely came down to judgement. This is another aspect of the analysis that would benefit from more accurate GPS data as quick transitions between downhill and uphill road sections could be easily identified.

## **5.2 Stop-start driving**

After applying the criteria for this scenario and separating samples according to payload 534 loaded and 596 empty samples were compared. A summary of the results is found in Table 8 and Table 9 below. The data is set out in Appendices D and E.

Figure 31 shows the sample distribution according to the total volume of fuel consumed during acceleration. For each sample, the fuel volume was compared to sample duration to obtain a fuel consumption rate. These results are shown below in Figure 32.

Table 8: Stop-Start Driving Volumetric Fuel Consumption

	Empty Trucks	Loaded Trucks
Mean fuel volume consumed (mL):	193.4660	307.0219
Standard deviation (mL):	38.0482	68.0633
Standard error of the mean (mL):	1.5585	2.9454

Table 9: Stop-Start Driving Fuel Consumption Rates

	Empty Trucks	Loaded Trucks
Mean fuel consumption rate (mL/sec):	49.0401	63.1523
Standard deviation (mL/sec):	11.7846	7.6810
Standard error of the mean (mL/sec):	0.4827	0.3324
Mean fuel rate in (L/hour):	176.5442	227.3483

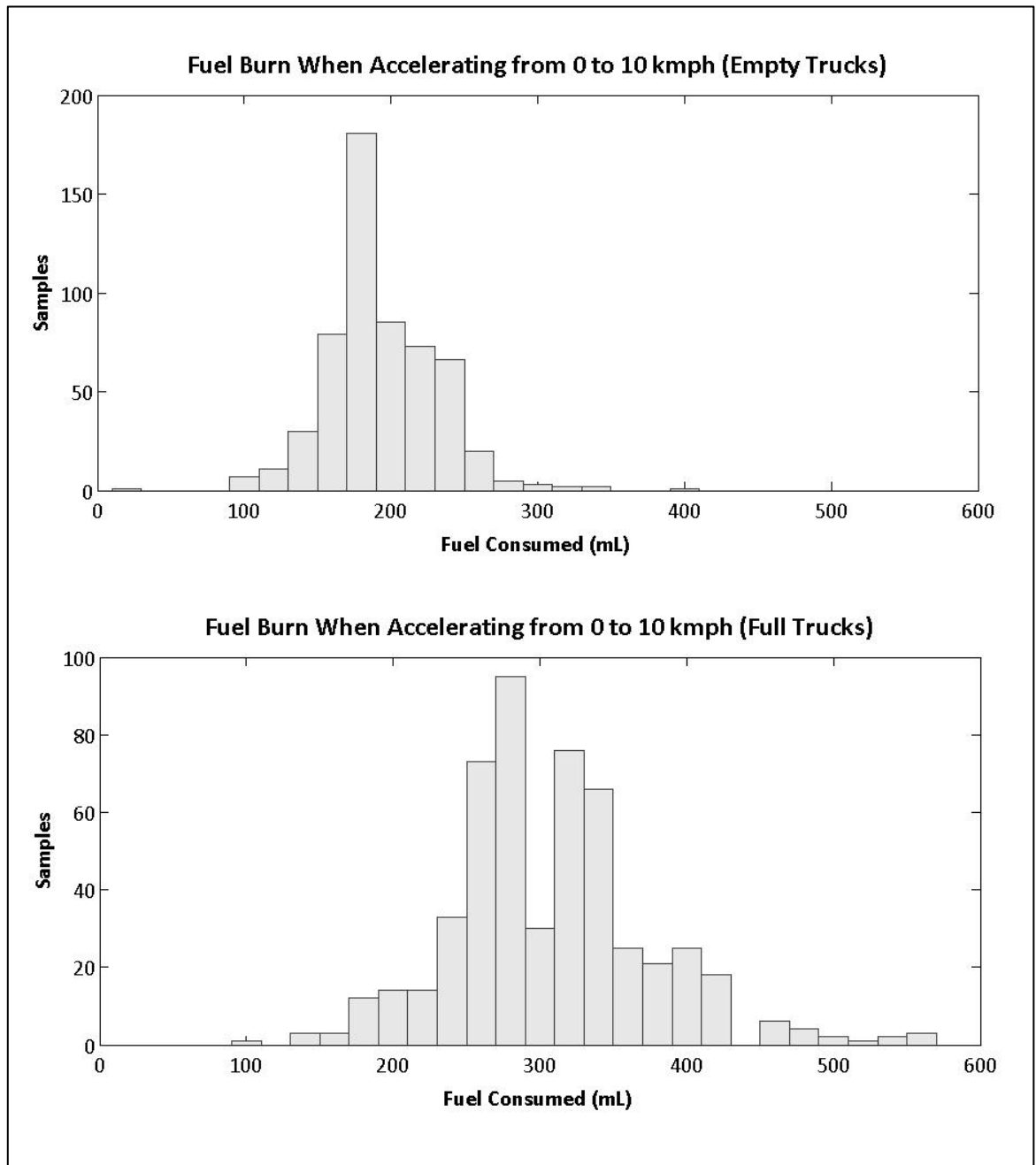


Figure 31: Volume of Fuel Burnt when Accelerating from 0 to 10 km/h

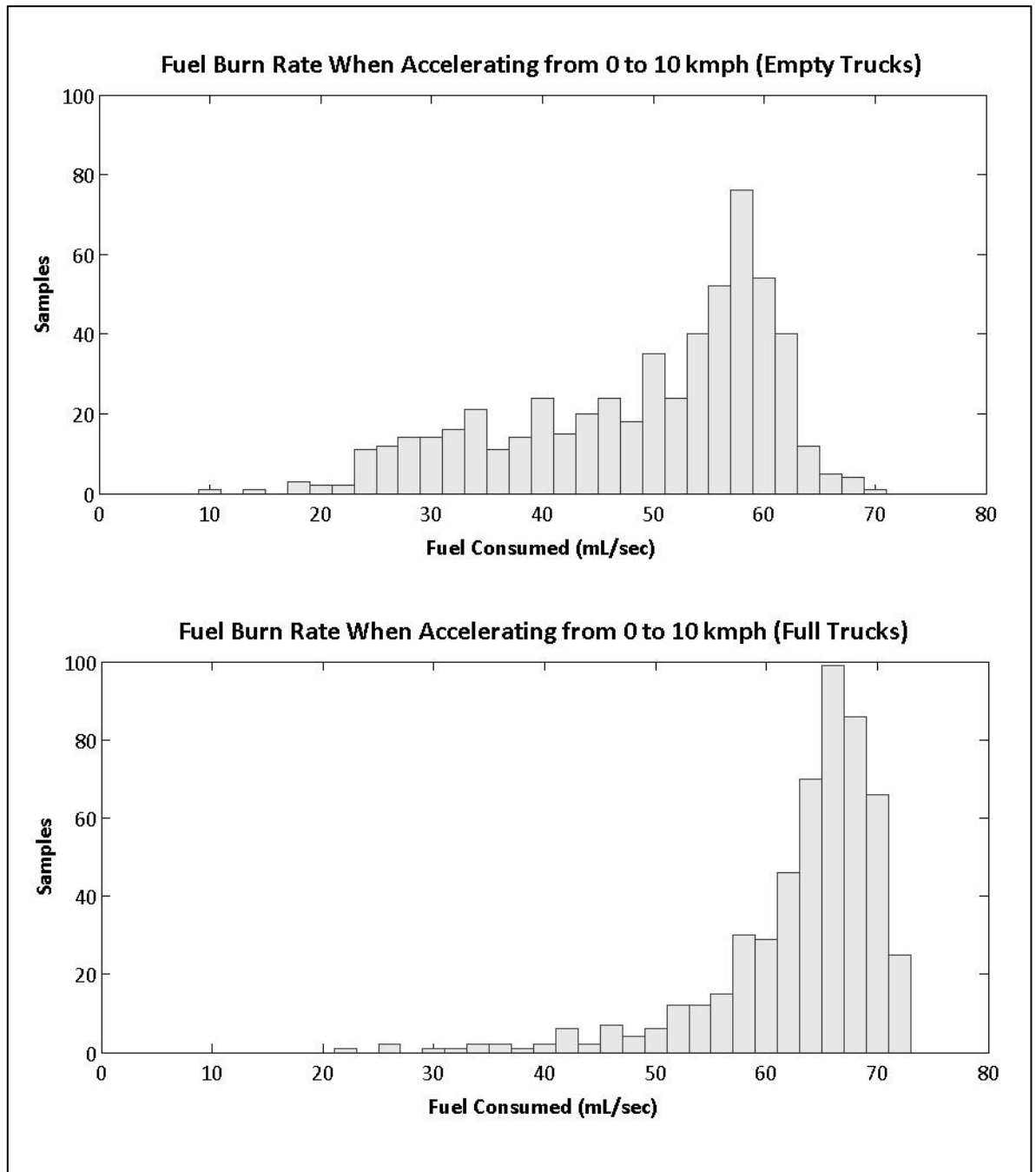


Figure 32: Fuel Consumption Rate During Acceleration from 0 to 10 km/h

### 5.2.1 Stop-Start Driving Summary and Discussion

Both the average volume of fuel consumed and the average rate of consumption were found for trucks accelerating from a stationary position to 10 km/h (refer to Table 8 and Table 9 above). The results show that each time a loaded truck stops and restarts approximately 310 mL of fuel is consumed. For unloaded trucks the

figure is approximately 195 mL. In order to understand how this relates to general operations these quantities must be compared to known benchmarks.

The average rate of consumption will be used for this purpose. For empty trucks the rate was 176.5 L/hour and for loaded trucks this was 227.3 L/hour. When compared to Caterpillar's hourly fuel consumption rate of 108.5 to 135.6 L/hour for applications rated as 'high' (refer to Table 1 above) it is clear the actual rate of consumption exceeds this, especially in the case of loaded trucks. This excessive fuel usage must be considered when designing roads that will require trucks to stop and restart unnecessarily.

More research would be needed to determine precisely how much extra fuel is consumed by stopping and restarting as opposed to continuous driving through the same section of road. The quantities found here (310 mL for loaded and 195 mL for unloaded trucks) are not directly equivalent to the energy lost through the loss of momentum due to stopping. These quantities are also based on acceleration to only 10 km/h whereas cruising speeds may be between 30 and 40 km/h. Nevertheless, as the true cost of a stoppage is likely to be higher, it is reasonable to use these quantities to calculate stoppage costs and they form a good starting point for future work.

Now that the cost of each stoppage can be calculated, this can be used to calculate the fuel costs incurred by placing intersections, queuing trucks at the entrance of a dump or any similar scenario. If the total number of stoppages can be estimated, the total fuel cost will also be known. This can be compared to the cost of eliminating an intersection or redesigning bottlenecks to allow free flow of traffic.

The distribution of total fuel consumed by loaded trucks (see Figure 31) is noteworthy in that it generally follows a normal distribution pattern, but there is a sudden drop in samples around 300 mL. Further analysis would be needed to determine the exact cause of this result. At the same time, once these samples were converted to a fuel consumption rate in mL/sec, the distribution is more consistent

(see Figure 32). One possibility is that the samples totalling 300 mL may be shorter in duration and thus use less fuel over all, while fitting into the broader population once expressed as a rate.

There was much greater variation in the fuel consumption rate for empty trucks when compared with loaded trucks (see Figure 32). This is likely because a loaded truck will almost always be working at 100% engine load with 100% throttle while accelerating; therefore there is less variation in samples due to driving style. The data for empty trucks encompasses a wider range of throttle and engine load measurements and it follows that there will be greater variation amongst the samples analysed.

Similarly, gear selection would also impact fuel consumption when accelerating. While accelerating from 0 to 10 km/h first gear will generally be used, but to reach a cruising speed between 30 and 40 km/h several gear shifts will take place and the timing will impact fuel consumption. Quantifying this effect will require further research.

### **5.3 Idling**

A total of 74095 samples were compared in order to determine fuel consumed while idling. It should be noted that unlike the ramp grade and stop-start driving analyses, each sample in the idling analysis is only one second in duration. Therefore, a much larger number of samples were identified and compared. A segment of this data is set out in Appendix F.

The distribution of samples is shown in Figure 33 below. The consumption rate ranged between approximately 8 and 14 L/hour. The mean rate of fuel consumption was 11.3 L/hour with a standard deviation of 1.71. In order to understand the variation, engine speed and load data for these samples was also compared to ensure that only true idling behaviour was being analysed.

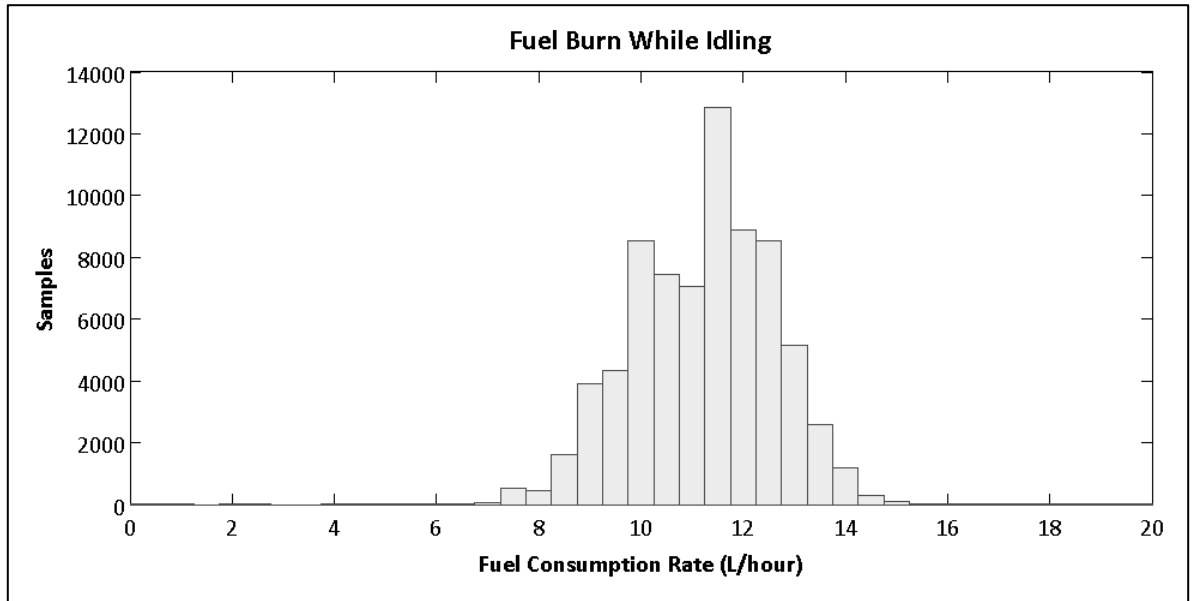


Figure 33: Fuel Consumption Rate While Idling

Taking a closer look at engine speed and load showed there was minimal variation in engine speed, while engine load showed slight variation. Engine speed is shown in Figure 34. The mean engine speed was 700 rpm with a standard deviation of 11. The mean engine load was 3.6% with a standard deviation of 1.5%. Engine load is shown in Figure 35.

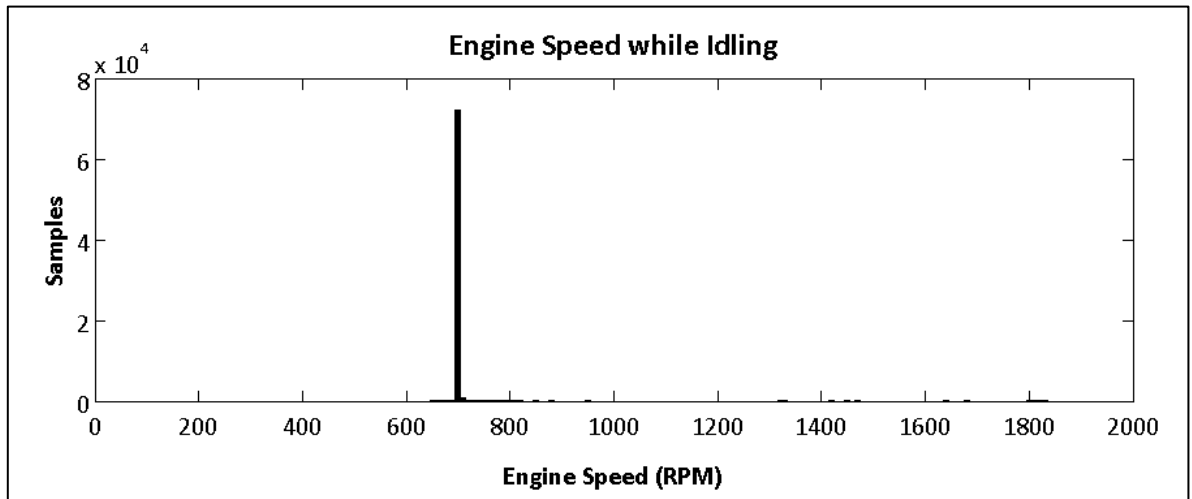


Figure 34: Engine Speed while Idling

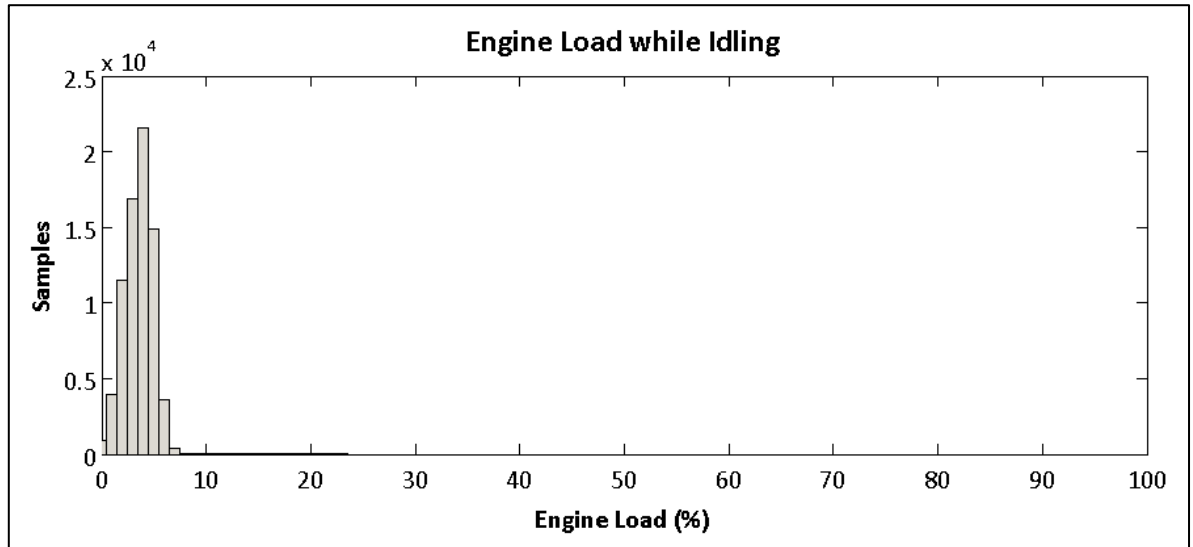


Figure 35: Engine Load while Idling

The variation in engine load may be due to changing accessory loads, which can in turn affect fuel consumption. Other variations in the fuel consumption rate may be linked to variation in fuel, engine and ambient temperatures. These temperatures can vary significantly depending on time of day, season and length of time spent operating.

