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DUTY CYCLE STUDY OF COAL MINE SHUTTLE CARS

A Thesis in
Energy and Mineral Engineering
by
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ABSTRACT

With recent advancements in battery technology, there is an acute interest in increasing the number of battery-powered haulers for use in underground mining. In an attempt to commercialize and implement the new battery technologies, machine manufacturers must determine the capacity, durability, and performance of these batteries over critical and tough conditions in underground mining operations. Study of the duty cycle of underground haulage units is the basis by which verification of the need and demands for power for such units can be determined for the purpose of sizing suitable batteries. This thesis discusses the measurement of duty cycles of coal mine shuttle cars in two underground coal mines in central Pennsylvania along with the discussion and analysis of the measured duty cycles. Observations and measurements were made to quantify/differentiate the performance of the shuttle cars under different road conditions and mine operating requirements. The measurement of the duty cycles for various shuttle cars was mostly performed by recording the available machine information through the vehicle on-board communication ports such as CAN bus interfaces. Each work cycle includes real time power consumption during different work segments (e.g., loading, loaded tramming, dumping, and empty tramming), mean power for the entire duty cycle, order and duration of peak powers, and required energy for the entire cycle and different work segments. Moreover, cycle timing and intermittent delays occurring during each

1 Controller Area Network
work segment are included in the duty-cycle study. The required energy by work cycle is summed over the course of each work shift and then correlated with utilization.

Analysis of the data has allowed for evaluation of these parameters and quantification of the arithmetic average, root mean square, and dispersions of related parameters such as cycle time, delay times, average power and energy consumptions, peak power and energy consumptions, and finally the proportion of power consumption in each segment of the duty cycle as well various functions. Statistical analysis is used to develop formulas for estimation of operating parameters of such haulage units based on the distance, weight of the haulage units, road conditions, utilization, and number of haulage trips during a working shift. The statistical models include average and peak power and energy consumptions. Also a separate analysis was performed to estimate the amount of machine utilization and delay times for each component of the work cycle. The observations and developed models allow for estimation of the required battery power and storage capacity for underground haulage units and expansion of the results to similar operational conditions with different panel geometries.
# TABLE OF CONTENTS

List of Figures ........................................................................................................ viii

List of Tables ........................................................................................................ xii

Acknowledgements .............................................................................................. xiii

Chapter 1. INTRODUCTION ................................................................................. 1

1.1 Thesis Overview ............................................................................................ 2

Chapter 2. BACKGROUND AND DEFINITIONS .............................................. 4

2.1 Duty Cycle vs. Driving Cycle .......................................................................... 4
2.2 Target Haulage Unit: Shuttle Car .................................................................... 4
2.3 Importance of Study ....................................................................................... 6

Chapter 3. LITERATURE REVIEW ...................................................................... 12

3.1 Brief Description of Underground Coal Mining ............................................ 12
3.1.1 Room-And-Pillar Mining ........................................................................... 14
3.2 Shuttle Car Operation .................................................................................... 15
3.3 Previous Studies and Measurements ............................................................... 16
3.3.1 CANMET Study ....................................................................................... 16
3.3.2 Southern Illinois University face haulage system time study ..................... 16
3.4 Measuring the Duty Cycles ............................................................................ 17
3.4.1 Developing Duty Cycle from the Driving Cycle on Non-mining Vehicles ....................................................................................... 18
3.4.2 Developing of Duty Cycle from the Accessible Parameters on Electric Control Unit ............................................................................. 21

Chapter 4. DEVELOPMENT OF THE DUTY CYCLES FRAMEWORK ............ 24

4.1 Determine Haulage Operation Condition ....................................................... 25
4.1.1 Rolling Resistance .................................................................................... 25
4.1.2 Grade Resistance .................................................................................... 26
4.1.3 Utilization ................................................................................................ 26
4.2 Data Acquisition System and Sensor ............................................................... 27
4.2.1 DAS #1: Kvaser Memerator Pro CAN logger ........................................... 28
4.2.2 DAS #2: Trailing Cable Power data recorder ........................................... 31
4.3 Shuttle Cars in the Case Study ........................................................................ 33
4.4 Pre-Installation and Testing .......................................................................... 34
4.4.1 Kvaser CAN Logger Testing .................................................................... 34
7.3 Recommendations for Future Work .......................................................... 107

References ........................................................................................................... 108