#### 5.4 Summary and General Discussion

This study has been able to quantify fuel consumption when a Caterpillar 785D truck, loaded or unloaded:

- Ascends ramps of various grades
- Is forced to stop and start, for example at intersections or when queuing
- Idles

For the case of ascending ramps, two functions were found to calculate fuel consumed in litres per kilometres by both loaded and unloaded trucks. This can be used to estimate fuel costs over the life of a ramp.

For the case of stop-start driving, the average volume of fuel consumed by each stop and restart was found for both loaded and unloaded trucks. For the case of idling, average hourly fuel consumption was found. This information can be used



to quantify the fuel costs incurred by intersection placement, queuing or similar situations.

The results are internally consistent and do not contradict known benchmarks for average fuel consumption, such as the hourly rates stated in Caterpillar's Performance Handbook (see Section 2.2.2, page 11) and company refuelling data.

This research was limited by resource availability (see Section 4.1.1, page 29) and as such only one truck could be studied. As stated previously, this truck is one of several 785D trucks on site that were all manufactured and purchased together. Refuelling data is monitored, and there is negligible variation in hourly fuel consumption between these trucks when they are operating in the same conditions. However, while the average hourly rate is the same across the fleet, without actually repeating this methodology using other trucks there is no way to be certain that the results for these specific road design scenarios will be repeated across the fleet. Although there is no reason to suspect that there would be noticeable variation between 785D trucks, it would be preferable to extend this research to another vehicle for the sake of completeness.

As discussed in Section 2.2.3, weather and climate were not considered in this study. As such, the influence of these variables has not been quantified, but based on the literature review this is expected to be relatively small in comparison to the variables that were considered. It should be noted that all samples were taken during Autumn months, so incorporating data from other seasons would provide more robust results that can reasonably be expected to reflect a yearly 'average' fuel consumption rate not influenced by temperature, humidity or air density.

The effect of driver style has also been mentioned previously. While variables such as throttle and engine load were used to isolate similar samples, more work would need to be done to determine the impact of gear selection on fuel consumption.

Overall, these results are useful in that they quantify fuel consumption rates that were not previously known. This new knowledge can be used when estimating and forecasting diesel costs, where in the past average hourly rates have been used to varying degrees of success. Most importantly, it can be used to quantify the fuel that will be used in different haul road scenarios, and this knowledge can be used to make design decisions that will optimise fuel costs with respect to road construction and maintenance costs.

## Chapter 6

# Ramp Fuel Consumption Tool

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### 6.1 Rationale

As ramps are one of the most frequently changing elements of the mine's haul road system, quantifying fuel costs before construction provides opportunity for optimisation. Accordingly, a Ramp Fuel Consumption Tool has been created to allow mining engineers to estimate fuel costs for a ramp design, then compare these to constructions and production costs in order to arrive at the optimal design given all other constraints.

A Microsoft Excel spread sheet was used for this purpose. Despite its limitations, this format was chosen as Excel is readily available on all company computers and there is a high degree of familiarity with this program across the tool's intended user group.

### 6.2 Functionality overview

The Ramp Fuel Consumption Tool allows user to:

- Enter the current diesel price
- Specify the number of loaded and unloaded trips to be taken on the ramp
- Specify an initial ramp design, in terms of length and height, for which a fuel cost will be calculated
- Enter alternative ramp geometries and obtain a cost difference between the alternative and initial designs

When a user first opens the file, they will see an explanation of the tool's intent accompanied by clear step-by-step instructions. Cells requiring user input have been highlighted so users can easily see where information is to be entered. Figure 36 shows a screenshot of the initial screen.

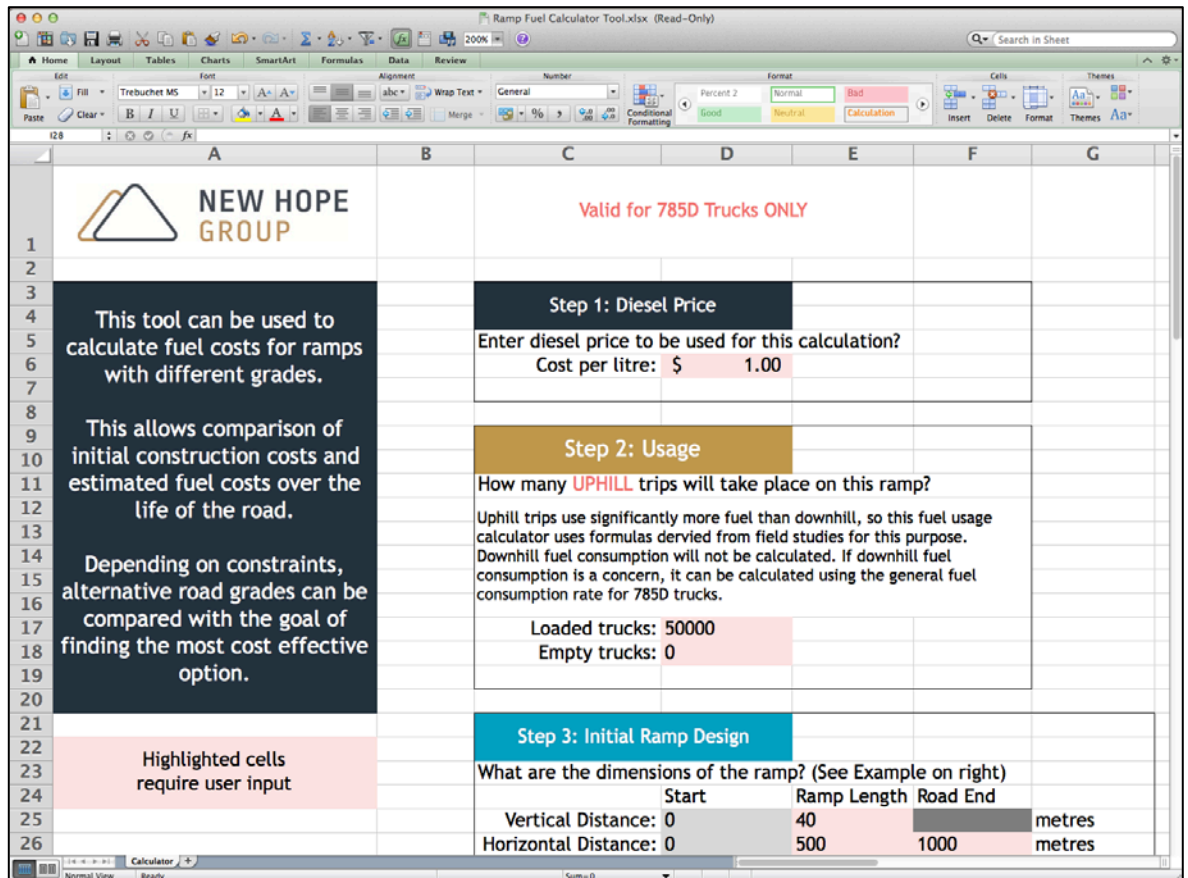


Figure 36: Screenshot showing the Ramp Fuel Consumption Tool

Steps 1 and 2 capture the diesel price and the number of trucks using the ramp over its life.

Step 3 requires the user to enter details about the ramp's geometry. A diagram has been provided to clarify the data that is required (Figure 38). Once the geometry has been entered, the ramp grade is automatically calculated. An estimate of the total volume of fuel consumed over the life of the ramp is calculated according to the ramp geometry, usage mix and the formulas identified in Section 5.1.2. The diesel price from Step 1 is then used to calculate the total fuel cost over the ramp's life, along with cost per trip for both loaded and unloaded trucks. Figure 37 is a screenshot showing a completed example for Step 3.

Step 3: Initial Ramp Design			
What are the dimensions of the ramp? (See Example on right)			
	Start	Ramp Length	Road End
Vertical Distance:	0	40	metres
Horizontal Distance:	0	500	1000 metres
This gives a grade of: 8.00%			
Fuel consumption estimate for the life of this ramp:			
	629881	Litres	
Total fuel cost:	\$ 629,881		
Cost per trip:	\$ 12.60	loaded	
	\$ 6.74	empty	

Figure 37: Screenshot of Step 3 Detail

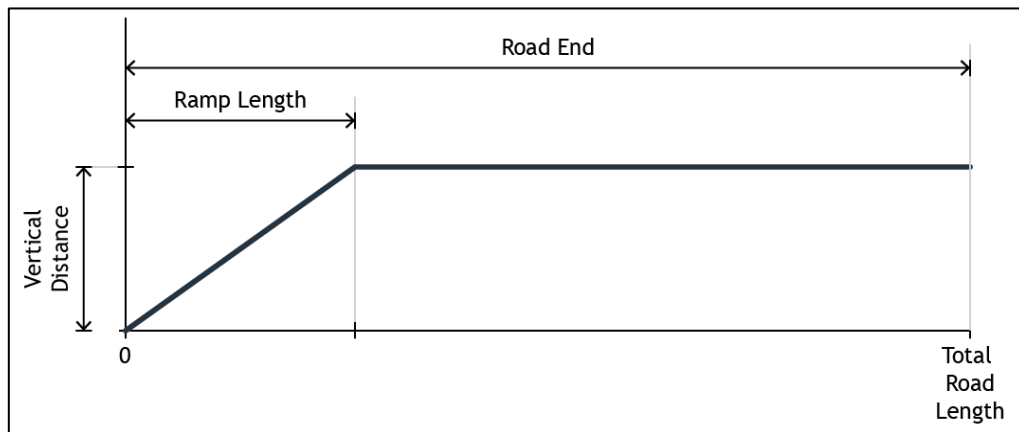


Figure 38: Step 3 Example Geometry

In Step 4 (Figure 39), the user can change the ramp length and see the effect this has on fuel costs. Like Step 3, fuel costs for the life of the road and per trip are displayed. Finally, a cost comparison is shown between the initial design (Step 3) and the alternative design (Step 4). A visual representation is also shown. A fuel cost comparison example can be found in Figure 39.

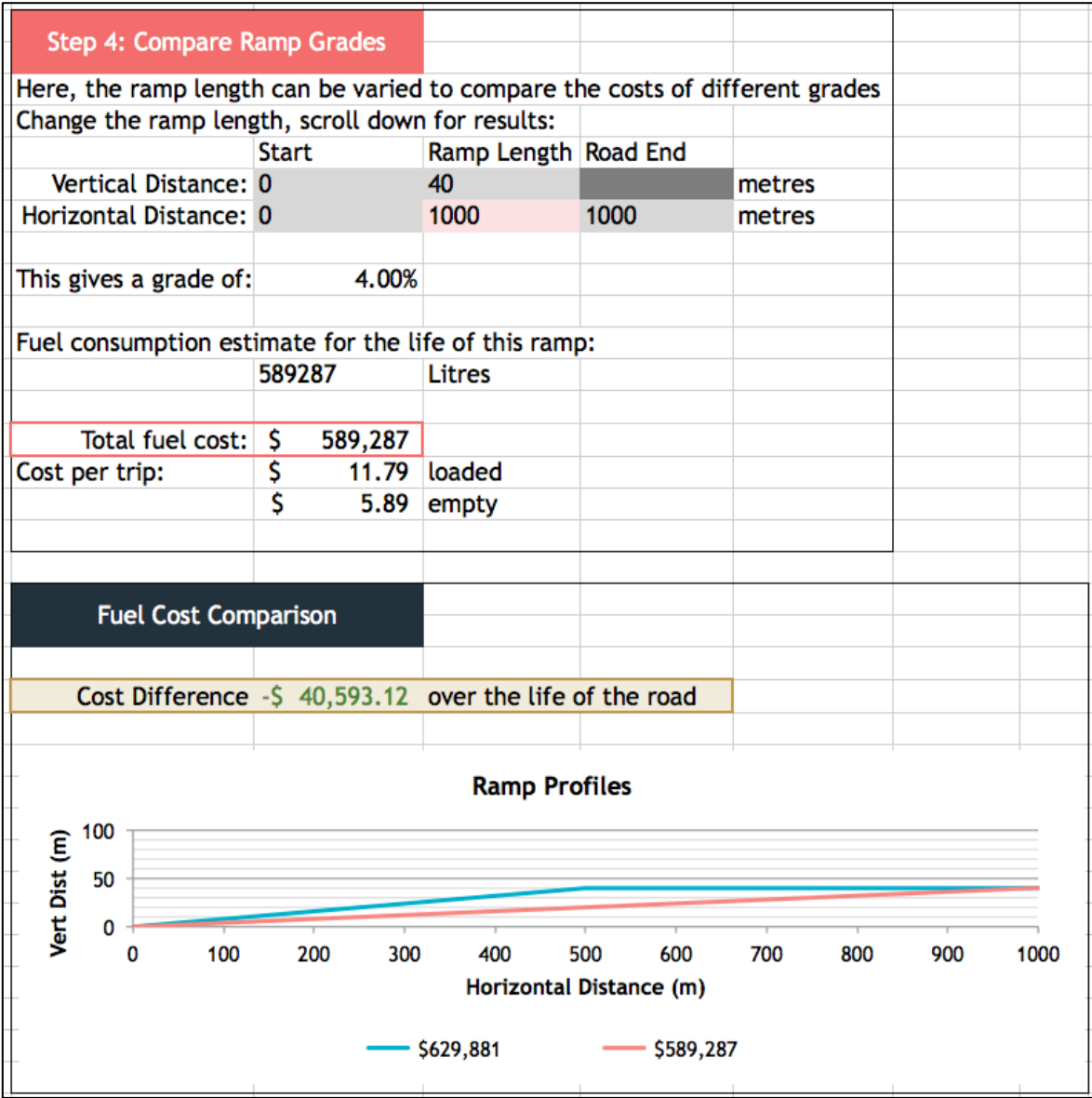


Figure 39: Step 4 and Fuel Cost Comparison

### **6.3 Benefits**

This tool uses the formulas found through the ramp analysis to facilitate optimal road design with respect to fuel consumption. It allows mining engineers to quickly calculate the fuel cost difference between ramp designs and compare this to construction and production costs. The mining team can then weigh their options, considering other constraints such as production targets, deadlines and machine availability in order to find the most effective solution.

Prior to this study, the relationship between fuel consumption and ramp grade was not quantified. Now that a cost estimation model is available, mining engineers can make better informed decisions when designing ramps. This is particularly useful for very large ramps or roads that will have high usage. It can also be used to assess the impact of diesel price fluctuations.

## Chapter 7

# Conclusions

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This study has successfully met the objectives set out in the introduction, namely:

- Conducting research into mine design, vehicle and operational factors that impact the fuel consumption of Caterpillar 785D off-highway trucks at the project sponsor's operations.
- The design and implementation of a data collection programme to record fuel consumption rates, vehicle operating data and road conditions as required.
- Analysis and comparison of variations in fuel consumption and the factors contributing to these variations.
- Quantifying fuel consumption in three haul road scenarios

### 7.1 Findings and Applications

Prior to this study, fuel costs were estimated using average hourly rates for the 785D truck fleet. Although it was understood that certain aspects of off-highway truck operations use more fuel than others (for example, driving on a ramp versus flat ground) the quantitative difference was not known.

As mentioned above, the study has established benchmark consumption rates in the three haul road scenarios, ascending ramps of various grades, stop-start driving (for example, at an intersection) and idling. This can be used to inform the haul road design decision-making process with the aim of designing the roads to optimise fuel consumption.



Fuel consumption in these three scenarios can be characterised by the quantities in Table 10. More information can be found in Chapter 5.

Table 10: Summary of Fuel Consumption Quantities

	Loaded	Unloaded
Ramps	Use formulas identified in Section 5.1.3 to calculate fuel use depending on ramp grade and length	
Stop-Start Driving	195 mL to accelerate from 0 to 10 km/h	310 mL to accelerate from 0 to 10 km/h
Idling	11.3 L/hour	

Some situations in which this information can be used to optimise fuel usage through haul road design include:

- Calculating the cost of fuel wasted by trucks queuing at a bottleneck and comparing this to the cost of modifying that road feature
- Calculating the fuel consumed by stoppages at a major intersection and using this to justify the construction of bypasses or implementing different traffic control measures

Ramps are slightly more complex so a Ramp Fuel Consumption Tool was created to simplify cost calculation. See Chapter 6 for more information on the tool's functionality. Once the fuel costs are calculated, that information could be used in situations like the following:

- A new ramp with a rise of 40 metres is required. Because of space constraints, switchbacks must be used to gain height. The cost of adding extra switchbacks to lengthen the road and reduce the grade can be compared to potential fuel savings.
- A ramp with a grade of 12% that was only intended for short-term use will actually be required for several months. Fuel costs for the remainder

of the ramp's life can be calculated and compared to the cost of rebuilding at a lower grade.

- A temporary ramp is required at short notice. A steep ramp is the simplest option, and also incurs fewer construction costs and production (time and equipment) losses. The Ramp Fuel Construction Tool can be used to check that the increased fuel used on a steep ramp will not exceed the construction and production savings.

This idea is illustrated in Figure 40. The total fuel cost will depend on the diesel price and the number and mix of loaded and unloaded trucks. Similarly, construction and production costs can vary greatly depending on a wide range of operational factors.

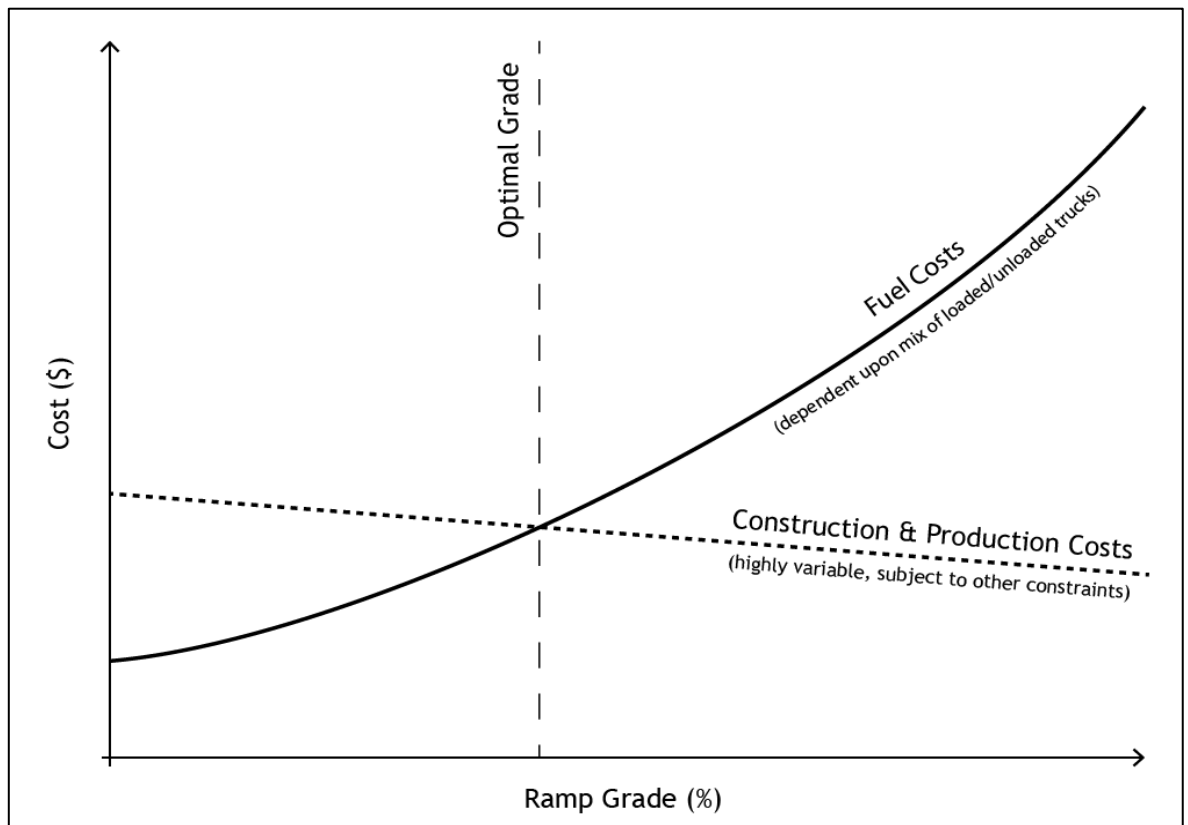


Figure 40: Relationship between Ramp Grade, Fuel Costs and Other Costs

Another application for this research stems from the use of condition monitoring data. This project successfully used condition monitoring data from three separate sources to quantify the relationship between ramp grades and fuel consumption.