Appendix A: CANMET Duty Cycle Study ......................................................... 112
Appendix B: Southern Illinois University Face Haulage System Time Study ........ 117
Appendix C: Developed Duty Cycles - Mine B, Study Area #2 & #3 ................. 119
Appendix D: Developed Duty Cycles - Mine B - Study Area #1 ....................... 125
Appendix E: Developed Duty Cycle - Mine A - Study Area #2 ......................... 131
Appendix F: Developed Duty Cycle - Mine A - Study Area #2 ......................... 137
Appendix G: Developed Duty Cycle - Mine A - Study Area #1 ......................... 143
Appendix H: Monitoring Equipment Technical Information .............................. 149
LIST OF FIGURES

Figure 2-1. Shuttle car (Courtesy of Joy global)................................. 6
Figure 3-1 Longwall mining .......................................................... 13
Figure 3-2 Room-and-pillar mining ............................................. 13
Figure 3-3 Cutting sequence in room-and-pillar mining .................. 15
Figure 3-4 Schematic drawing of a typical CAN bus communication architecture, ( http://warwickcontrol.com) ......................................................... 22
Figure 4-1 DAS #1 connected to master controller module of shuttle car .......... 30
Figure 4-2 Picture of Wiring of Kvaser CANbus logger to Saminco master controller module................................................................. 31
Figure 4-3 Schematic drawing of DAS #2 mounted on Rectifier at Mine B ......... 32
Figure 4-4 Picture of Data logger mounted in Rectifier .......................... 33
Figure 4-5 Picture of Connecting Kvaser CAN data logger to a scoop ............. 35
Figure 4-6 Collected tram motor CAN parameters from Fairchild Scoop .......... 36
Figure 4-7 Collected pump motor CAN parameters from Fairchild Scoop ......... 36
Figure 4-8 Barbara Mine Pump Station ........................................... 37
Figure 4-9 Picture of 3CT Power Transducer Installation for Trial Purposes on Water Pump ................................................................. 38
Figure 4-10 Picture of Barbara Mine Pump Station Electric Panel and Data Collection System ................................................................. 38
Figure 4-11 Power Transducer Data Collection Testing on Pump Station ........ 39
Figure 4-12 Mine A studied areas .................................................... 40
Figure 4-13 Mine A, study area#1 layout ........................................... 42
Figure 4-14 Mine A, study area # 2 layout ........................................ 43
Figure 4-15 Mine B, #1, #2 and #3 study areas, mine layout .................... 44
Figure 4-16 Cutting sequence in room-and-pillar mining ........................ 45
Figure 4-17 Mine B, study area #1 layout .................................................................45
Figure 4-18 #2 study area layout - Mine B .................................................................47
Figure 4-19 #3 study area layout – Mine B .................................................................48
Figure 5-1 Screenshot of data for shuttle car driver’s input signals .......................52
Figure 5-2 Plot of #1 Classifier: Area under conveyor signal during loading and
dumping cycles ........................................................................................................53
Figure 5-3 Plot of #2 Classifier: Mean-to-peak ratio of conveyor signal during
loading and unloading cycles .................................................................................54
Figure 5-4 Plot of the recorded power consumption data and duration of detected
peaks ..........................................................................................................................58
Figure 5-5 Picture of total effective grade ratio per haulage trip ...............................62
Figure 5-6 Comparison of battery capacity between the intermittent and
continuous discharge. Courtesy of (Lawson, n.d.) .................................................65
Figure 6-1 Boxplot of energy consumption during a shift [kWh] ...............................66
Figure 6-2 Boxplot of shuttle car utilization % per shift .........................................67
Figure 6-3 Boxplot of number of haulage trips during a shift .................................67
Figure 6-4 Histograms of haulage cycle timing for various working conditions ......68
Figure 6-5 Boxplots of Mean power consumption of duty cycle components [kW]...70
Figure 6-6 Correlation between power density and haul road total grade
[kW/tonne/grade/cycle] ..........................................................................................73
Figure 6-7 Boxplot of maximum peak power observed during each haulage cycle
[kW] .........................................................................................................................75
Figure 6-8 Box plot of maximum peak power density observed during tramming
cycles [kW/tonne] .................................................................................................76
Figure 6-9 Plot of peak power duration against recorded peak power (peak powers
> 150KW)  a) Mine A, coal haulage  b) Mine A, rock haulage  c) Mine A,
rock haulage  d) Mine B, coal haulage  e) Mine B, coal haulage ............................77
Figure 6-10 Plots of peak power duration against recorded peak power (peak powers < 150KW) a) Mine A, coal haulage  b) Mine A, rock haulage  c) Mine A, rock haulage  d) Mine B, coal haulage  e) Mine B, coal haulage........78

Figure 6-11 Histograms of energy consumption of haulage trips for various working conditions .................................................................80

Figure 6-12 Plot of Energy consumption vs. number of haulage trips per shift (Mine A) .............................................................................82

Figure 6-13 Plot of Energy consumption vs. number of haulage trips per shift (Mine B)........................................................................82

Figure 6-14 Boxplot of energy consumption of duty cycle components [kWh] ........83

Figure 6-15 Histograms of haulage cycle energy density ..........................85

Figure 6-16 Energy density per haulage cycle for study area #1 and #2 at mine B ....87

Figure 6-17 The correlation between normalized energy and maximum hauling distance in panel ................................................................................88

Figure 6-18 Stop-start frequency during haulage trips – Mine A - (a) Aug – Sep, rock hauling, (b) July - Aug, rock hauling, (c) July, coal hauling...............90

Figure 6-19 Boxplot of tramming cycles stop-start frequency – Mine B – (a) September, coal hauling,  (b) Nov - Dec, coal hauling.................................92

Figure 6-20 Histogram of the ratio of mid-cyle delays to cycle time (coal haulage) ..93

Figure 6-21 Histogram of the ratio of mid-cyle delays to cycle time (rock haulage)..94

Figure 6-22 Box plot of the duration of intermittent delays during empty tramming cycles............................................................................95

Figure 6-23 Box plot of the duration of intermittent delays during loaded tramming cycles.................................................................................95

Figure 6-24 Histograms of ratio of delay-to-delay intervals to haulage cycle time ....96

Figure 6-25 Summary of statistical analysis delay-to-delay intervals ..................97

Figure 6-26 Energy-utilization (Mine A)..........................................................100

Figure 6-27 Energy-utilization (Mine B)...........................................................101
Figure 6-28 Histogram of energy difference of haulage trips between two following entries .......................................................... 102
LIST OF TABLES

Table 2-1 Battery Powered Coal Hauler Advantages and Disadvantages (Myors, 1998) ........................................................................................................................................... 11

Table 4-1 Available parameters on the Saminco’s CAN bus .............................................. 29

Table 4-2 Case work shuttle cars and their specifications (courtesy of Joy Global) ... 34

Table 5-1 Estimation of additional power requirement due to the number of intermittent delay (factor) per cycle (Lineberry, 1986) .................................................................................. 64

Table 6-1 Summary of statistical information for haulage cycle time [sec] .................... 69

Table 6-2 Comparison of haulage cycle time [sec] .............................................................. 69

Table 6-3 Descriptive statistical evaluation of values of mean power consumptions [kW] during tramming cycles ................................................................................................. 72

Table 6-4 Descriptive statistical evaluation of values of mean power consumptions (loading and unloading cycles) ................................................................................................. 72

Table 6-5 Information of mean power, total grade, and weight ratio .............................. 73

Table 6-6 Peak power duration [s] ........................................................................................ 79

Table 6-7 Peak power energy [kWh] ..................................................................................... 79

Table 6-8 Summary of statistical analysis of energy consumption per haulage trip [kWh]/trip ............................................................................................................................... 81

Table 6-9 Comparison of haulage cycle energy consumption ........................................ 81

Table 6-10 Selected gross weight for calculating the energy density ............................. 84

Table 6-11 Energy density of haulage cycles [kWh]/tonne/cycle ........................................ 86

Table 6-12 Comparison of haulage cycles energy density [kWh]/tonne/cycle .......... 86

Table 6-13 Statistical analysis of power crest factor (tramming cycles) ......................... 97

Table 6-14 Statistical analysis of power crest factor (loading/unloading cycles) ...... 98

Table 6-15 Summary of statistical analysis of averaged power crest factor ............... 98

Table 6-16 Summary of crest factors over a certain threshold (percentage of haulage cycles) ................................................................................................................................. 99
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Chapter 1. INTRODUCTION