This is significant in that the same data and methodology can be used to optimise other aspect of off-highway truck operation or to predict maintenance requirements. Examples may include:

- Monitoring the number of gear changes and using that information to predict transmission life
- Using GPS and VIMS data to monitor the intensity of work being done and using this to predict changes in site wide fuel consumption, increased component wear or premature failures.
- Monitoring cycle and wait times and using this to assign trucks to haul circuits in the most efficient way possible
- Observing when individual vehicles fuel consumption exceeds expected levels and using this to trigger a maintenance inspection notification

## **7.2 Recommendations**

For the purpose of estimating fuel costs, it is clear that while a simple average hourly fuel consumption rate can be appropriate for long term estimates, it is not adequate for estimates with high intensity haul routes. Any discrepancy between fuel cost estimates and actual consumption can be exacerbated by high diesel prices. Accordingly, if a high degree of accuracy is needed in short term estimates, the quantities summarised in Table 10 should be used to estimate fuel consumption on the relevant haul road features. Average hourly rates, whether from refuelling records or manufacturer specifications, should be reserved for calculating fuel consumed by medium or low intensity operations.

Any mine will always require ramps and sometimes steep ramps cannot be avoided. The Ramp Grade Calculation Tool described in Chapter 6 should be adopted and used to determine optimum ramp grades for new roads. This is particularly important for heavy use ramps and steep ramps as these situations offer the greatest opportunity for optimisation.

Like ramps, it is impossible to completely eliminate intersections from an open cut mining environment. Traffic rules such as giving way to loaded trucks are used by

some operations to reduce fuel waste, but this may also introduce unacceptable safety risks. With that in mind, the cost of fuel wasted through stopping and restarting at intersections should be calculated and compared to the cost of redesigning intersections in a way that allows trucks to avoid stopping without endangering other mine traffic. For high traffic intersections, this may involve separating heavy and light vehicles so that it is clear that other traffic must give way to haul trucks.

The cost of queuing at shovels should be calculated and compared to the shovel's hourly operating costs to determine acceptable waiting times for off-highway trucks. The cost of queuing at other bottlenecks should also be considered and eliminated where this can be done safely and cost effectively.

Another option highlighted in the literature is to turn the engine off while queuing, but in this situation such action is not likely to save fuel. This is because the 785D engine keeps running for approximately five minutes after the ignition is switched off in order to keep the turbocharger cooling system running. Unless the wait would exceed this time limit, no fuel would be saved. As a result, switching the ignition off whilst waiting cannot be recommended without further research.

If bottlenecks cannot be avoided, traffic signals could be implemented en route to these locations informing operators of the expected wait time. Operators can then regulate their speed by coasting on flat or downhill road sections (where safe to do so) with the aim of minimising queuing times while also saving fuel.

It is also recommended that this research be continued and extended in order to maximise its benefits. This is outlined in detail below.

### **7.3 Further Work**

As mentioned in the ramp grade analysis discussion, this project would benefit from the collection of more accurate GPS data. This would allow greater automation of the analysis process as ramp grades, start and finish points could be

accurately identified by the Matlab script. This in turn will allow a greater volume of data to be analysed more quickly with minimal human input. It is anticipated that the survey team could assist with this task

Building upon this point, the data processing method should also be automated to deal with a larger volume of data. Dealing with the different file types, time scales and synchronisation was somewhat labour intensive and could be improved. It is recommended that these methodology improvements be made before expanding this project to other sites or vehicles.

Once this has been completed, the analysis should be repeated with data from other 785D trucks. This will allow the original assumptions and results to be tested and validated while also increasing the number of samples included in the analysis. Ideally this would incorporate data collected throughout the year. This will ensure that seasonal variation is captured and built into the fuel consumption model.

Extending the project to other off-highway trucks in the fleet will ensure the company maximises the value of this research. As shown in Figure 41, the Caterpillar 785D is one of the smaller trucks used across the company's operations. It is possible that the larger trucks offer even greater opportunities to reduce fuel consumption. Notwithstanding any potential savings, fuel consumption due to haulage cannot be truly optimised without understanding and quantifying the fuel use of each different off-highway truck.

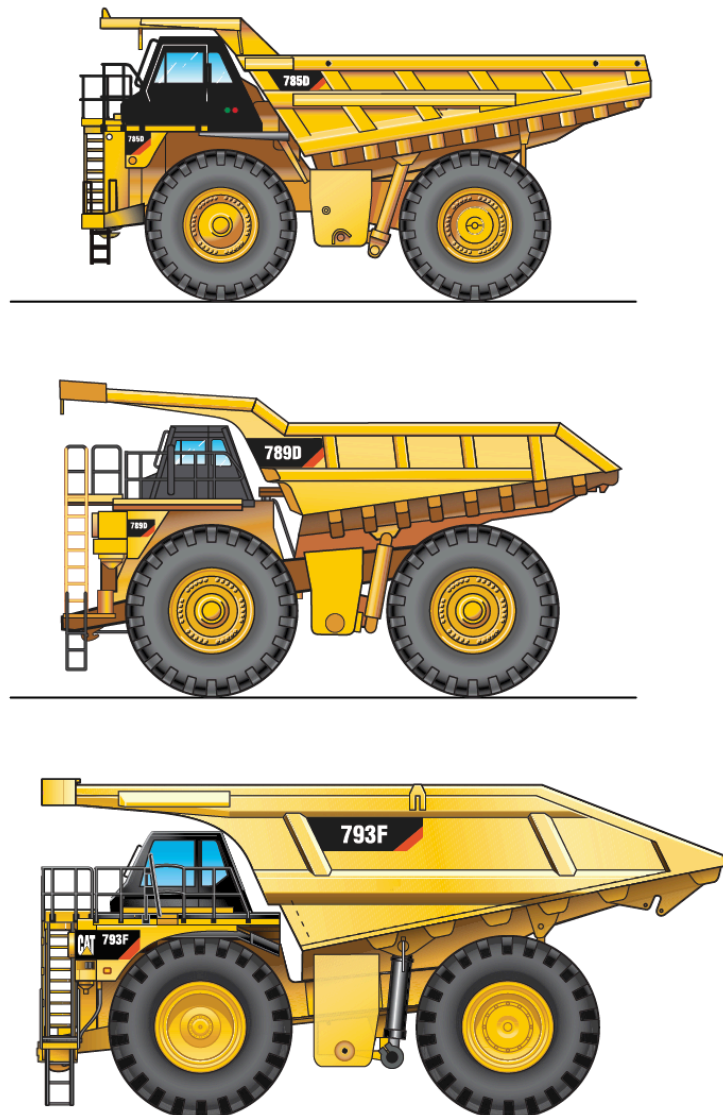


Figure 41: A selection of Caterpillar off-highway trucks used on New Hope sites (Caterpillar 2011, 2013, n.d.). These illustrations are roughly to scale, from top: 785D, 789D, 793F.

Driving style and particularly gear selection was another recurring theme throughout this study. Finding the optimum gearshift points and operating speeds for this particular fleet of 785D trucks is likely to offer fuel saving opportunities. This could likely form another undergraduate project for future engineering students. Any findings could be used to create operator training programs.

Finally, work should be done to identify other aspect of mine or off-highway truck operations that can be optimised through analysis of the collected data. Examples are provided in Section 7.1.

#### **7.4 Conclusions**

Optimisation of fuel consumption is not as simple as eliminating haul road features such as intersections and ramps from the open cut mining environment. There are many conflicting factors that must be considered including construction costs, safety, production and operational concerns. Any reduction in fuel costs will have a corresponding trade off in one of these other areas.

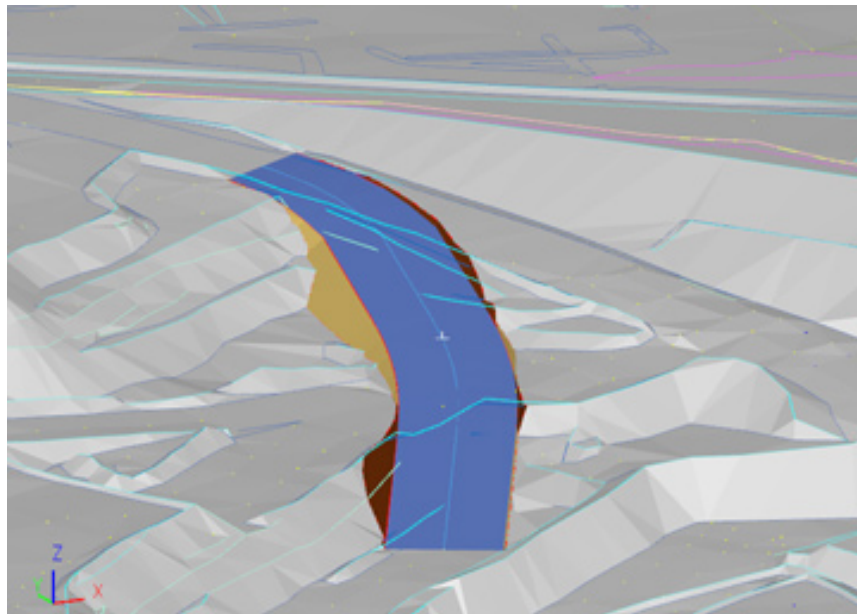


Figure 42: Haul road design must consider many factors (*Geovia* 2015)

As there are many variables influencing fuel consumption, optimisation cannot be achieved without first quantifying fuel usage rates in each operation's unique circumstances. This study focussed on benchmarking fuel consumption with respect to a specific site and truck model in defined operating contexts. With these quantities now defined, mining engineers can take steps to design new haul roads that will generate the lowest fuel cost possible in light of other constraints.

In order to make the most of optimisation opportunities, the fuel consumption of other haul vehicles must be determined. This will allow mining engineers to take an even more holistic approach to haul road design. Optimising fuel costs in this manner will not only provide an economic benefit to the mine operator, but it will reduce diesel consumption and emissions over the life of the mine.



## Appendices

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## **Appendix A – Project Specification**

**FOR** Kristy Kubler (0061037585)

**TOPIC** Optimisation of off-highway truck fuel consumption through mine haul road design

**SUPERVISORS** Dr Paul Baker, USQ  
Trent Knack, New Hope Group

**ENROLMENT** ENG4111 – S1, 2015 – EXT  
ENG4112 – S2, 2015 – EXT

**PROJECT AIM** To investigate variation in off-highway truck fuel consumption in an open cut coal mine; define the influence of haul road design on fuel consumption and understand the cost implications for the mining operation.

**SPONSORSHIP** New Hope Group

**PROGRAMME** Issue A, 18<sup>th</sup> March 2015

1. Research mine design and operational factors that impact the fuel consumption of Caterpillar 785 off-highway trucks as applicable to New Hope Coal at their open cut operations.
2. Design a data collection programme to record fuel consumption rates, vehicle operating data and environmental conditions, as appropriate.
3. Analyse variations in fuel consumption and road design factors contributing to instantaneous fuel consumption.

4. Evaluate different mine road design scenarios with respect to fuel consumption.
5. Prepare an academic dissertation on the research

As time permits

6. Create a decision making tool for mining engineers to improve understanding of mine design factors and their associated costs/savings in terms of fuel consumption.
7. Quantify any costs associated with different mine road designs and compare this to any saving in fuel costs.

## Appendix B – Matlab scripts

### Hobo Data Logger Conversion Script

```
%% Convert Fuel Burn data for analysis
% After importing data from the Hobo Data Logger, this script
will
% differentiate fuel burn to find instantaneous fuel burn in
Litres/hour at
% intervals of 1 second
% The file will export the data in csv format
clc;
%% Convert Timestamp to Serial Format
% Note, this will only work in 2015, you will need to manually
change the
% date below to make it work otherwise.
Time = datenum(T24) - datenum('1-jan-2015 00:00');
%% Sampled Time in seconds
TimeSample = Time*24*3600;
TimeSample = TimeSample';
%% Find time elapsed in seconds
% Note, Time is in the serial format
TimeTotal = Time(end)-Time(1);
% Need to convert this value to seconds
TimeTotal = 1 + TimeTotal*24*3600;
% Find time end
TimeEnd = TimeTotal + TimeSample(1);
% Display result for manual check
disp(['Time elapsed in seconds = ', num2str(TimeTotal)])
disp(['Time elapsed in hours = ', num2str(TimeTotal/3600)])
disp(['Time elapsed in days = ', num2str(TimeTotal/(3600*24))])
disp(' ')
%% Create a time array with 1 second timesteps
TimeEnd = ceil(TimeEnd); % round up to nearest whole number
TimeStart = floor(TimeSample(1));
TimeEven = TimeStart:1:TimeEnd; % from 1 up to end of sample
with 1 sec intervals
%% Smooth out fuel burn
% Delete zero entries and linearly interpolate in between
% This should be valid except for at smoko times or when parked
up. At these
% times, 100mL will be spread over a very long time period.
% There are no other instances where this will pose an issue
% The only options are 0, 100, 200 & 300
i = 1; % Captures indexes of Fuel to be kept
n = 2;
while n < length(Fuel)
    if Fuel(n) == 0
        n = n+1;
    else
        i(end+1) = n;
        n = n+1;
    end
end
end
%% Work out the fuel consumption in mL per second
% Pull out the timestamps recorded by i
Timei = TimeSample(i);
Fueli = Fuel(i);
% Use the difference in Timei to find mL per second
```

```

n = 2;
FuelR = zeros(size(Fueli));
while n < length(Fueli)
    if Fueli(n) > 0
        FuelR(n) = Fueli(n)/(Timei(n)-Timei(n-1));
        n = n+1;
    else
        n = n+1;
    end
end
%% Put the samples into the 1 second time sequence where they
belong
% Slot values into new longer Fuel2 vector and FuelRate vector
Fuel2 = zeros(size(TimeEven));
FuelRate = zeros(size(TimeEven));
n = 1;
j = 1;
while n < length(Timei) && j < length(TimeEven)
    if abs(Timei(n) - TimeEven(j)) < 0.001;
        Fuel2(j) = Fueli(n);
        FuelRate(j) = FuelR(n);
        n = n+1;
        j = j+1;
    else
        j = j+1;
    end
end
%% Need to spread the calculated values across the FuelRate
array
% Work backwards filling in gaps
n = length(FuelRate) - 1;
while n > 0
    if FuelRate(n) == 0
        FuelRate(n) = FuelRate(n+1);
        n = n - 1;
    else
        n = n - 1;
    end
end
%% Convert to Litres per Hour
FuelLH = (FuelRate./1000).*3600;
%% Plot to check
% mL per second
figure(1);
plot(TimeEven, FuelRate, TimeSample, Fuel,'o')
legend('Fuel Burn - mL per sec','Fuel Burn - DL Pulses')
%% Work out roughly average L/H (doesn't take into account
breaks)
% This is just a check in case a ridiculous figure is returned
AvgFuel = (sum(Fuel))/(TimeTotal/3.6);
disp(['Average Fuel Burn (L/hour) for this sample =
',num2str(AvgFuel)])
disp('Please note: Time spent parked up will distort this
result.')
disp(' ')
%% Transpose vectors
Timei = Timei';
TimeSample = TimeSample';
TimeEven = TimeEven';
FuelRate = FuelRate';
FuelLH = FuelLH';

```

```

FuelPulse = Fuel2';
%% Header records the first time from data so this can be
exported
TimeFormat = 'HH:MM:SS';
Header1 = {char(Date(1)), ',', datestr(T24(1),TimeFormat), ',', ','};
Header2 = {'Time Elapsed (secs),Fuel Pulse,Fuel Rate mL/sec,Fuel
Rate L/hr'};
Header1 = cell2mat(Header1);
Header1 = char(Header1);
Header2 = cell2mat(Header2);
Header2 = char(Header2);
%% Variables to be output: TimeStamp, Time Secs, FuelInterp,
FuelLH
output = [TimeEven FuelPulse FuelRate FuelLH];
%% Create file name
filename = char(Date(1));
filename = strrep(filename, '/', '-');
filename = [filename, '_', datestr(T24(1),TimeFormat), '_HB.csv'];
%% Export File
dlmwrite(filename,Header1,'');
dlmwrite(filename,Header2,'-append','delimiter','');
dlmwrite(filename,output,'-append');
disp('Check folder for csv file')
disp('The file has been named')
disp(filename)
disp(' ')