Most mobile mining machinery is powered by either diesel fuel or electric power. Mining equipment manufacturers have tried to incorporate new battery technology into light-duty mobile equipment as a safer and more efficient source of propulsion, especially in underground mining environments. In order to commercialize and implement the new batteries, machine manufacturers must verify battery durability and performance in critical and tough working conditions in mining operations to assure high performance and low downtime of such units in underground mining operations. The critical and normal working conditions of batteries are defined by the duty cycles of the mobile equipment. Learning the duty cycles is the key to rational sizing of batteries as a source of power. Highly unpredictable duty cycles affect the battery lifetime and its performance (Duvall, 2005). The battery’s cell dimensions, the number of cells, electrode shape, and electrode surface area will be optimized for a designated duty cycle. For instance, increasing the surface area of the electrodes enhances the battery’s peak power handling capability and its charging time; while increasing the volume of electrolyte in the cell increases the cell’s energy storage capacity, which adversely reduces the peak power capacity. This is the main tradeoff in sizing a battery for a specific mobile equipment. Battery manufacturers would be able to adjust the battery design and cell configuration based on the battery application and requested duty cycles for the battery.

Battery test procedures will be designed based on the normal and critical duty cycles to evaluate the battery performance during both normal and high-demand
conditions. The literature survey shows that most of the studies on the duty cycle of mining equipment have in the past focused on driving cycle of trucks used in surface mining. Only one study was found that pertains to the duty cycle of underground haulage units (Barnes and Miller, 2003) which includes coal-mine shuttle cars. This thesis focuses on studying the duty cycle of coal mine shuttle cars which are the most popular underground coal mine face hauler in room-and-pillar mining operations. Evaluating the impact of different duty cycles on the battery or hauler performance was not included in this thesis.

Once the timing and power consumption of the haulage units for driving and their duty cycles in underground mining operations were measured, a correlation was sought to connect the duty cycles with the haulage operation characteristics such as the mine geometry, the number of haulage units, the capacity of haulage units, utilization, and the haul-road condition. This assessment then provides a basis for the estimation of battery requirement when haul-road conditions and the haulage operation change and for estimation of the required size of batteries for different situations.

1.1 Thesis Overview

The first chapter of the thesis is the introduction. It discusses the objectives of this study and focuses on describing the demand for battery-powered underground haulage units. Chapter 2 discusses the previous studies on this topic and gives a more detailed discussion of the definition of duty cycle and other parameters. Chapter 3 provides a background on underground coal mining haulage systems and reviews the
previous research and methodologies pertinent to characterizing mobile mining equipment in underground operations. Chapter 4 describes the parameters affecting the shuttle car duty and timing cycles, followed by a brief explanation of the methodology used in the case studies to measure the duty cycles. Chapter 5 discusses the programs developed for collecting and analyzing field data using MATLAB software. Chapter 6 presents and discusses the analysis of the collected field data. This chapter also offers statistical-experimental models correlating the duty cycle and the studied parameters. Finally, Chapter 7 presents the conclusions and results of this thesis and gives some of the recommendations for future work on this project.
Chapter 2. BACKGROUND AND DEFINITIONS

This chapter discusses the background information about the underground haulage units and gives related definitions of the duty cycles and subcomponents of each cycle. It also provides a brief overview of the available literature on this topic.

2.1 Duty Cycle vs. Driving Cycle

Before getting through the rest of the thesis, it is essential to define the terminology used for this study to ensure clarity of the terms and definitions. The term “Duty Cycle,” which is frequently used in this thesis, simply defines how much an underground haulage vehicle is used in a certain period of time, most likely an 8-hour work shift. Duty cycles are typically represented by power usage, energy consumption, or the load profile versus time. On the other hand, “Driving Cycle” describes how a vehicle is used. The driving cycle refers to what the vehicle driving pattern is and what its speed versus time is. Parameters such as the frequency of the vehicle’s stops and starts, vehicle idle time, average speed, vehicle mileage, and vehicle downtime could be calculated from the driving cycles. Duty cycles and driving cycles can be obtained using various methodologies which are explained in following sections.

2.2 Target Haulage Unit: Shuttle Car

Shuttle cars are rubber-tired units used to haul coal from the continuous miner to the panel “feeder breaker”, which loads the coal on to the panel belt conveyor and
regulates/distributes the load delivered in batches by various haulage units. Shuttle cars are the most common panel haulage vehicles accounting for over 70% of any such units in underground room and pillar mining or development sections. They may be powered by electricity or battery. A shuttle car is open on both ends. As Figure 2-1 illustrates, a central chain conveyor moves coal from the loading end to the discharge end and distributes the load during the loading cycle, and it moves the coal off the unit, thus allowing loading and discharge without the need to make turns or maneuvering at either location. Typical shuttle car capacities range between 9 and 33 tonnes. Shuttle car cycle time varies depending on haulage operation, work conditions, and panel arrangements.