```

## SAFEmine Conversion Script

```
%% VERSION 2.0
%% Convert SafeMine data to meters and export to csv
% After importing SafeMine data into Matlab, this script will
convert the
% gps coordinates (Deg Latitude, Deg Longitude, Metres Altitude)
to metres.
% Altitude is measured in 1 metre increments.
% Find horizontal dist between altitude incrememnts
% Use this dist to find slope between altitude increments
% Find fuel burned over this distance and slope
% combined with VIMS and Hobo DataLogger data for further
analysis.
%
%
%% Important!!! Time imported should be UTC+00:00
%
%
clc;
close all;
%% Find time elapsed in seconds
% Note, Time is in the serial format
TimeTotal = Time(end)-Time(1);
% Need to convert this value to seconds
TimeTotal = TimeTotal*24*3600;
% Need to find the starting second and ending second
TimeTotal = ceil(TimeTotal);
TimeStart = floor(Time(1)*24*3600);
TimeEnd = TimeStart + TimeTotal;
% Display result for manual check
disp(['Time elapsed in seconds = ',num2str(TimeEnd)])
disp(['Time elapsed in hours = ',num2str(TimeTotal/3600)])
disp(' ')
%% Create a time array with 1 second timesteps
TimeEven =
(TimeStart/(24*3600)):(1/(24*3600)):(TimeEnd/(24*3600));
%% Use geod2ecef function to convert to metres
% Need to reduce the magnitude of numbers in the x and y
directions
% to make plots easier to read. Because of the location
% in the southern hemisphere, latitude will naturally be
negative and
% longitude naturally positive, hence the different signs in the
code below
% The constants are arbitrarily chosen to create an origin in a
convenient
% location for plotting. Also ensures that every SM data set can
be
% compared using same coordinate system.
flat = geod2ecef(Latitude, Longitude, Altitude);
flat(:,1) = flat(:,1) + 5020000;
flat(:,2) = flat(:,2) - 2590000;
%% Identify unique entries from Time
% Some time stamps double up so pull out the indexes of the
unique stamps
[Timeu, iu, ic] = unique(Time);
%% Map X, Y and Altitude coordinates to TimeEven
% X direction
X1 = (-1)*flat(:,1);
X = interp1(Timeu,X1(iu),TimeEven,'linear');
```

```

% Y direction
Y1 = flat(:,2);
Y = interp1(Timeu,Y1(iu),TimeEven,'linear');
% Altitude to be called Z
Z = interp1(Timeu,Altitude(iu),TimeEven,'linear');
%% Map Speed to TimeEven
SpeedEven = interp1(Timeu,Speed(iu),TimeEven,'linear');
%% Now there are evenly spaced coordinates in all directions
%
%
%
%% Find HORIZONTAL distance travelled at each timestep
% Start at the second data point and use pythagoras between n
and n-1
Horz = zeros(1,length(Z));
n = 2;
while n < length(Horz)
    Horz(n) = sqrt((X(n)-X(n-1))^2+(Y(n)-Y(n-1))^2);
    n = n + 1;
end
%% Need to find peaks and troughs of Altitude
% Use 'findpeaks' to figure out peaks and troughs
[temp, Max] = findpeaks(Z,'minpeakdistance',100);
[temp, Min] = findpeaks((Z.*(-1)),'minpeakdistance',100);
% To exclude the effects as the gradient levels out at the top
and bottom
% of ramps, take 2 seconds from the peak indices and add 5
seconds to the
% trough indices
Max = Max - 2;
Min = Min + 2;
% Make a new array which will have a '1' at the base of ramps
and a '2' at
% the top of ramps
Ramp = zeros(1,length(Z));
Ramp(Min) = 1;
Ramp(Max) = 2;
%% Find distance travelled between troughs and peaks (1's and
2's)
RLength = Horz; %RLength - Horizontal Ramp Length
% The following loop will find the culmulative distance covered
by the
% truck, but it resets to zero at every '1' or trough. It will
culmsum again
% until the next '1' is found.
n = 2;
while n < length(Horz)
    if Ramp(n) == 1
        RLength(n) = 0;
        n = n + 1;
    else
        RLength(n) = RLength(n) + RLength(n-1);
        n = n + 1;
    end
end
%% Find Altitude change between troughs and peaks (1's and 2's)
% Check Ramp array, hold values of 1's until a 2 is found, then
save
% difference in an array called RHeight for Ramp Height
RHeight = zeros(1,length(Z));
temp = 0;

```



```

n = 1;
while n < length(RHeight)
    if Ramp(n) == 1
        temp = Z(n);
        n = n + 1;
    elseif Ramp(n) == 2
        RHeight(n) = Z(n) - temp;
        n = n + 1;
    else
        n = n + 1;
    end
end
%% Divide change in Altitude by Distance (RHeight / RLength) to
get slope which can be used as a very rough guide during
analysis
temp = (RHeight+1) ./ RLength;
% Just keep the ones that correspond to peaks
Slope = zeros(1,length(Z));
Slope(:) = NaN;
Slope(Max) = temp(Max);
%% Plot to check
% Truck Path
% Original
figure(1);
plot3(X1,Y1,Altitude)
daspect([1 1 1])
% Interpolated
figure(2);
plot3(X,Y,Z)
daspect([1 1 1])
% Show Slopes to check if there are any crazy results
figure(3);
plot(TimeEven,Slope,'x')
axis([0 1 0 0.25])
% Show Elevation just for fun
figure(4);
plot(TimeEven,Z)
%% Concatenate arrays for export
TimeSM = TimeEven';
X = X';
Y = Y';
Z = Z';
SpeedEven = SpeedEven';
Ramp = Ramp';
RHeight = RHeight';
RLength = RLength';
Slope = Slope';
output = [TimeSM, X, Y, Z, SpeedEven, Ramp, RHeight, RLength,
Slope];
%% Header records the first time from data so this can be
exported
prompt = 'Enter the filename for this data: ';
Header1 = input(prompt,'s');
Header2 = {'TimeSM,X,Y,Z,Speed,Ramp S/F,Ramp Height, Ramp Length
H, Slope'};
Header2 = cell2mat(Header2);
Header2 = char(Header2);
%% Create file name
filename = Header1;
filename = [filename, '__SM.csv'];
%% Export File

```

```
dlmwrite(filename,Header1,'');  
dlmwrite(filename,Header2,'-append','delimiter','');  
dlmwrite(filename,output,'-append');  
disp('The file has been named')  
disp(filename)  
disp(' ')
```

## Combining VIMS, Hobo and SAFEmine data

```
%% Assemble 2.0
% Fixed up from the last version. This time, the code looks at
the
% timestamps for all three inputs (SM, Hobo and VIMS) and sorts
them into a
% 24 hour span of time, leaving blanks where there is no data.
%% Setup a global time
% 1 = 00:00:01 and 36400 = 00:00:00 (the next day)
GlobalSecs = 1:1:(24*3600);
GlobalSecs = GlobalSecs';
%% Align all times to Hobo Time
AdjSeconds = Seconds + 1; % add 1 seconds
AdjSecondsV = SecondsV - 617; % Take 10 mins 3 seconds off
%% Create matched arrays
% Now we want to create new arrays matched to global time
% Make a blank array
Blank = GlobalSecs;
Blank(:) = NaN;
% Start with Hobo
M_HB_FuelLhr = Blank;
M_HB_FuelmLsec = Blank;
M_HB_Secs = Blank;
n = 1;
i = 1;
if TimeElapsedsecs(i) < 1
    i = i + 1;
else
end
while n < length(GlobalSecs) && i < length(FuelRateLhr)
    if GlobalSecs(n) == TimeElapsedsecs(i)
        M_HB_Secs(n) = TimeElapsedsecs(i);
        M_HB_FuelLhr(n) = FuelRateLhr(i);
        M_HB_FuelmLsec(n) = FuelRateLsec(i);
        n = n + 1;
        i = i + 1;
    else
        n = n + 1;
    end
end
%
disp('Hobo Matched')
% Next is Safe Mine
n = 1;
i = 1;
M_SM_X = Blank;
M_SM_Y = Blank;
M_SM_Z = Blank;
M_SM_Speed = Blank;
M_SM_RampSF = Blank;
M_SM_RHeight = Blank;
M_SM_RLength = Blank;
M_SM_RSlope = Blank;
M_SM_Secs = Blank;
while AdjSeconds(i) < 1
    i = i + 1;
end
while n < length(GlobalSecs) && i < length(X)
    if GlobalSecs(n) == AdjSeconds(i)
        M_SM_X(n) = X(i);
```

```

        M_SM_Y(n) = Y(i);
        M_SM_Z(n) = Z(i);
        M_SM_Speed(n) = Speed(i);
        M_SM_RampSF(n) = RampSF(i);
        M_SM_RHeight(n) = RampHeight(i);
        M_SM_RLength(n) = RampLength(i);
        M_SM_RSlope(n) = Slope(i);
        M_SM_Secs(n) = AdjSeconds(i);
        n = n + 1;
        i = i + 1;
    else
        n = n + 1;
    end
end
%
disp('Safe Mine Matched')
% Finally VIMS
% Convert original time to serial time for checking
VIMStime = datenum(VIMSTimeTime);
% Procedure continues below
n = 1;
i = 1;
M_VIMStime = Blank;
M_ActualGear = Blank;
M_BodyPos = Blank;
M_EngFuelRate = Blank;
M_EngLoad = Blank;
M_EngSpd = Blank;
M_SelectGear = Blank;
M_GroundSpd = Blank;
M_ParkBrk = Blank;
M_Payload = Blank;
M_ServBk = Blank;
M_Throttle = Blank;
while AdjSecondsV(i) < 1
    i = i + 1;
end
while n < length(GlobalSecs) && i < length(ActualGear352)
    if GlobalSecs(n) == AdjSecondsV(i)
        M_VIMStime(n) = VIMStime(i);
        M_ActualGear(n) = ActualGear352(i);
        M_BodyPos(n) = BodyPos726(i);
        M_EngFuelRate(n) = EngFuelRate129(i);
        M_EngLoad(n) = EngLoad121(i);
        M_EngSpd(n) = EngSpd100(i);
        M_SelectGear(n) = GearSelect351(i);
        M_GroundSpd(n) = GroundSpd725(i);
        M_ParkBrk(n) = ParkBk453(i);
        M_Payload(n) = Payload728(i);
        M_ServBk(n) = ServBrkStatus3304(i);
        M_Throttle(n) = Thrott1Pos125(i);
        n = n + 1;
        i = i + 1;
    else
        n = n + 1;
    end
end
disp('VIMS Matched')
disp(' ')

```

```

%% Header records variable names
Header1 = {'Global Count,VIMS Time,SM Secs,X,Y,Z,SM Speed,Ramp
S/F,Ramp Height,Ramp Length,Slope,Actual Gear,Select Gear,Body
Pos,Eng Fuel Rate,Eng Load,Eng Speed,Ground Speed,Park
Brake,Payload,Service Brake,Throttle,HB Secs,Fuel Rate
mL/sec,Fuel Rate L/hr'};
Header1 = cell2mat(Header1);
Header1 = char(Header1);
%% Variables to be output: TimeStamp, Time Secs, FuelInterp,
FuelLH
output = [GlobalSecs M_VIMSTime M_SM_Secs M_SM_X M_SM_Y M_SM_Z
M_SM_Speed M_SM_RampSF M_SM_RHeight M_SM_RLength M_SM_RSlope
M_ActualGear M_SelectGear M_BodyPos M_EngFuelRate M_EngLoad
M_EngSpd M_GroundSpd M_ParkBrk M_Payload M_ServBk M_Throttle
M_HB_Secs M_HB_FuelmLsec M_HB_FuelLhr];
%% Create file name
filename = input('enter date DDMMYYYY: ','s');
filename = [filename, '_Comb.csv'];
%% Export File
dlmwrite(filename,Header1,'');
dlmwrite(filename,output,'-append');
disp('Check folder for csv file')
disp('The file has been named')
disp(filename)
disp(' ')
%% Will need to use Payload_ext.m
% This script will pull out only loaded trucks
% Then you can single out speeds/throttle pos etc

```

### Ramp Analysis – Curve Matching Script

Please note: Curve fitting tool was initial used to identify best degree polynomials and some sections of this code were generated by the Curve Fitting tool

```

%% Ramp Analysis
% After reading in the ramp samples this codes will determine a
formula
% that can be used to estimate fuel burn in L / km for trucks
operating
% across ramps of different grades.
%
close all;
clc;
%% Payload Distribution
% Plots the Payloads on a histogram type chart
X = 0:5:160;
figure(1)
set(gca,'FontSize',20)
hist(Payload,X,'FaceColour','r')
title('Payload Distribution');
xlabel('Payload in Metric Tons');
ylabel('Count');
xlim([-10 160]);
%% Plot raw data
figure(2)
set(gca,'FontSize',20)
scatter(Slope*100,FuelMLm,'x')
title('Fuel Consumption vs Slope (Raw Data)');
xlabel('Slope (%)');
ylabel('Fuel Consumption (L / km)')

```

```

%% Delete according to drive style
% Saves all samples with a '1' driving style
n = 1;
i = 1;
Payload2 = 1;
Slope2 = 1;
FuelMLm2 = 1;
while n < length(DriveStyle)
if DriveStyle(n) == 1
    Payload2(i) = Payload(n);
    Slope2(i) = Slope(n);
    FuelMLm2(i) = FuelMLm(n);
    i = i + 1;
    n = n + 1;
else
    n = n + 1;
end
end
%% Seperate Loaded and Unloaded
% If Payload is greater than 5 (arbitrarily chosen so I know it
keeps 0's)
% that data goes in arrays ending in E (for empty), otherwise
ending in 3
n = 1;
i = 1;
j = 1;
% Empties
PayloadE = 1;
SlopeE = 1;
FuelMLmE = 1;
% Full
Payload3 = 1;
Slope3 = 1;
FuelMLm3 = 1;
while n < length(Payload2)
if Payload2(n) < 5
    PayloadE(i) = Payload2(n);
    SlopeE(i) = Slope2(n);
    FuelMLmE(i) = FuelMLm2(n);
    i = i + 1;
    n = n + 1;
else
    Payload3(j) = Payload2(n);
    Slope3(j) = Slope2(n);
    FuelMLm3(j) = FuelMLm2(n);
    j = j + 1;
    n = n + 1;
end
end
%% Put limits on Payload Range
n = 1;
i = 1;
Payload4 = 1;
Slope4 = 1;
FuelMLm4 = 1;
while n < length(Payload3)
    if Payload3(n) < 143 && Payload3(n) > 112.5
        Payload4(i) = Payload3(n);
        Slope4(i) = Slope3(n);
        FuelMLm4(i) = FuelMLm3(n);
        i = i + 1;
    end
end

```

```

        n = n + 1;
    else
        n = n + 1;
    end
end
%% Plot with different colours
figure(3)
set(gca,'FontSize',20)
scatter(SlopeE*100,FuelMLmE,'x')
hold all
scatter(Slope3*100,FuelMLm3,'x','r')
hold all
scatter(Slope4*100,FuelMLm4,'x','k')
title('Fuel Consumption vs Slope (Acceptable Runs)');
xlabel('Slope (%)');
ylabel('Fuel Consumption (L / km)')
legend('Empty Trucks','Under/Overloaded','Loaded Trucks','Location','NorthWest')
%% Fit polynomials for loaded trucks
% Try cubic and 5th degree polynomials
% Find coefficients for cubic
[p3,s3,mu3] = polyfit(Slope4,FuelMLm4,3);
%
% For some reason, when I use the above, the value of p3 is not
the right
% coefficients, no idea what's happening so just find p3 again
and use this
% one for graphing.
%
p3 = polyfit(Slope4,FuelMLm4,3);
disp('Cubic Coefficients for Loaded Trucks =')
disp(p3)
% Find coefficients for 5th deg
[p5,s5,mu5] = polyfit(Slope4,FuelMLm4,5);
p5 = polyfit(Slope4,FuelMLm4,5); % see comment above
disp('5th Deg Coefficients for Loaded Trucks =')
disp(p5)
% Use polyval to make arrays for plotting
X = 0:0.001:0.25;
loaded3 = polyval(p3,X);
loaded5 = polyval(p5,X);
% Determine R^2 values and therefore best fit
mu = mean(FuelMLm4);
S = sum((FuelMLm4 - mu).^2);
J3 = sum((polyval(p3,Slope4)-FuelMLm4).^2);
J5 = sum((polyval(p5,Slope4)-FuelMLm4).^2);
r2_3 = 1-J3/S;
r2_5 = 1-J5/S;
% Error
[error3,delta3] = polyval(p3,Slope4,s3,mu3);
%ste = sqrt(diag(inv(s3.R)*inv(s3.R')))./s3.normr.^2./s3.df)
%% Plot functions
figure(4)
plot(X*100,loaded3,X*100,loaded5)
hold all
scatter(Slope4*100,FuelMLm4,'o','r')
set(gca,'FontSize',20)
title('Curve Fitting for Loaded Trucks');
xlabel('Slope (%)');
ylabel('Fuel Consumption (L / km)')
legend('3rd Degree','5th Degree','Data','Location','NorthWest')

```

```

%% Fit polynomials for Empty Trucks
% Find coefficients for cubic
[e3,se3,mue3] = polyfit(SlopeE,FuelMLmE,3);
e3 = polyfit(SlopeE,FuelMLmE,3);
disp('Cubic Coefficients for Empty Trucks =')
disp(e3)
% Find coefficients for 5th deg
[e5,se5,mue5] = polyfit(SlopeE,FuelMLmE,5);
e5 = polyfit(SlopeE,FuelMLmE,5);
disp('5th Deg Coefficients for Empty Trucks =')
disp(e5)
empty3 = polyval(e3,X);
empty5 = polyval(e5,X);
% Determine R^2 values and therefore best fit
mu = mean(FuelMLmE);
S = sum((FuelMLmE - mu).^2);
Je3 = sum((polyval(e3,SlopeE)-FuelMLmE).^2);
Je5 = sum((polyval(e5,SlopeE)-FuelMLmE).^2);
re2_3 = 1-Je3/S;
re2_5 = 1-Je5/S;
%% Plot curve fitting
figure(5)
plot(X*100,empty3,X*100,empty5)
hold all
scatter(SlopeE*100,FuelMLmE,'o','r')
set(gca,'FontSize',20)
title('Curve Fitting for Empty Trucks');
xlabel('Slope (%)');
ylabel('Fuel Consumption (L / km)');
legend('3rd Degree','5th Degree','Data','Location','SouthWest')
hold off
%% Plot functions
%% Fit: Loaded 'Fuel Consumption vs Ramp Grade (3rd Degree
Polynomial)'.
[xData, yData] = prepareCurveData( Slope4, FuelMLm4 );

% Set up fittype and options.
ft = fittype( 'poly3' );
opts = fitoptions( ft );
opts.Lower = [-Inf -Inf -Inf -Inf];
opts.Upper = [Inf Inf Inf Inf];

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

% Plot fit with data.
figure(6)
h = plot( fitresult, xData, yData, 'predfunc', 0.95 );
% Labels
set(gca,'FontSize',20,'LineWidth',1)
title('Fuel Consumption vs Slope - Loaded Trucks');
xlabel( 'Slope (%)' );
ylabel( 'Fuel Consumption (L / km)' );
legend( h, 'Scatter Data', '3rd Degree Polynomial', 'Lower
bounds (95% Confidence)', 'Upper bounds (95% Confidence)',
'Location', 'NorthWest' );
grid on
%% Fit: Loaded 'Fuel Consumption vs Ramp Grade (5th Degree
Polynomial)'.
[xData, yData] = prepareCurveData( Slope4, FuelMLm4 );

```



```

% Set up fittype and options.
ft = fittype( 'poly5' );
opts = fitoptions( ft );
opts.Lower = [-Inf -Inf -Inf -Inf];
opts.Upper = [Inf Inf Inf Inf];

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

% Plot fit with data.
figure(7)
h = plot(fitresult, xData, yData, 'predfunc', 0.95);
% Labels
set(gca, 'FontSize',20, 'LineWidth',1)
title('Fuel Consumption vs Slope - Loaded Trucks');
xlabel( 'Slope (%)' );
ylabel( 'Fuel Consumption (L / km)' );
legend( h, 'Scatter Data', '5th Degree Polynomial', 'Lower
bounds (95% Confidence)', 'Upper bounds (95% Confidence)',
'Location', 'NorthWest' );
grid on
%% Fit: Empty 'Fuel Consumption vs Ramp Grade (3rd Degree
Polynomial)'.
[xData, yData] = prepareCurveData( SlopeE, FuelMLmE );

% Set up fittype and options.
ft = fittype( 'poly3' );
opts = fitoptions( ft );
opts.Lower = [-Inf -Inf -Inf -Inf];
opts.Upper = [Inf Inf Inf Inf];

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

% Plot fit with data.
figure(8)
h = plot(fitresult, xData, yData, 'predfunc', 0.95);
% Labels
set(gca, 'FontSize',20, 'LineWidth',1)
title('Fuel Consumption vs Slope - Empty Trucks');
xlabel( 'Slope (%)' );
ylabel( 'Fuel Consumption (L / km)' );
legend( h, 'Scatter Data', '3rd Degree Polynomial', 'Lower
bounds (95% Confidence)', 'Upper bounds (95% Confidence)',
'Location', 'NorthWest' );
grid on
%% Fit: Empty 'Fuel Consumption vs Ramp Grade (5th Degree
Polynomial)'.
[xData, yData] = prepareCurveData( SlopeE, FuelMLmE );

% Set up fittype and options.
ft = fittype( 'poly5' );
opts = fitoptions( ft );
opts.Lower = [-Inf -Inf -Inf -Inf];
opts.Upper = [Inf Inf Inf Inf];

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );

```

```
% Plot fit with data.
figure(9)
h = plot(fitresult, xData, yData, 'predfunc', 0.95);
% Labels
set(gca, 'FontSize', 20, 'LineWidth', 1)
title('Fuel Consumption vs Slope - Empty Trucks');
xlabel('Slope (%)');
ylabel('Fuel Consumption (L / km)');
legend(h, 'Scatter Data', '5th Degree Polynomial', 'Lower
bounds (95% Confidence)', 'Upper bounds (95% Confidence)',
'Location', 'NorthWest');
grid on
```

## Stop Start Analysis

Two scripts were used, StopStart and StopStart2. The first extracts relevant data from each day's combined data. StopStart2 then analyses all the extracted data relevant to Stop-Start driving.

```
%% Stop - Start Analysis
% Read in a combo file manually, then sue this script to collect
samples
%% Intro
% Need array for start and finishes, need array for counts.
counts will be
% used to inspect elements like throttle, load.
%% Convert VIMS fuel to mL per second
Fuel = EngFuelRate*1000/3600;
%% Labelling start and finishes
Stst = GroundSpeed;
Stst(:) = 0;
Counter = Stst;
% Loop to check for 0 km/h - 10 km/h samples
n = 1;
while n < length(Stst)
if GroundSpeed(n) < 1 && GroundSpeed(n+1) > 1 && BodyPos(n) <
100
    Stst(n) = 1;
    Counter(n) = 1;
    n = n + 1;
    while GroundSpeed(n) >= GroundSpeed(n-1)
        if GroundSpeed(n) >= 10
            Stst(n) = 2;
            Counter(n) = Counter(n-1)+1;
            n = n + 1;
            break
        elseif GroundSpeed(n) < 10
            Counter(n) = Counter(n-1)+1;
            n = n + 1;
            continue
        else
            n = n + 1;
            continue
        end
    end
end
else
    n = n + 1;
end
end
%% Tallying fuel
n = 2;
FuelSum = Stst;
FuelSum(1) = Fuel(1);
while n < length(Stst)
    if Stst(n) == 1
        FuelSum(n) = 0;
        n = n + 1;
    else
        FuelSum(n) = FuelSum(n-1) + Fuel(n);
        n = n + 1;
    end
end
end
```

```

%% Averaging Engine Load
%% Sorting the results
% First find all indices in Stst that equal 2
Twos = find(Stst>1);
Results = FuelSum(Twos);
% Now record Payload, Counter, Fuel mL/sec
PayRes = Payload(Twos);
CounterRes = Counter(Twos);
FuelTimeRes = Results./(CounterRes-1);
% Split into full and empty
Empty = find(PayRes<5);
Full = find(PayRes>10);
% For Empty
ResultsE = Results(Empty);
PayE = PayRes(Empty);
CounterE = CounterRes(Empty);
FuelTimeE = FuelTimeRes(Empty);
% For Full
ResultsF = Results(Full);
PayF = PayRes(Full);
CounterF = CounterRes(Full);
FuelTimeF = FuelTimeRes(Full);
%% Plot
% Bins for histogram plot
bins = 0:30:600;
% Empty Trucks
figure(1)
set(gca,'FontSize',20)
hist(ResultsE,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Empty Trucks)');
xlabel('Fuel Consumed (mL)');
ylabel('Samples')
% Full Trucks
figure(2)
set(gca,'FontSize',20)
hist(ResultsF,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Full Trucks)');
xlabel('Fuel Consumed (mL)');
ylabel('Samples')
%% Exporting data
%% Header variable names for master file
Header1 =
{'ActualGear,SelectGear,BodyPos,EngFuelRate,EngLoad,EngSpeed,GroundSpeed,StopStart,Fuel,FuelSum,Counter,ParkBrake,Payload,ServiceBrake,Throttle'};
Header1 = cell2mat(Header1);
Header1 = char(Header1);
%% Header variable names for sample files
Header2 = {'Fuel,Count,Fuel mL/sec,Payload'};
Header2 = cell2mat(Header2);
Header2 = char(Header2);
%% Variables to be output:
% For master file
output1 = [ActualGear SelectGear BodyPos EngFuelRate EngLoad EngSpeed GroundSpeed Stst Fuel FuelSum Counter ParkBrake Payload ServiceBrake Throttle];
% For empty trucks
output2 = [ResultsE CounterE FuelTimeE PayE];

```

```

% For full trucks
output3 = [ResultsF CounterF FuelTimeF PayF];
%% Create file name
filename = input('enter date DDMMYYYY: ', 's');
filename1 = [filename, '_Stop_.csv'];
filename2 = [filename, '_StopE.csv'];
filename3 = [filename, '_StopL.csv'];
%% Export Files
% For master file
dlmwrite(filename1, Header1, '');
dlmwrite(filename1, output1, '-append');
disp('Check folder for csv file')
disp(filename1)
disp(' ')
% For empty trucks
dlmwrite(filename2, Header2, '');
dlmwrite(filename2, output2, '-append');
disp('Check folder for csv file')
disp(filename2)
disp(' ')
% For full trucks
dlmwrite(filename3, Header2, '');
dlmwrite(filename3, output3, '-append');
disp('Check folder for csv file')
disp(filename3)
disp(' ')

```

```

%% StopStart2
% After using "StopStart" to collect all results, use
"StopStart2" to plot
% the results
%% Exclude all samples with a duration of 9 seconds or longer
% Empty Trucks
n = 1;
while n < length(EmptyCount)
    if EmptyCount(n) > 9
        EmptyTime(n) = NaN;
        FuelEmpty(n) = NaN;
        n = n + 1;
    else
        n = n + 1;
    end
end
% Full Trucks
n = 1;
while n < length(FullCount)
    if FullCount(n) > 9
        FullTime(n) = NaN;
        FuelFull(n) = NaN;
        n = n + 1;
    else
        n = n + 1;
    end
end
%% Mean, Standard Deviation etc for the VOLUME
% Empty
meanE = nanmean(FuelEmpty);
stdE = nanstd(FuelEmpty);
semE = nanstd(FuelEmpty)/sqrt(length(FuelEmpty));
% Loaded
meanL = nanmean(FuelFull);
stdL = nanstd(FuelFull);
semL = nanstd(FuelFull)/sqrt(length(FuelFull));
% Print results
disp('For Empty Trucks')
disp('Mean fuel consumption (mL):')
disp(meanE)
disp('Standard deviation (mL):')
disp(stdE)
disp('Standard error of the mean (mL):')
disp(semE)
disp(' ')
disp('For Loaded Trucks')
disp('Mean fuel consumption (mL):')
disp(meanL)
disp('Standard deviation (mL):')
disp(stdL)
disp('Standard error of the mean (mL):')
disp(semL)
disp(' ')
%% Mean, Standard Deviation etc for the RATE
% Empty
meanEmpty = nanmean(EmptyTime);
stdEmpty = nanstd(EmptyTime);
varEmpty = nanvar(EmptyTime);
semEmpty = nanstd(EmptyTime)/sqrt(length(EmptyTime));
% Loaded
meanLoaded = nanmean(FullTime);

```

```

stdLoaded = nanstd(FullTime);
varLoaded = nanvar(FullTime);
semLoaded = nanstd(FullTime)/sqrt(length(FullTime));
% Print results
disp('For Empty Trucks')
disp('Mean fuel consumption (mL/sec):')
disp(meanEmpty)
disp('Standard deviation (mL/sec):')
disp(stdEmpty)
disp('Standard error of the mean (mL/sec):')
disp(semEmpty)
disp('This gives a mean fuel rate in L/hour of:')
disp(meanEmpty*3.6)
disp(' ')
disp('For Loaded Trucks')
disp('Mean fuel consumption (mL/sec):')
disp(meanLoaded)
disp('Standard deviation (mL/sec):')
disp(stdLoaded)
disp('Standard error of the mean (mL/sec):')
disp(semLoaded)
disp('This gives a mean fuel rate in L/hour of:')
disp(meanLoaded*3.6)
disp(' ')
%% Plot for mL/sec
% Bins for histogram plot
bins = 0:2:80;
% Empty Trucks
figure(1)
set(gca,'FontSize',20)
hist(EmptyTime,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Empty Trucks)');
xlabel('Fuel Consumed (mL/sec)');
ylabel('Samples')
% Full Trucks
figure(2)
set(gca,'FontSize',20)
hist(FullTime,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Full Trucks)');
xlabel('Fuel Consumed (mL/sec)');
ylabel('Samples')
%% Plot for fuel volume mL
% Bins for histogram plot
bins = 0:20:700;
% Empty Trucks
figure(3)
set(gca,'FontSize',20)
hist(FuelEmpty,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Empty Trucks)');
xlabel('Fuel Consumed (mL)');
ylabel('Samples')
% Full Trucks
figure(4)
set(gca,'FontSize',20)
hist(FuelFull,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Full Trucks)');
xlabel('Fuel Consumed (mL)');

```

```
ylabel('Samples')
%% Plot for count
% Bins for histogram plot
bins = 0:1:12;
% Empty Trucks
figure(5)
set(gca,'FontSize',20)
hist(EmptyCount,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Empty
Trucks)');
xlabel('Time (seconds)');
ylabel('Samples')
% Full Trucks
figure(6)
set(gca,'FontSize',20)
hist(FullCount,bins)
title('Fuel Burn When Acceleration from 0 to 10 kmph (Full
Trucks)');
xlabel('Time (seconds)');
ylabel('Samples')
```



## Idling Analysis

Two scripts were used, Idle1 and Idle2. The first extracts relevant data from each day's combined data. Idle2 then analyses all the extracted data relevant to idling behaviour.

```
%% Idling Analysis P1
% Read in combo files and export data relevant to idling
n = 1;
i = 1;
% Set up an array to capture samples. Values will be overwritten
IdleSamples = [1;1;1];
EngineRPM = [1;1;1];
EngineLoad = [1;1;1];
%% Loop to extract suitable values
while n < length(EngFuelRate)
    % Speed, Park Brake and Throttle used to ensure stationary
    if GroundSpeed(n) == 0 && ParkBrake(n) > 100 && Throttle(n)
    < 1 && EngFuelRate(n) > 0
        IdleSamples(i) = EngFuelRate(n);
        EngineRPM(i) = EngSpeed(n);
        EngineLoad(i) = EngLoad(n);
        i = i + 1;
        n = n + 1;
    else
        n = n + 1;
    end
end
%% Plots
% Plot the results so can visually check if anything went wildly
wrong
bins = 0:1:25;
figure(1)
hist(IdleSamples,bins)
% Display mean just for interest
mean(IdleSamples)
%% Header variable names for sample files
Header = {'Fuel,RPM,Load'};
Header = cell2mat(Header);
Header = char(Header);
%% Variables to be output:
output = [IdleSamples EngineRPM EngineLoad];
%% Create file name
filename = input('enter date DDMMYYYY: ','s');
filename = [filename, '_Idle.csv'];
%% Export Files
dlmwrite(filename,Header,'');
dlmwrite(filename,output,'-append');
disp('Check folder for csv file')
disp(filename)
disp(' ')
%% After this is run, save the IdleSamples in a new file and use
with
%% Idling Analysis P2
%

```

```
%% Idling Analysis P2
% Read in collected idling data
```

```

%% Some 0 values are in the array which distort the results so
they will
% be replaced with NaN
n = 1;
while n < length(IdleSamples)
    if IdleSamples(n) == 0
        IdleSamples(n) = NaN;
        n = n + 1;
    else
        n = n + 1;
    end
end
%% Plot results
figure(1)
bins = 0:0.5:25;
hist(IdleSamples,bins)
set(gca,'FontSize',20)
title('Fuel Burn While Idling');
xlabel('Fuel Consumption Rate (L/hour)');
ylabel('Samples');
%% Calculate mean etc
mean = nanmean(IdleSamples);
std = nanstd(IdleSamples);
sem = nanstd(IdleSamples)/sqrt(length(IdleSamples));
%% Display results
disp('Mean rate of fuel consumption (L/hour):')
disp(mean)
disp('Standard deviation (L/hour):')
disp(std)
disp('Standard error of the mean (L/hour):')
disp(sem)

```

## Appendix C – Ramp Grade Data Samples

Slope	Full	Payload	Fuel ML/m	Drive Style
0.67%	0	0	4.228177977	2
1.73%	1	121	8.517157212	1
1.54%	1	122.8	7.787136966	1
1.54%	1	126.8	7.281500044	1
1.15%	0	0	4.039447979	2
1.47%	1	128.1	7.406908626	2
4.94%	0	0	5.642146837	1
2.61%	1	132.5	9.79048365	2
6.75%	0	0	9.15495974	1
3.00%	1	138.2	15.75787894	3
3.79%	1	135.9	13.59211025	1
1.31%	1	130.1	8.405379443	1
12.86%	1	137.4	24.90000474	2
1.44%	0	0	4.427775975	1
3.50%	1	140.6	10.74838774	2
6.28%	1	115.2	14.94023904	2
4.16%	1	118.5	13.16062894	2
5.80%	0	0	7.735447689	1
5.05%	1	115.8	13.26761014	2
5.73%	0	0	5.939215204	2
1.19%	0	0	4.936454896	2
6.09%	1	106.2	14.35406699	1
4.01%	0	0	4.875250932	1
3.07%	0	0	3.941193211	1
6.00%	1	132.8	16.29083426	1
5.68%	0	0	6.38781111	1
6.99%	1	126.1	16.60693995	2
5.73%	0	0	7.360758976	1
2.18%	0	0	6.681190995	2
5.65%	1	127.4	14.48046903	2
5.68%	0	0	5.203405866	1
6.46%	1	142	14.93983687	1
0.95%	1	142	5.514413756	2
1.51%	0	0	4.266166175	1
8.79%	1	134.5	17.57469244	1
2.01%	0	0	4.561673723	1
5.89%	1	126.1	13.88187784	2
11.14%	1	126.1	16.70378619	2
4.21%	0	0	5.07371814	1
7.11%	1	121.5	15.79778831	1
5.63%	0	0	4.827303227	2
1.77%	0	0	1.24003543	2
7.21%	1	131.6	16.02820965	1
5.49%	0	0	4.312203536	2
6.84%	1	135	14.57763338	2
3.80%	0	0	5.0613691	2
1.34%	0	0	5.004144132	1
11.60%	1	136.7	18.56579253	2
4.11%	1	129.1	16.43385374	2

Slope	Full	Payload	Fuel ML/m	Drive Style
4.22%	0	0	5.015055693	2
1.09%	0	0	4.651812656	1
5.89%	0	127.8	14.12699581	2
1.71%	1	116.7	6.427836819	2
1.27%	0	0	5.178215143	1
6.43%	1	123.7	12.68310111	1
4.21%	0	0	3.3043076	2
1.43%	0	0	5.861678367	1
5.98%	1	119.5	13.95381288	1
5.77%	0	0	4.740313273	2
1.35%	0	0	5.391319975	1
5.76%	1	119.4	15.40772909	2
5.34%	0	0	4.961832061	2
8.63%	0	0	4.451807164	2
1.42%	0	0	5.848851498	2
5.54%	1	127.3	14.03042387	2
4.74%	0	0	4.897014305	2
6.57%	1	130	15.19632003	1
5.62%	0	0	5.856995596	2
4.63%	0	0	3.470776066	2
6.73%	1	144.1	16.83501684	1
3.82%	0	0	4.302664457	2
7.11%	0	0	5.925937778	2
1.40%	0	0	5.028028585	2
10.05%	1	127.9	20.10252287	1
4.86%	0	0	5.207971669	1
6.13%	1	136.5	14.16973039	1
0.83%	1	136.5	4.980286366	1
3.75%	0	0	4.014344591	2
6.39%	1	115.8	12.3811412	1
1.87%	1	113.8	4.511237633	2
4.42%	0	0	4.415023652	1
4.46%	0	0	3.979370941	2
3.59%	1	122.5	11.27337945	2
1.62%	1	122.5	6.842684222	1
3.43%	0	0	4.16115925	1
1.39%	0	0	4.431483433	2
5.39%	1	146.3	14.91891845	1
3.61%	0	0	4.29774798	2
1.65%	0	0	5.196913912	2
5.97%	1	112.5	14.57032529	2
6.05%	0	0	4.839099927	2
2.95%	1	128.1	12.79288985	1
5.58%	0	0	9.7727828	1
7.94%	0	0	8.287173005	2
1.63%	0	0	6.734143335	2
10.00%	1	125.3	20	1
1.45%	0	0	5.631437757	2
3.87%	0	0	6.99720112	2