Shuttle cars are capable of tramming with a maximum speed of 3.5 m/s (8 mph or 12 ft/s). However, the Code of Federal Regulations (CFR) has limited the top speed of a shuttle car by 2.7 m/s (6 mph or 8.8 ft/s). This speed can be reached in less than 3 seconds. It means that the shuttle car maximum acceleration would reach to 0.9 m/s$^2$ (3 ft/s$^2$). The acceleration of 1.36 miles per hour per second (2 ft/s$^2$) is recommended for underground haulage operation (Gunderman, 1980).

The maximum cable length is also limited by the available codes and prevailing regulations as a function of cable size. The cable length is normally kept less than 250 m (750 feet).
2.3 Importance of Study

Underground coal producers have been looking for high productivity and high equipment efficiency in underground haulage systems. In operations, the haulage system has the greatest potential for productivity improvements. A study (Chugh, McGolden, Carty, and Hirschi, 2001) indicates that face haulage is still the major bottleneck to productivity. The continuous miner can only produce as much as its haulage system can move. Under ideal conditions, all forms of face haulage work well, but in certain conditions when mine plan changes, the face haulage units must present enough flexibility to fit the new mining condition and still keep high productivity.

The electricity-powered shuttle car is the most popular face haulage unit at present. Ramcars, coal haulers, and Freedom cars are the other types of cyclic face haulage units employed in underground coal mine operations. Ramcars are cable-less, articulated haulage units which could be powered either by battery or diesel fuel. The Freedom car is a battery-powered shuttle car manufactured by Philips Machine. The
capacity of haulage units is the most critical parameter for choosing a face hauler. Shuttle cars and Freedom cars have a big advantage over ram-cars when it comes to capacity. Despite the flexibility, which cable-less ramcars offers, it adds more change-out and waiting delays to the haulage cycles because ramcar’s load and dump from the same end. This requires the ramcar to turn around twice in each haulage cycle.

(Chugh et al., 2003) compared the productivity of a coal mine in Illinois by changing the haulage unit from electricity-powered shuttle cars to Freedom cars for the same capacity. Based on this study, a 12% increase in productivity was observed by replacing one car; and a 24% increase in productivity was recorded by changing all three cars to the Freedom cars, which resulted from the flexibility that they offer.

Electric haulers are increasingly replacing diesel-powered vehicles in underground coal mine operations. Although diesel engines could provide high power and high mobility, undesirable factors such as higher maintenance, more heat and noise pollution, and a higher ventilation cost made diesel-powered units less favorable. Electric propulsion systems could work more efficient than diesel engines in an intermittent operation (Miller, 2000). Diesel ramcars have pretty much been regulated out of existence (Hirschi, 2012).

Electricity-powered shuttle cars impose several limitations and drawbacks to the underground mine operation (Paterson and Knights, 2012). Trailing cables reduce the flexibility and mobility of the haulage units. The maximum haul route length is limited to 200-250 m (~600-750) ft and it should be kept within this range to reduce the change-out delays. Electricity-powered haulage units must always return along the same path and
must not pass the route of the other unit to not run over each other’s cable. At some points, trailing cables restrict the mine geometry by adding more entries while trying to reach to farther entries. On the other hand, battery-powered haulage units could fit better to the variable on-demand requirements related to the geometry and physical characteristics of the panel. This is because battery-powered shuttle cars would be able to move in any direction and pass each other’s route without any interference in a case of need. This advantage permits the cable-less shuttle cars to choose the best haul path to reduce the haulage timing cycles.

In addition to mobility problems, cable faults, cable wear, and cable handling issues are the other major problems with the trailing cables (Gunderman, 1980; Hrebar, 1944; Paterson and Knights, 2013). Based on the study conducted by (Paterson and Knights, 2013), 15% of the electricity-powered haulage unit maintenance was due to trailing cable issues and electrical faults. Battery-powered shuttle cars eliminate the cable-maintenance delays and associated costs. Battery haulage units could save $25,000 per year on cable maintenance (Chugh et al., 2003).

Articulation steering is a big potential which could be added to the battery-powered haulers. The articulation feature makes the hauler more maneuverable, as compared to shuttle cars, by allowing efficient operation in difficult bottom conditions. This feature keeps the hauler from high-centering on the undulating bottom (Fiscor, 1998). Furthermore, an articulation steering system could allow for building a longer shuttle car, resulting in higher load capacity. In the same coal seam height, battery-
powered shuttle cars could load 10% to 15% more coal compared to the electricity-powered ones (Fiscor, 1998).