Slope	Full	Payload	Fuel ML/m	Drive Style
3.96%	1	133.4	16.3059007	2
6.28%	1	115.2	13.33854845	1
0.89%	1	115.2	5.731476933	1
5.46%	0	0	8.777405009	2
9.40%	1	120.9	17.76198934	2
1.79%	1	120.9	6.564853846	1
6.02%	0	0	6.95302843	2
9.40%	1	123.2	19.38103107	1
5.83%	0	0	6.999030903	1
6.11%	1	116.6	14.73169987	1
0.97%	1	116.6	5.470758794	2
5.39%	0	0	9.128053551	2
5.48%	1	113.8	15.52511416	1
3.97%	0	0	6.522972206	2
1.89%	0	0	2.436953651	2
10.29%	1	114.8	18.00874711	1
3.83%	0	0	6.585136406	1
1.26%	0	0	4.623921085	1
8.25%	1	125.3	15.66571023	1
1.04%	1	125.3	6.147037128	1
3.97%	0	0	4.895161948	1
1.34%	0	0	4.80197676	1
5.34%	1	112.5	14.87030308	1
7.06%	0	0	7.058835294	2
1.36%	0	0	5.01107325	1
5.62%	1	106.4	14.18769024	2
5.57%	0	0	6.79825	1
9.52%	1	121.2	18.69158879	1
1.40%	1	121.2	6.698959085	1
6.16%	0	0	6.172839506	1
1.32%	0	0	5.146982838	1
6.93%	1	119.1	14.55180442	1
1.57%	0	0	5.019882673	1
4.72%	1	113.3	12.39669421	1
5.53%	0	0	6.712999526	2
1.69%	0	0	4.793863854	1
3.24%	1	106.8	7.28626943	1
5.18%	0	0	6.554225291	1
1.55%	0	0	4.792664029	1
4.76%	1	104.9	13.03386378	1
1.08%	1	104.9	5.492143846	1
8.30%	1	113	16.56823188	1
0.99%	1	113	5.807763043	1
5.44%	0	0	5.679752817	1
1.46%	0	0	4.367606915	1
10.03%	1	126.5	20.7032743	1
3.31%	1	126.5	7.288281759	2
1.12%	1	126.5	6.256703611	1
5.93%	0	0	6.280862861	2
3.22%	1	114.2	13.19736053	1
5.35%	0	0	6.316454364	2

Slope	Full	Payload	Fuel ML/m	Drive Style
1.60%	0	0	5.340168749	1
5.71%	1	105.8	12.99657757	2
5.71%	1	105.8	14.48855404	1
1.01%	1	105.8	5.732849226	1
6.07%	0	0	5.808238763	2
1.40%	0	0	5.66999953	1
4.85%	1	121.8	10.07929042	2
5.63%	0	0	8.471553415	2
2.06%	0	0	5.321339605	1
5.77%	1	109.6	13.25554823	1
1.53%	0	0	4.330432555	1
9.86%	1	118	18.48201084	1
5.42%	1	118	8.646280036	2
1.72%	1	118	5.800718258	1
5.87%	0	0	6.617091001	1
9.22%	1	114.7	16.13274948	1
6.03%	0	0	6.030160804	2
1.42%	0	0	4.814272903	1
3.39%	1	128.2	9.882925346	1
0.88%	1	128.2	4.808392831	1
5.81%	0	0	7.885780692	1
1.03%	0	0	5.07548152	1
4.75%	1	113.1	15.43576348	1
2.34%	1	113.1	7.149356558	1
5.98%	0	0	6.837022477	1
1.49%	0	0	5.305286672	1
5.66%	1	120.5	15.64172224	1
1.07%	1	120.5	4.688725665	1
6.17%	0	0	7.707010297	2
1.28%	0	0	4.558428833	1
4.84%	1	102	10.37326516	2
5.61%	0	0	10.28200742	2
5.67%	1	110.4	14.185202	2
4.08%	0	0	5.2227503	1
1.38%	0	0	4.127988567	2
5.13%	1	120.2	14.35441039	2
5.31%	0	0	7.297333156	2
6.22%	1	133	14.30615165	1
0.83%	1	133	6.621874798	1
6.17%	0	0	7.049700388	2
6.75%	1	151.9	15.18959142	1
5.93%	0	0	7.911392405	2
1.27%	0	0	4.447748486	1
4.84%	1	113.7	13.08012789	2
6.11%	0	0	8.953529001	2
17.76%	1	110.6	28.53848371	1
13.27%	0	0	12.64860659	1
17.08%	1	127.8	28.95938309	1
13.10%	0	0	13.35901658	1
16.75%	1	121.7	29.75617623	1
13.06%	0	0	12.36505067	1

Slope	Full	Payload	Fuel ML/m	Drive Style
16.27%	1	131.3	29.05978791	1
12.88%	0	0	11.36303839	1
17.62%	1	124.8	31.85465158	1
12.67%	0	0	14.49340895	2
16.84%	1	136.6	35.48744105	1
12.85%	0	0	15.15380967	2
12.78%	0	0	12.79150844	1
16.82%	1	131.9	32.49426726	1
12.29%	0	0	13.75645338	1
16.54%	1	124.4	32.78456113	1
12.99%	0	0	11.95524085	1
2.09%	1	125.2	11.4853878	4
17.00%	1	125.2	31.68802087	1
12.33%	0	0	10.57748886	1
12.42%	0	0	12.43501674	1
17.51%	1	130.9	30.02201615	1
12.73%	0	0	12.32806919	1
18.32%	1	137.3	34.71987809	1
11.93%	0	0	13.09925866	2
16.64%	1	122.6	34.32970386	1
12.54%	0	0	12.51795087	1
17.67%	1	126.9	36.80719654	1
10.72%	0	0	10.72194425	1
17.04%	1	132.6	30.03013053	1
11.83%	0	0	13.43927062	1
18.10%	1	127.5	31.40670081	1
11.83%	0	0	12.54855746	1
16.62%	1	130.2	35.30731208	1
12.17%	0	0	12.04906747	1
18.83%	1	126.9	31.01840056	1
11.82%	0	0	13.13102122	2
1.57%	0	0	3.853238337	2
17.37%	1	124.9	35.08381906	1
12.28%	0	0	12.30374194	1
18.06%	1	122.2	35.3431823	1
10.40%	0	0	9.732523408	1
17.08%	1	121.7	34.16261404	1
11.90%	0	0	12.25183448	1
16.47%	1	130.8	34.91919172	1
16.40%	0	0	12.44004307	2
17.18%	1	118.9	31.95678618	1
5.26%	1	118.9	21.99118594	2
12.08%	0	0	11.94321544	2
17.97%	1	122.7	31.1154054	1
11.20%	0	0	10.93975537	1
17.83%	1	124.5	31.41316806	1
11.25%	0	0	11.16330318	1
18.10%	1	134.6	33.18278977	1
13.05%	0	0	12.72887496	1
18.36%	1	128.8	38.47004626	1
12.20%	0	0	10.8736175	1

Slope	Full	Payload	Fuel ML/m	Drive Style
18.29%	1	124.6	31.79304037	1
12.48%	0	0	12.50742628	1
17.33%	1	125.6	32.25464804	1
11.58%	0	0	11.34188308	1
17.16%	1	123.1	32.0323749	1
12.21%	0	0	12.21517624	1
18.56%	1	128.9	28.34938169	1
11.83%	0	0	13.15356448	2
16.97%	1	136.9	30.1823011	1
12.69%	0	0	13.19296464	2
17.37%	1	127.5	26.68621	1
18.40%	1	123.1	30.10788659	1
12.02%	0	0	12.19418443	1
10.64%	1	121.4	20.46412639	1
5.87%	0	0	7.039857326	2
10.87%	1	144.9	21.74700979	1
0.97%	1	149.9	7.728721863	2
6.37%	0	0	7.966011683	2
10.10%	1	121.7	20.2020202	1
6.25%	0	0	6.254560617	2
13.60%	1	115	25.83627958	1
11.65%	1	115	25.75587906	1
12.66%	1	115	29.53967342	1
15.03%	1	115	31.08688978	1
8.44%	0	0	12.65395647	2
10.22%	0	0	11.00412655	1
10.94%	0	0	12.56895468	1
0.96%	0	0	4.326923077	2
5.18%	0	0	8.730484799	2
1.61%	0	0	3.716661562	2
9.53%	1	140.4	22.22927914	1
1.17%	1	140.4	8.18905007	1
4.04%	0	0	6.063668519	2
1.13%	0	0	3.667417074	2
10.18%	1	117.3	22.05109068	1
10.46%	1	119.8	20.91321018	1
1.18%	1	119.8	8.231420508	1
5.72%	0	0	6.005490734	2
3.03%	1	134.3	15.15771604	2
4.06%	1	134.3	7.105156313	2
8.05%	0	0	6.32387435	2
0.88%	0	0	4.291429904	2
9.62%	1	138.6	22.45388933	1
5.24%	0	0	8.304195804	2
12.37%	1	139.8	22.68041237	1
8.44%	1	139.8	9.845288326	2
5.47%	0	0	6.833152634	2
12.47%	1	140.9	18.701493	1
11.25%	1	140.9	9.144625774	2
8.56%	1	140.9	26.93467186	2
12.18%	1	118.7	21.32131217	1

Slope	Full	Payload	Fuel ML/m	Drive Style
5.63%	0	0	6.103859517	2
9.70%	1	102.9	16.19433198	1
3.37%	0	0	4.373931517	2
10.07%	1	149	18.87267237	1
10.70%	1	117.2	18.72659176	1
8.41%	1	117.2	9.455768018	2
5.63%	0	0	7.501172058	2
1.60%	1	138.6	8.326627468	1
10.74%	1	138.6	19.33446476	1
5.45%	0	0	6.136642575	2
13.06%	1	150.2	21.2231038	1
9.32%	1	150.2	9.904451177	2
5.61%	0	0	7.951356408	2
12.10%	1	117.7	22.17741935	1
7.04%	0	0	10.0345635	1
12.01%	1	134.8	19.52186449	1
4.00%	0	0	6.17078052	2
5.85%	0	0	7.14541557	2
10.48%	1	122.3	20.95337873	1
21.51%	1	122.1	49.46236559	1
4.18%	1	122.1	10.28591353	1
2.89%	1	136.7	7.034885818	1
21.31%	1	129.1	47.94476763	1
4.97%	1	129.1	9.935419771	1
20.44%	1	120.7	44.70558181	1
4.55%	1	120.7	11.1444687	1
4.76%	1	135.5	10.94508423	1
21.72%	1	126.5	52.6227865	1
4.55%	1	126.5	11.7504359	1
19.99%	1	126.6	50.874866	1
5.01%	1	126.6	11.28243701	1
21.40%	0	0	32.09554747	2
11.55%	0	0	17.56834809	2
2.46%	0	0	4.846636108	2
4.30%	0	0	6.983240223	2
4.54%	0	0	7.456106227	1
8.24%	0	0	12.58639297	1
11.51%	1	120.9	21.10514198	1
8.77%	1	120.9	10.96491228	2
5.30%	0	0	6.622516556	2
1.02%	0	0	3.616050302	2
5.52%	1	124.5	19.32900732	1
8.29%	1	124.5	12.43437414	1
5.36%	0	0	7.365742601	2
1.12%	0	0	4.067401485	2
5.37%	1	108	24.16431736	1
2.87%	1	108	12.20037319	2
5.47%	0	0	6.386861314	2
10.01%	1	122.8	18.75937969	2
6.15%	0	0	5.766569276	2
1.00%	0	0	5.24383849	2

Slope	Full	Payload	Fuel ML/m	Drive Style
10.70%	1	111.3	13.36898396	2
5.66%	0	0	7.422592959	2
8.85%	1	124	13.28217237	1
8.55%	1	124	12.11516534	2
9.58%	1	108.1	20.74688797	1
10.08%	1	108.1	12.59445844	2
5.27%	0	0	6.147900931	2
9.81%	1	116.1	12.26091221	2
5.59%	0	0	6.286086795	2
1.27%	0	0	4.025747836	2
5.04%	0	0	6.935687264	2
1.63%	0	0	5.283454995	1
10.20%	1	126.9	8.924018358	2
3.42%	1	122	12.53589825	2
10.24%	1	122	10.23541453	2
5.30%	0	0	7.414468806	2
3.87%	1	128	23.22430811	1
9.08%	1	128	10.35502959	2
4.97%	0	0	29.61854899	2
3.68%	1	122.8	11.25297078	2
10.73%	1	122.8	12.16545012	2
11.81%	1	113.7	21.65951246	1
5.84%	0	0	5.258852402	2
2.83%	1	122.1	11.6888637	2
10.65%	1	122.1	11.75716118	2
5.42%	0	0	8.128319064	2
1.33%	0	0	4.646449449	2
4.28%	1	114	12.84246575	2
2.91%	1	118.5	12.74581209	2
9.22%	1	128.5	10.14572957	2
5.46%	0	0	6.147540984	2
7.52%	1	120.8	14.09244645	1
8.28%	1	120.8	13.45198675	2
6.15%	0	0	6.531427693	2
1.48%	0	0	5.407524511	1
10.99%	1	135	10.98599286	2
5.53%	0	0	6.609489994	2
11.05%	1	130.1	14.26730486	2
5.73%	0	0	5.925080275	2
9.01%	1	124.6	15.75973163	1
10.16%	1	124.6	11.0198357	2
5.74%	0	0	5.86461126	1
1.30%	0	0	4.356947084	2
10.07%	1	119.2	16.78415576	1
5.11%	1	140	14.22215739	2
7.01%	1	113.8	8.760512615	2
5.70%	0	0	6.455021814	2
3.34%	1	135.6	14.19505678	2
9.45%	1	135.6	11.2476207	2
0.92%	0	0	4.77595881	2
4.04%	1	131	14.79966633	2

Slope	Full	Payload	Fuel ML/m	Drive Style
3.67%	1	130.1	10.08859622	2
5.55%	0	0	4.854368932	2
7.71%	0	0	9.960158077	2
10.32%	1	136.9	19.7812027	1
8.03%	1	136.9	12.84521516	2
4.21%	1	124	12.97517183	2
11.50%	1	124	12.65531523	2
6.05%	0	0	7.183908046	2
11.16%	1	131.5	14.87873828	1
9.98%	1	132.4	11.76470588	2
17.06%	1	121.3	31.77031241	1
12.56%	0	0	12.73413151	2
16.84%	1	140.4	30.65109376	1
12.09%	0	0	13.6359613	1
2.56%	1	136.1	14.78935132	1
17.82%	1	136.1	29.32187658	1
11.80%	0	0	11.79680012	1
2.98%	1	116.4	16.2738936	1
18.00%	1	116.4	38.35575088	1
11.65%	0	0	11.94443797	1
17.78%	1	132.7	41.84012887	1
11.76%	0	0	12.02422659	1
11.06%	0	0	12.70313812	1
17.05%	1	131.6	40.92455388	1
12.16%	0	0	12.55199167	1
18.30%	1	140.4	39.96841051	1
12.33%	0	0	13.34743101	1
17.09%	1	138.5	37.75009438	1
11.39%	0	0	12.30736301	1
3.73%	1	130.2	14.20392465	2
19.19%	1	130.2	50.36937542	1
11.83%	0	0	12.6712377	1
11.40%	0	0	13.53874218	1
4.41%	1	126.7	17.08723308	1
16.89%	1	126.7	36.00640114	1
11.20%	0	0	12.23293874	1
5.36%	1	124.6	17.9902929	1
16.36%	1	124.6	36.27930799	1
10.31%	0	0	11.76174886	1
18.98%	1	147.2	43.38924218	1
10.96%	0	0	12.24605548	1
2.79%	1	131.7	15.36684859	1
17.90%	1	131.7	39.56926034	1
11.17%	0	0	12.64033646	1
3.17%	1	132.7	14.51666117	1
18.50%	1	132.7	42.78000671	1
12.29%	0	0	13.06017926	1
2.17%	1	115.8	12.23377937	1
17.20%	1	115.8	37.68051835	1
12.26%	0	0	13.34807978	1
2.41%	1	122.4	12.63142699	1

Slope	Full	Payload	Fuel ML/m	Drive Style
19.48%	1	122.4	40.79197311	1
10.33%	0	0	11.78313928	1
18.73%	1	128.8	41.40541819	1
11.50%	0	0	11.95730485	1
2.88%	1	111.5	14.74745876	1
19.74%	1	111.5	39.48907216	1
10.77%	0	0	12.98689667	1
15.32%	0	0	22.98095863	1
4.75%	1	129.5	14.94159196	1
17.31%	1	129.5	40.2244422	1
11.96%	0	0	13.37967944	2
8.66%	1	137.7	21.64656783	2
17.68%	1	137.7	41.75262796	1
12.25%	0	0	13.16269946	1
2.66%	0	0	6.384687417	2
3.75%	1	132.2	15.36501274	1
19.27%	1	132.2	40.93044343	1
10.48%	0	0	12.56254297	1
18.24%	0	0	19.23899102	1
2.46%	1	131.4	13.50637869	1
18.48%	1	131.4	40.04127331	1
11.75%	0	0	13.22432571	1
10.36%	1	118.2	18.64203157	1
20.83%	1	118.2	37.7564837	1
15.08%	0	0	18.259765	1
2.89%	1	129.7	12.20239709	1
23.11%	1	129.7	39.10415926	1
10.94%	0	0	10.64938205	1
17.97%	1	132.3	42.92745261	1
12.09%	0	0	13.39514704	1
2.94%	1	129.1	13.70499988	1
19.63%	1	129.1	40.41990507	1
11.38%	0	0	14.15534239	1
2.24%	1	124.2	13.65213295	1
10.61%	0	0	12.65326409	2
12.43%	1	129.2	26.89457327	1
17.55%	1	129.2	40.3560692	1
10.65%	1	136.9	22.74971442	1
12.79%	1	136.9	28.14018931	1
11.51%	1	136.9	28.0615916	1
16.09%	1	136.9	38.88441942	1
18.62%	1	136.9	37.24759851	1
12.57%	1	78.4	21.73229996	1
12.39%	1	92	23.23132202	1
13.59%	1	92	25.93553168	1
18.33%	1	92	34.99416764	1
8.88%	1	92	15.78220556	1
16.42%	1	92	28.28725249	1
3.51%	0	0	7.147779641	2
12.14%	1	43.1	16.72261517	1
4.30%	0	0	7.786907255	2

Slope	Full	Payload	Fuel ML/m	Drive Style
12.14%	1	123.1	27.38551663	1
17.55%	1	123.1	39.72763473	1
11.41%	1	128.7	14.7851402	2
13.28%	1	128.7	28.47447625	1
22.92%	1	128.7	42.56224729	1
11.46%	1	127.1	26.84231797	1
14.37%	1	127.1	32.83735249	1
18.73%	1	127.1	40.80376732	1
13.72%	0	0	16.08401533	1
11.80%	1	137.6	28.153343	1
13.30%	1	137.6	31.72004502	1
19.01%	1	137.6	45.61870367	1
17.71%	1	137.6	41.05652114	1
13.16%	1	120.4	29.19888139	1
14.12%	1	120.4	29.53261428	1
19.61%	1	120.4	36.15727803	2
9.50%	0	0	11.88105637	1
7.29%	0	0	8.504778876	2
13.19%	1	113.1	32.98153034	1
13.26%	1	113.1	28.62129145	1
17.62%	1	113.1	33.16749585	1
11.81%	1	123.3	23.24654623	1
12.29%	1	123.3	30.3534003	1
18.03%	1	123.3	33.97115918	1
18.90%	1	123.3	42.51930241	1
10.89%	1	117	23.73465957	1
18.00%	1	117	38.39508543	1
11.97%	1	129	27.66848413	1
15.51%	1	129	26.17978726	1
18.44%	1	129	50.71461503	1
12.80%	0	0	14.68215027	1
11.97%	1	112.7	23.40467223	1
13.25%	1	112.7	28.71870398	1
14.11%	1	112.7	29.30323421	1
18.85%	1	112.7	39.27976621	1
16.17%	1	118.7	27.28375101	2
15.98%	1	117.4	25.97506394	2
12.60%	0	0	14.09352979	1
5.40%	0	0	15.67398119	2
11.45%	1	130.7	24.5754179	1

Slope	Full	Payload	Fuel ML/m	Drive Style
11.85%	1	130.7	26.16947947	1
15.08%	1	130.7	29.65718307	2
18.11%	1	130.7	34.62198123	1
13.88%	1	130.7	42.79435577	1
11.01%	1	112.4	22.80770743	1
12.40%	1	112.4	28.24858757	1
15.35%	1	112.4	30.69423129	1
19.00%	1	112.4	39.67544369	1
9.49%	0	0	12.45512202	1
5.67%	1	127.2	16.52752068	1
12.42%	0	0	14.39008191	1
2.70%	1	119.9	13.9476289	1
19.30%	1	113.9	39.40237058	1
12.52%	0	0	14.60958493	1
11.21%	0	0	12.97033476	1
2.94%	1	110.4	13.23091624	1
19.09%	1	110.4	37.11637574	1
13.68%	0	0	15.09647592	1
17.55%	1	120.3	39.78841923	1
9.69%	0	0	12.2199421	1
19.00%	1	110.3	44.499555	1
9.97%	0	0	12.99798531	1
16.24%	1	113.1	39.13171884	1
12.47%	0	0	14.49115856	1
17.63%	1	109.4	38.35437681	2
12.25%	0	0	13.69566784	1
11.49%	0	0	13.55692435	1
1.69%	1	129.4	11.95432043	1
17.79%	1	129.4	41.51444703	1
11.42%	0	0	13.69835648	1
17.01%	1	133.7	42.53490101	1
11.64%	0	0	13.58465876	1
16.90%	1	147.3	42.26042565	1
10.15%	0	0	11.91695209	1
16.71%	0	0	17.99640072	1
17.40%	1	134.4	42.78648817	1
12.42%	0	0	13.47908924	1
4.26%	1	131.9	13.83714742	2



## Appendix D – Stop-Start Data for Loaded Trucks

Fuel (mL)	Time	mL/sec	Payload
401.78	7	66.963	155.7
372.56	7	62.093	149.9
329.14	6	65.828	138.1
257.99	5	64.497	131.8
247.43	5	61.858	129.9
335.79	6	67.158	133.9
367.12	7	61.188	132.9
232.62	5	58.156	148.5
385.47	7	64.245	142.4
334.74	6	66.947	116.6
263.53	5	65.882	140.6
240.64	5	60.16	142.1
327.5	6	65.5	157.4
319.42	6	63.883	145.6
324.71	6	64.942	122.7
229.26	5	57.316	142.6
317.82	6	63.564	142.1
331.54	6	66.308	132.6
205.35	5	51.337	138.8
327.07	6	65.414	129.2
240.38	6	48.075	137.9
166.44	11	16.644	81.5
244.82	5	61.205	78.4
152.21	7	25.368	42.4
207.61	5	51.903	132.1
397.58	7	66.264	123.1
250.29	5	62.573	130.1
333.93	6	66.786	128.7
253.71	5	63.427	105.3
262.54	5	65.635	143.9
255.19	5	63.799	144.2
274.14	5	68.535	151.7
232.03	6	46.406	150.9
250.53	5	62.632	150.9
351.64	6	70.328	121.5
336.26	6	67.253	124.5
391.97	7	65.329	127.4
322.01	6	64.403	104.8
307.31	7	51.218	121.1
263.74	5	65.934	135.7
407.35	13	33.946	115.4
173.61	4	57.87	121
236.38	5	59.094	128.8
284.9	6	56.981	112.8
319.29	6	63.858	134.4
159.67	8	22.81	129.6
232.22	8	33.175	138.4
245.19	5	61.299	129.6
245.07	6	49.014	135.5
263.88	5	65.969	121.6
219.25	5	54.812	148.5
230.1	5	57.524	141.6
267	5	66.75	134.4
308.93	6	61.786	120.3
308.5	6	61.7	132.4

Fuel (mL)	Time	mL/sec	Payload
241.15	5	60.288	129
288.86	6	57.772	129.7
300.28	7	50.046	151.1
277.62	7	46.271	155.8
211.08	5	52.771	147.8
214.5	6	42.9	144.3
263.83	5	65.958	133.9
329.93	6	65.986	152.3
342.9	6	68.581	131.1
325.28	6	65.056	147.4
328.51	6	65.703	129.7
254.69	5	63.674	133.7
265.04	5	66.26	130.8
259.18	5	64.795	135.6
369.82	7	61.637	126.8
343.01	6	68.603	155
254.44	5	63.611	138.2
388.56	7	64.759	138.2
399.81	7	66.634	148.1
397.75	7	66.292	135.9
423.14	8	60.448	152.2
399.86	7	66.644	130.1
404.99	7	67.498	151.4
325.06	6	65.011	137.4
414.71	7	69.118	124.1
321.93	6	64.386	115.8
414.61	7	69.102	102.2
270.54	5	67.635	106.2
362.97	7	60.495	134.3
387.12	7	64.521	108.6
411.38	7	68.562	134.5
341.38	6	68.275	94.5
324.67	6	64.933	126.1
336.94	6	67.389	114.7
391.54	7	65.257	138.9
473.6	8	67.657	123.4
392.33	7	65.389	123.7
378.61	7	63.102	100.4
391.25	7	65.208	119.5
457.99	8	65.427	119.3
283.71	7	47.285	135.6
252.33	6	50.467	141.8
292.93	6	58.586	142.3
300.67	6	60.133	145.3
244.33	5	61.083	136.5
326.04	6	65.208	124.2
356.93	7	59.488	115.8
386.36	7	64.394	140.1
230.99	5	57.747	131.8
386.32	7	64.387	146.2
251.51	5	62.878	122.5
404.68	7	67.447	170.7
282.57	6	56.514	146.3
398.5	7	66.417	129.1
537.12	9	67.141	123

Fuel (mL)	Time	mL/sec	Payload
196.72	4	65.574	104.5
280.79	5	70.198	130
410.92	7	68.486	137.9
285.86	5	71.465	132.9
207.68	4	69.227	117.4
288.24	6	57.647	115.2
271.24	5	67.809	124.6
327.67	6	65.533	121.7
276.99	5	69.247	126.4
358.75	6	71.75	123.4
354.71	6	70.942	116.3
360.31	6	72.061	127.8
208.04	4	69.347	122.9
287.67	5	71.917	131.5
343.31	6	68.661	123.9
349.5	6	69.9	113.3
418.56	7	69.759	128.5
334.74	6	66.947	126.7
410.53	7	68.421	117.7
359.25	6	71.85	102.2
344.32	6	68.864	120.1
415.67	7	69.278	121.9
560.12	9	70.016	128.9
620.97	10	68.997	117
357.81	6	71.561	105
323.87	6	64.775	117
424.28	7	70.713	109.5
279.43	5	69.858	114.9
267.25	5	66.812	132.3
213.31	4	71.102	100.9
273.46	5	68.365	130.1
503.18	8	71.883	97
338.79	6	67.758	124.2
280.85	5	70.212	105.9
343.72	6	68.744	117.8
281.81	5	70.451	161.6
303.86	6	60.772	123.3
284.01	5	71.003	120.8
284.88	5	71.219	126.1
281.76	5	70.441	131.9
273.56	5	68.389	129.4
373.61	7	62.269	132.3
299.58	6	59.917	143.2
258.49	6	51.697	140.8
326.85	7	54.475	135
379.32	7	63.22	130.8
301.32	6	60.264	146.2
333.97	6	66.794	134.8
282.64	6	56.528	140.1
313.01	6	62.603	123.5
321.99	6	64.397	140.5
314.93	6	62.986	143.3
294.86	6	58.972	138.8
299.61	6	59.922	131.9
281.85	7	46.975	128.8
311.75	6	62.35	134.3
343.81	11	34.381	148
294.47	6	58.894	112.5

Fuel (mL)	Time	mL/sec	Payload
331.1	9	41.387	140.3
241.4	6	48.281	133.4
344.64	7	57.44	143.6
293.18	6	58.636	142
283.71	6	56.742	137
245.85	6	49.169	144.3
316.58	8	45.226	136.2
276.49	8	39.498	130.7
451.58	8	64.512	144.4
250.36	5	62.59	132.5
334.85	7	55.808	131.4
417.74	7	69.623	143.1
283.53	5	70.882	115.4
256.51	5	64.128	122.4
348.31	6	69.661	115
253.18	5	63.295	115
276.03	5	69.007	104.9
287.97	6	57.594	148.4
265.54	5	66.385	130.8
278.75	5	69.688	142.5
197.58	4	65.861	140.5
276.88	5	69.219	160.3
344.6	6	68.919	125.7
265.51	5	66.378	130.3
272.72	5	68.181	100.2
335.07	6	67.014	159.7
214.14	4	71.38	140
273.42	5	68.354	145.3
280.54	5	70.135	146.3
418.39	7	69.731	118.9
353.65	6	70.731	128.4
562.19	9	70.274	133.6
322.01	6	64.403	128
282.24	5	70.559	119.8
329.4	6	65.881	122.1
358.36	6	71.672	130
271.01	5	67.753	127.1
257.79	5	64.448	126.1
259.53	5	64.882	137.1
471.89	8	67.413	135.5
272.4	5	68.101	139
531.49	9	66.436	126.5
274.65	5	68.663	126.3
285.47	5	71.368	121.1
267.64	5	66.91	124.5
337.12	6	67.425	116
275.5	5	68.875	130.5
167.61	5	41.903	125.5
284.49	5	71.122	131.4
265.44	5	66.361	114.1
339.49	6	67.897	131.9
277.08	5	69.271	100.8
270.64	5	67.66	125.1
314	6	62.8	99.8
350.68	6	70.136	134.7
354.14	6	70.828	128.3
333.24	6	66.647	125

Fuel (mL)	Time	mL/sec	Payload
276.96	5	69.24	110.1
214.15	4	71.384	116.2
279.5	5	69.875	118.6
275.43	5	68.858	96
357.83	6	71.567	121.1
359.97	6	71.994	101.2
429.86	7	71.644	109
421.5	7	70.25	119
493.47	8	70.496	111.1
425.12	7	70.854	110
409.62	7	68.271	124.1
404.53	8	57.79	135.3
391.22	7	65.204	138.1
234.62	5	58.656	135.3
288.68	6	57.736	144.1
134.46	6	26.892	131
298.5	6	59.7	137
360.69	8	51.528	143.9
400.17	7	66.694	121.5
273.56	5	68.389	123.9
347.78	7	57.963	142.7
262.18	6	52.436	136.7
345.08	6	69.017	149.9
289.07	5	72.267	143.4
235.36	5	58.84	126.1
268.74	6	53.747	146.8
268.32	6	53.664	134.6
319.46	6	63.892	152.5
228.79	5	57.198	160.9
347.44	8	49.635	149
243.24	5	60.809	149.1
296.51	6	59.303	137
424.94	7	70.824	122.3
275.79	5	68.948	154.3
262.97	5	65.743	142.2
304.79	6	60.958	163.5
196.67	4	65.556	135.1
266.07	5	66.517	127
342.67	6	68.533	138.3
328.94	6	65.789	134.7
342.89	6	68.578	117
266.35	5	66.587	120.7
276.46	5	69.115	131.8
279.69	6	55.939	127.7
335.76	6	67.153	142.6
329.72	6	65.944	134.2
281.19	5	70.299	150.4
270.6	5	67.649	146
265.69	5	66.424	157.3
342.75	6	68.55	142.1
277.22	5	69.306	144.7
272.57	5	68.142	166.4
204.85	4	68.282	137
280.67	5	70.167	136.2
244.64	5	61.16	126
276.17	5	69.042	135.2
343.25	6	68.65	132.3
275.33	5	68.833	98.7

Fuel (mL)	Time	mL/sec	Payload
285.4	5	71.351	133.6
247.5	5	61.875	128.3
186.81	4	62.269	135.2
197.56	4	65.852	144.7
271.94	5	67.986	140.8
272.72	5	68.181	120.9
306.61	6	61.322	118.5
276.82	5	69.205	137.8
411.07	7	68.512	159.8
270.75	5	67.688	151.6
270.82	5	67.705	154.4
381.04	8	54.435	143.3
320.04	6	64.008	137.5
256.01	6	51.203	124.7
307.31	6	61.461	146.4
365.32	11	36.532	115.5
287.71	6	57.542	131.5
379.62	7	63.271	134.4
323.43	6	64.686	124.6
389.12	7	64.854	104.1
345.43	6	69.086	108.2
328.01	6	65.603	115.3
371.61	7	61.935	130.7
300.15	6	60.031	108
261.08	5	65.271	98.6
286.92	6	57.383	129
397.08	7	66.181	128
335.04	6	67.008	138.8
257.94	5	64.486	153.1
327.96	6	65.592	148.1
326.67	6	65.333	106.9
318.33	6	63.667	145.2
389.86	8	55.694	135.7
336.86	6	67.372	137.4
296.78	6	59.356	117.5
254.33	5	63.583	119.7
375.1	7	62.516	142
325.71	9	40.714	129
407.97	7	67.995	141.9
384.22	7	64.037	144.9
311.65	6	62.331	135.9
320.57	7	53.428	144.7
321.39	6	64.278	122.2
397.94	7	66.324	133.3
333.94	6	66.789	127.5
329.86	6	65.972	128.5
329.36	6	65.872	132.8
267.35	5	66.837	132.7
350.08	6	70.017	131.4
344.44	7	57.407	134.5
331.28	6	66.256	147.7
260.83	5	65.208	149.9
326.72	6	65.344	153
324.53	6	64.906	150.8
313.57	6	62.714	135.9
409.62	7	68.271	137.7
337.81	6	67.561	141.6
326.33	6	65.267	168

Fuel (mL)	Time	mL/sec	Payload
359.46	7	59.91	137.4
345.56	6	69.111	130.9
389.15	7	64.859	132.3
324.83	6	64.967	142.7
343.65	6	68.731	136.6
321.17	7	53.528	129.6
310.79	7	51.799	148.1
270.79	7	45.132	142.2
256.11	6	51.222	153.6
260.39	8	37.198	120.7
318.79	6	63.758	131.9
326.64	6	65.328	150.4
339.83	8	48.548	157.1
330.46	7	55.076	126
283.39	6	56.678	153.7
367.69	7	61.282	148.8
332.01	7	55.336	134.7
266.24	6	53.247	112.1
317.5	7	52.917	103.9
213.61	5	53.403	103.9
261.65	5	65.413	122.4
318.94	6	63.789	144.3
297.14	6	59.428	106
264.26	5	66.066	104.4
258.9	5	64.726	79.2
262.89	5	65.722	90.3
251.69	5	62.924	96.9
324.58	6	64.917	137.5
256.94	5	64.236	117.2
333.75	6	66.75	121.5
293.44	6	58.689	115.8
382.74	7	63.789	123.7
312.03	6	62.406	117.2
468.46	8	66.923	127.8
274.5	6	54.9	119.8
406.86	7	67.81	124.9
258.26	5	64.566	115.7
478.07	8	68.296	146.1
313.61	6	62.722	130.5
777.22	12	70.657	145.7
266.93	5	66.733	139.2
379.14	7	63.19	133.9
313.14	6	62.628	116.9
342.83	6	68.567	114.6
300.57	6	60.114	117.9
328.68	6	65.736	123.1
322.57	6	64.514	130.1
487.11	8	69.587	125.7
394.72	7	65.787	142.1
346.89	6	69.378	119.5
290.08	6	58.017	126.8
400.92	7	66.819	132.7
325.49	6	65.097	123.9
333.1	6	66.619	144.3
385.14	7	64.19	156.9
316.06	6	63.211	138.2
247.03	5	61.757	152.6
247.21	5	61.802	136.3

Fuel (mL)	Time	mL/sec	Payload
323.24	6	64.647	153.6
258.35	5	64.587	118.2
263.93	5	65.983	145.5
342.01	6	68.403	132.4
260	5	65	157.6
281.92	6	56.383	141.9
262.07	5	65.517	157.4
256.11	5	64.028	139.6
245.42	5	61.354	152.6
180.68	4	60.227	163.1
276.57	5	69.142	141.6
271.63	7	45.271	144.2
320.97	6	64.194	144.4
247.32	5	61.83	141.9
317.62	6	63.525	148.1
450.15	8	64.308	142.5
207.5	4	69.167	142.9
269.06	5	67.264	147.9
271.08	5	67.771	137.5
278.57	5	69.642	135.2
386.35	7	64.391	127.1
342.94	6	68.589	147.4
334.74	6	66.947	127.6
342.07	6	68.414	134.3
298.31	6	59.661	150.8
353.49	6	70.697	127
281.86	5	70.465	137.4
329.89	6	65.978	152.7
523.69	9	65.462	147.6
461.17	8	65.881	155.3
301.5	6	60.3	136.9
342.46	6	68.492	129.9
396.26	7	66.044	151.2
333.42	7	55.569	145
325.25	6	65.05	142.7
333.96	6	66.792	149
321.96	8	45.994	132.3
554.78	9	69.347	146
100.38	4	33.458	98.1
423.47	7	70.579	96.6
259.11	5	64.778	99.9
179.68	7	29.947	96.4
140.53	5	35.132	133.7
171.4	5	42.851	129.8
179.39	4	59.796	125.5
171.74	5	42.934	140.9
233.79	5	58.448	131.1
182.22	4	60.741	130.4
197.19	7	32.866	117.7
176.12	5	44.031	116.5
259.4	5	64.851	113.6
171.79	5	42.948	111.1
313.26	6	62.653	134.4
248.19	5	62.049	122.3
283.82	6	56.764	125.8
272.17	5	68.042	128.7
185.03	4	61.676	117.4
334.58	6	66.917	125.9

Fuel (mL)	Time	mL/sec	Payload
339.14	6	67.828	130.9
275.07	5	68.767	120.8
194.5	4	64.833	131.8
275.35	5	68.837	128.3
251.62	5	62.906	132.9
266.57	5	66.642	116.9
198.21	4	66.069	108.3
258.58	5	64.646	118.6
264.19	5	66.049	118.8
248.43	5	62.108	124.1
269.12	5	67.281	118
270.82	5	67.705	118.4
258.21	5	64.552	124.8
270.19	5	67.549	121.3
326.32	6	65.264	106.1
272.38	5	68.094	89.8
277.85	5	69.462	131.9
345.89	6	69.178	127.2
343.31	6	68.661	125.5
223.19	5	55.799	119.7
281.04	5	70.26	119.3
358.12	7	59.688	109.5
352.51	6	70.503	127.4
244.14	5	61.035	119.2
277.32	5	69.33	125.9
308.64	6	61.728	117.4
287.01	6	57.403	108.7
178.68	4	59.56	128.6
276.5	5	69.125	139.5
296.82	7	49.47	138.2
253.64	5	63.41	106.7
268.78	5	67.194	114.8
213.93	4	71.31	131
251.68	5	62.92	130.9
265.71	6	53.142	134
147.06	5	36.764	155.8
231.69	5	57.924	136.9
210.22	5	52.556	126.7
317.93	6	63.586	137.8
222.6	6	44.519	139.5

Fuel (mL)	Time	mL/sec	Payload
308.58	6	61.717	157.8
235.83	5	58.958	140.5
257.5	5	64.375	137.8
228.58	5	57.146	143.6
332.83	6	66.567	145.7
271.47	5	67.868	140.1
235.47	5	58.868	152.3
315.44	6	63.089	132.3
325.24	6	65.047	125.6
406.29	7	67.715	124.1
273.33	5	68.333	136.4
278.61	6	55.722	123.4
615.75	10	68.417	128.9
243.97	5	60.993	147.5
272.81	5	68.201	139.6
266.03	5	66.507	151.8
271.04	5	67.76	138.4
284.04	5	71.01	133.1
355.17	6	71.033	117.2
424.82	7	70.803	126.2
355.11	6	71.022	123.3
288	5	72	125.3
320.75	6	64.15	130.8
266.76	5	66.691	131.3
205.6	4	68.532	138
342.62	6	68.525	127.1
325.22	6	65.044	148.9
298.06	6	59.611	143.5
310.1	6	62.019	129.4
347.08	6	69.417	145.9
340.5	6	68.1	139.7
349.88	6	69.975	142.7
329.26	7	54.877	135.7
347.78	6	69.556	132.2
274.56	5	68.639	123.7
327.82	6	65.564	151.5
468.28	8	66.897	153.9

## Appendix E – Stop-Start Data for Empty Trucks

Fuel (mL)	Time	Fuel/sec (mL/sec)
239.96	8	34.28
168.08	7	28.014
195.83	5	48.958
133.6	4	44.532
243.81	6	48.761
202.86	8	28.98
99.431	21	4.9715
234.54	8	33.506
197.33	7	32.889
166.65	6	33.331
137.04	6	27.408
151.62	7	25.271
206.53	6	41.306
207.12	5	51.781
175.78	4	58.593
183.96	4	61.319
226.99	6	45.397
192.04	5	48.01
196.5	6	39.3
240.83	6	48.167
183.26	8	26.181
110.67	5	27.667
189.25	7	31.542
272.33	5	68.083
178.54	5	44.635
225.38	7	37.562
189.89	4	63.296
230.54	5	57.635
265.01	6	53.003
344.28	9	43.035
195.75	13	16.313
102.33	3	51.167
230.01	5	57.503
203.17	12	18.47
150.58	4	50.194
269.86	5	67.465
178.5	4	59.5
239.71	7	39.951
219.89	5	54.972
235.49	5	58.872
186.97	4	62.324
200.85	9	25.106
201.15	10	22.35
164.44	6	32.889
217.22	5	54.306
125.58	7	20.931
212.83	5	53.208
139.74	9	17.467
251.75	6	50.35
187.83	6	37.567
62.417	10	6.9352
168.65	5	42.163
218.65	6	43.731
240.44	6	48.089
185.04	4	61.681

Fuel (mL)	Time	Fuel/sec (mL/sec)
226.35	6	45.269
178.08	8	25.44
205.01	5	51.253
216.94	5	54.236
237.33	5	59.333
232.62	5	58.156
165.67	4	55.222
175.25	4	58.417
221.56	5	55.389
175.46	4	58.486
185.32	4	61.773
171.29	4	57.097
161.74	5	40.434
229.67	5	57.417
175.26	4	58.421
178.92	4	59.639
178.6	4	59.532
163.32	4	54.44
239.85	5	59.962
235.72	5	58.931
184.01	4	61.338
171.4	4	57.134
166.65	4	55.551
173.21	4	57.736
180.14	5	45.035
234.12	6	46.825
181.86	4	60.62
178.79	4	59.597
193.99	5	48.497
183.78	4	61.259
164.4	4	54.801
170.28	4	56.759
198.39	5	49.597
202.47	9	25.309
179.67	5	44.917
152.72	4	50.907
241.6	5	60.399
167.33	4	55.778
183.04	4	61.014
173.18	4	57.727
194.56	5	48.639
147.97	5	36.993
187.36	4	62.454
167.93	4	55.977
185.39	7	30.898
230.21	8	32.887
176.54	4	58.847
180.6	5	45.149
177.04	4	59.014
303.47	9	37.934
150.44	5	37.611
171.24	4	57.079
181	4	60.333
213.62	6	42.725
174.65	4	58.218

Fuel (mL)	Time	Fuel/sec (mL/sec)
224.31	5	56.076
175.92	4	58.639
149.46	4	49.819
185.75	4	61.917
152.89	6	30.578
234.43	5	58.608
179.19	4	59.731
182.51	4	60.838
246.72	5	61.681
161.07	4	53.69
187.86	4	62.62
185.22	4	61.741
177.26	4	59.088
173.49	6	34.697
174	4	58
179.32	4	59.773
253.6	5	63.399
197	5	49.25
168.57	4	56.19
186.65	4	62.218
170.33	4	56.778
233.81	6	46.761
181.28	4	60.426
136.89	4	45.63
182.61	4	60.87
183.35	4	61.116
178.97	4	59.657
184.39	4	61.463
330.9	9	41.363
124.1	4	41.366
148.11	8	21.159
198.46	5	49.615
214.78	5	53.694
197.5	5	49.375
279.4	13	23.284
259.11	8	37.016
172.85	5	43.212
224.37	5	56.094
262.71	11	26.271
224.6	7	37.433
240.79	12	21.89
203.21	5	50.802
227.67	11	22.767
220.14	6	44.028
194.11	10	21.568
177.18	5	44.295
134.12	6	26.825
200.92	9	25.115
159.12	6	31.825
203.51	7	33.919
309.18	9	38.648
166.38	4	55.458
216	5	54
176.78	4	58.926
175.5	4	58.5
220.82	5	55.205
140.46	4	46.819
251.44	5	62.861

Fuel (mL)	Time	Fuel/sec (mL/sec)
182.43	7	30.405
150	4	50
242.58	5	60.646
179.89	5	44.972
242.49	8	34.641
216.35	5	54.087
182.9	4	60.968
251.76	6	50.353
190.53	6	38.106
201.68	5	50.42
183.9	4	61.301
218.76	5	54.691
174.36	4	58.12
139.49	6	27.897
182.08	5	45.521
204.62	10	22.736
172.65	4	57.551
160.38	4	53.458
176.21	6	35.242
172.25	4	57.417
156.28	4	52.093
173.24	4	57.745
159.71	4	53.236
219.65	5	54.913
165.94	4	55.315
163.74	5	40.934
242.82	6	48.564
190.19	4	63.398
257.88	6	51.575
232.93	6	46.586
218.97	5	54.743
167.24	4	55.745
180.17	4	60.056
173.83	4	57.944
229.36	5	57.34
165.79	4	55.264
183.14	4	61.046
171.43	4	57.144
239.15	5	59.788
151.38	4	50.458
247.12	5	61.781
209.28	7	34.88
216.46	5	54.115
245.78	6	49.156
215.04	5	53.76
207.93	5	51.983
226.43	5	56.608
173.54	4	57.847
223.21	5	55.802
169.89	4	56.63
223.29	5	55.823
183.44	4	61.148
223.68	5	55.92
139.57	5	34.892
230.5	5	57.625
147.94	4	49.315
181.29	4	60.431
165.26	6	33.053

Fuel (mL)	Time	Fuel/sec (mL/sec)
202.53	7	33.755
163.93	4	54.644
257.29	5	64.323
178.99	7	29.831
230.85	5	57.712
235.29	6	47.058
186.57	4	62.19
175.03	4	58.343
209.43	5	52.358
264.03	6	52.806
177.79	4	59.264
224.42	5	56.104
193.54	10	21.505
192.38	4	64.125
250.24	5	62.559
180.58	7	30.097
200.11	5	50.028
174.64	4	58.213
185.47	4	61.824
250.07	5	62.517
168.03	4	56.009
222.07	5	55.517
171.19	4	57.065
186.71	4	62.236
181.67	4	60.556
177.86	4	59.287
172.78	4	57.593
182.31	4	60.769
171.83	4	57.278
177.69	4	59.231
233.94	5	58.486
181.19	4	60.398
202.9	6	40.581
163.83	5	40.958
176.28	4	58.759
122.88	3	61.438
258.29	8	36.899
178.89	4	59.63
180.93	4	60.31
178.68	4	59.56
184.33	4	61.444
194.85	9	24.356
189.11	4	63.037
212.25	10	23.583
207.19	5	51.799
229.11	10	25.457
203.79	6	40.758
176.38	4	58.792
177.76	4	59.255
215.54	5	53.885
181.46	4	60.486
165.12	7	27.521
217.67	5	54.417
201.39	5	50.347
176.9	4	58.968
188.75	4	62.917
170.88	4	56.958
172.51	4	57.505

Fuel (mL)	Time	Fuel/sec (mL/sec)
246.25	5	61.562
219.5	5	54.875
196.33	4	65.444
220.69	5	55.174
167.35	6	33.469
171.93	4	57.31
221.17	5	55.292
237	5	59.25
196.76	5	49.191
230.39	5	57.597
196.19	5	49.049
233.06	5	58.264
194.38	5	48.594
129.01	4	43.005
168.12	4	56.042
215.97	6	43.194
166.18	4	55.394
223.08	6	44.617
225.31	5	56.326
180.68	4	60.227
151	5	37.75
182.81	6	36.561
190.11	4	63.37
184.32	4	61.44
165.93	5	41.483
187.32	5	46.83
219.86	5	54.965
181.67	4	60.556
171.65	4	57.218
226.15	5	56.538
225.46	5	56.365
160.06	5	40.014
178	4	59.333
242.4	13	20.2
177.83	4	59.278
230.04	5	57.51
221.03	5	55.257
235.56	5	58.889
185.78	4	61.926
185.97	4	61.991
224.96	5	56.24
172.18	4	57.394
180.12	4	60.042
204.89	5	51.222
233.28	5	58.319
185.43	6	37.086
244.29	5	61.073
163.25	4	54.417
162.07	4	54.023
183.49	4	61.162
179.9	6	35.981
222.37	5	55.594
235.33	5	58.833
171.89	4	57.296
200.83	8	28.69
172.06	4	57.352
247.88	6	49.575
231.85	5	57.962



Fuel (mL)	Time	Fuel/sec (mL/sec)
181.03	4	60.343
181.86	4	60.62
109.83	7	18.306
224.61	5	56.153
231.9	9	28.988
247.87	7	41.312
92.931	5	23.233
238.25	5	59.562
215.18	12	19.562
262.99	11	26.299
206.31	6	41.261
171.07	4	57.023
205.69	5	51.424
185.06	4	61.685
181.46	7	30.243
184.6	5	46.149
209.53	5	52.382
191.56	4	63.852
172.61	4	57.537
203.6	4	67.866
217.21	5	54.302
180.38	4	60.125
224.21	5	56.052
181.82	4	60.606
184.07	10	20.452
183.76	4	61.255
192.53	8	27.504
190.31	4	63.435
167.43	4	55.81
192.79	5	48.198
138.85	7	23.141
197.01	5	49.253
197.72	4	65.907
164.14	4	54.713
184.26	4	61.421
194.21	8	27.744
207.9	5	51.976
163.97	5	40.993
182.06	5	45.514
188.06	7	31.343
164.57	8	23.51
161.53	5	40.382
182.54	21	9.1271
159.89	5	39.972
174.47	7	29.079
139.12	7	23.188
117.69	6	23.539
189.61	4	63.204
124.03	5	31.007
196.87	11	19.687
170.64	6	34.128
164.85	6	32.969
126.35	4	42.116
184.07	9	23.009
102.57	8	14.653
169.12	4	56.375
189.51	4	63.171
140.19	4	46.731

Fuel (mL)	Time	Fuel/sec (mL/sec)
230.15	5	57.538
172.38	4	57.458
237.57	5	59.392
245.39	7	40.898
193.96	5	48.49
166.99	4	55.662
145.53	5	36.382
226.47	5	56.618
160.94	4	53.648
186.07	5	46.517
182.64	6	36.528
197.89	4	65.963
163.61	4	54.537
106.49	4	35.495
85.194	10	9.466
91.181	5	22.795
140.78	7	23.463
46.806	11	4.6806
194.93	5	48.733
231.43	5	57.858
184.4	9	23.05
238.31	5	59.576
264.44	9	33.056
191.22	5	47.806
175.58	4	58.528
185.92	5	46.479
160.5	6	32.1
181.85	5	45.462
172.15	4	57.384
228.69	5	57.174
197.36	5	49.34
183.01	5	45.753
204.71	5	51.177
176.32	4	58.773
149.93	4	49.977
172.39	4	57.463
170.38	5	42.594
158.62	7	26.438
173.9	5	43.476
210.46	5	52.615
174.89	6	34.978
243.12	5	60.781
221.33	5	55.333
164.76	4	54.921
230.4	5	57.601
172.1	4	57.366
209.04	5	52.26
169.25	4	56.417
131.71	4	43.903
164.08	5	41.021
215	5	53.75
205.31	5	51.326
165.29	4	55.097
173.38	5	43.344
204.56	5	51.139
136.38	4	45.458
193.17	5	48.292
217.58	5	54.396

Fuel (mL)	Time	Fuel/sec (mL/sec)
181.76	4	60.588
101.89	6	20.378
237.36	5	59.34
159.79	5	39.948
155.36	4	51.787
140.64	7	23.44
217.03	5	54.257
199.24	6	39.847
223.61	6	44.722
160.64	6	32.128
164.35	5	41.087
162.17	5	40.542
170.32	5	42.58
187.72	5	46.931
130.43	5	32.608
166.26	4	55.421
144.6	11	14.46
157.35	5	39.337
157.31	4	52.435
182.64	5	45.66
252.68	12	22.971
223.32	5	55.83
136.9	6	27.381
211.85	8	30.264
10.694	2	10.694
89.139	10	9.9043
201.28	5	50.319
122.39	8	17.484
203.53	5	50.882
135.67	5	33.917
176.19	7	29.366
286.92	6	57.383
153.06	4	51.019
393.56	8	56.222
175.62	5	43.906
200.46	6	40.092
256.62	5	64.156
150.82	4	50.273
213.04	8	30.435
220.24	13	18.353
207.08	4	69.028
147.56	7	24.593
203.99	5	50.997
270.79	6	54.158
222.18	6	44.436
204.03	4	68.009
236.96	11	23.696
227.86	8	32.552
250.89	6	50.178
159.99	4	53.329
236.1	8	33.728
232.15	5	58.038
174.38	4	58.125
188.56	5	47.139
184.93	4	61.644
228.15	8	32.593
175.75	4	58.583
246.18	6	49.236

Fuel (mL)	Time	Fuel/sec (mL/sec)
175.36	4	58.454
209.51	7	34.919
238.76	7	39.794
253.35	6	50.669
138.97	5	34.743
160.36	6	32.072
160.28	5	40.069
184.71	8	26.387
154.58	4	51.528
221.08	5	55.271
174.86	5	43.715
209.67	5	52.417
210.39	8	30.056
199.69	5	49.924
252.47	6	50.494
235.31	5	58.826
203.26	5	50.816
182.49	4	60.829
201.81	8	28.829
209.9	5	52.476
218.61	5	54.653
263.89	5	65.972
185.6	4	61.866
223	5	55.75
173.01	7	28.836
244.62	5	61.156
234.31	8	33.472
232.86	5	58.215
322.6	7	53.766
195.14	6	39.028
151.54	7	25.257
183.44	11	18.344
190.39	5	47.597
111.82	3	55.91
185.1	5	46.274
282.26	9	35.283
214.47	5	53.618
232.06	6	46.411
226.36	5	56.59
140.53	5	35.132
233.12	5	58.281
197.22	5	49.306
186.07	6	37.214
206.44	9	25.806
244.14	7	40.69
217.57	7	36.262
205.17	7	34.194
219.22	9	27.403
204.71	9	25.589
198.58	12	18.053
188.46	5	47.115
166.26	6	33.253
191.19	6	38.239
202.69	6	40.539
233.36	7	38.894
258.72	9	32.34
198.11	4	66.037
302.6	6	60.519

Fuel (mL)	Time	Fuel/sec (mL/sec)
211.78	6	42.356
321.89	7	53.648
221.28	5	55.319
289.42	8	41.345
185.31	6	37.061
237.11	5	59.278
232.6	9	29.075
211.99	8	30.284
168.62	4	56.208
160.19	11	16.019
176.86	4	58.954
160.38	4	53.458
161.51	6	32.303
181.33	7	30.222
197.4	5	49.351
174.5	4	58.167
180.6	4	60.199
182.42	4	60.806
137.56	4	45.852
122.89	4	40.963
134.71	4	44.903
158.38	5	39.594

## Appendix F – Idling

Only the first 100 samples are shown here. See attached CD for all samples.

Fuel	RPM	Load
12.7	719.5	13
8.2	712	2
11.4	698	4
12.85	696.5	5
12.7	698.5	5
12.45	700.5	5
12.85	699.5	5
12.45	702.5	5
12	701	4
18.15	750	6
10.2	717.5	2
11.65	700.5	4
12.85	695.5	5
13.4	698.5	5
13.05	698.5	5
13.2	699.5	5
13.2	702	5
12.7	701	5
12.85	700.5	5
12.7	701	5
12.85	699.5	5
12.7	701	5
12.85	700	5
12.6	700.5	5
12.6	700	5
12.6	700.5	5
12.95	699	5
12.6	701	5
12.6	699.5	5
12.35	701.5	5
12.7	699	5
12.45	700.5	5
12.6	700	5
12.35	700.5	4
12.6	700.5	5
12.35	700.5	5
12.35	699	5
12.45	700.5	5
12.45	700	4
12.6	700.5	5
12.35	700	5
12.35	701	5
12.45	700.5	5
12.35	699.5	5
12.1	701	4

Fuel	RPM	Load
12.1	700.5	4
12.35	699.5	5
12.35	700.5	4
12.35	700.5	4
12.1	700.5	4
12.1	700	4
12.35	700.5	4
12.35	700.5	5
12.1	699.5	4
12.35	700	4
12.25	700	5
12.25	700	4
11.9	700	5
12.35	700	4
12.25	699.5	5
12.35	701	5
12.1	699	5
12	700.5	5
12.25	700.5	5
12.35	700.5	5
12.1	701	4
12.25	701	4
12.1	699.5	4
12.25	700.5	5
11.9	699	4
12	701	4
12.25	699	5
12.25	699.5	4
12.25	699.5	5
12.1	700.5	4
12.1	700	5
12.35	700.5	5
12.1	699	5
12.25	700.5	4
12.25	699	5
12.35	699	5
12.45	699	5
12.35	699.5	4
12.6	699	5
12.45	699.5	5
12.7	699.5	5
12.45	700.5	5
12.85	699.5	5
12.6	701	5
12.6	700.5	5

Fuel	RPM	Load
12.45	700	5
12.45	701	5
12.35	701	5
12.6	701	5
12.45	700	5
12.35	701	4
12.35	701	5
12.45	700	5
12.35	700.5	5
12.35	700	5

## **Appendix G – Other**

A CD has been attached with:

- Appendices II to IV
- Appendix V in full
- Ramp Fuel Consumption Tool (Microsoft Excel file)
- Processed Data
- Combined Data

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