With recent advancements in battery technology, Joy Global has incorporated a battery propulsion system into three types of its coal haulers, BH-10, BH-18, and BH-20, for different seam-height applications, which could work up to 16 hours under ideal conditions. Although battery-powered haulers provide several advantages, they introduce some drawbacks.

First of all, the cost of using battery haulers is higher than the trailing cable versions. Battery haulers require auxiliary equipment such as 2-3 extra batteries, a charging station, and maintenance tools. Secondly, batteries add more weight to the haulage units, which results in increasing the energy consumption and decreasing the hauler performance. Greenhill and Knights (2013) have shown that, for a flat haul road, an increase of 6.25% in weight causes an increase of 1% on cycle time. Thirdly, battery change-out time is a major limitation on the haulers availability, which interrupts the mining operation to some degree. It takes the hauler approximately 20 to 30 minutes to change out the battery (Fiscor, 1998). Under normal conditions, a fully-charged battery must run for a full working shift without being changed out. The performance and availability of battery haulers deteriorate when the mine encounters bad conditions. In the worst case, the battery would probably need to be changed out at mid-shift. An efficient battery-swap mechanism should be considered to reduce the battery change-out time.

Declining battery life is another big issue. The correct way of utilizing batteries in the haulage cycle per unit is to have one battery in operation, one in charge, and one
cooling after charging. Since a battery pack is expensive, some operators use two batteries per unit rather than three to save money. This situation on saving money often makes a battery surpass its proper working time and exceed its recommended service temperature because of overwork, which can cause damage to the battery and reduce its cycle life. Table 2-1 lists the advantages and disadvantages of employing battery-powered haulers in coal mines.

Based on the above discussion, battery-powered shuttle cars seem to be a comprehensive solution increasing productivity on in a room-and-pillar haulage operation if the battery issues can be resolved. Table 2-1 summarizes the strengths and weaknesses of battery-powered haulage units used in underground coal mines during the last decade, as acquired from Myors (1998). Most of the issues mentioned in this table have been improved with recent advancements in battery technology.

Joy Global currently has incorporated a long-life battery propulsion system into three types of its coal haulers, BH-10, BH-18, and BH-20 which could work up to 16 hours under ideal conditions. Two models of a Caterpillar face hauler, FH-110 and FH-120, are also powered with a powerful lead-acid battery.

In an attempt to evaluate the performance of new battery technologies for use in underground mining, the duty cycles of shuttle car has been studied in this thesis.
Table 2-1 Battery Powered Coal Hauler Advantages and Disadvantages (Myors, 1998)

<table>
<thead>
<tr>
<th>Safety</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td></td>
</tr>
<tr>
<td>• Elimination of trailing cables - arcing in hazardous zone.</td>
<td>• Physical size of the BPCHs.</td>
</tr>
<tr>
<td>• Manual handling - trailing cables.</td>
<td>• Stored energy - potential to ignite CH4 during ventilation failure</td>
</tr>
<tr>
<td>• Articulation - improved roadway conditions.</td>
<td>• Chemical energy - burns, fires.</td>
</tr>
<tr>
<td>• Ergonomics - driver compartment/seat.</td>
<td>• Driver visibility when loaded.</td>
</tr>
<tr>
<td>• Driver compartment canopies.</td>
<td></td>
</tr>
<tr>
<td>• No diesel fumes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity</td>
<td></td>
</tr>
<tr>
<td>Advantages</td>
<td></td>
</tr>
<tr>
<td>• 16 tonne payload.</td>
<td>• Less capacity than continuous haulage.</td>
</tr>
<tr>
<td>• Rapid coal discharge.</td>
<td>• Battery life - roadway conditions/grades.</td>
</tr>
<tr>
<td>• Flexible wheeling routes.</td>
<td>• Cycle time to achieve optimum battery performance.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
</tr>
<tr>
<td>Advantages</td>
<td></td>
</tr>
<tr>
<td>• No trailing cable/wheel unit repairs.</td>
<td>• Battery Charge/Change station.</td>
</tr>
<tr>
<td>• Less mechanical components.</td>
<td>• Requires special ratio feeder.</td>
</tr>
<tr>
<td>• Advantage gained from one or more units.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Employee Morale</td>
<td></td>
</tr>
<tr>
<td>Advantages</td>
<td></td>
</tr>
<tr>
<td>• No diesel fumes.</td>
<td>• Battery life/changing.</td>
</tr>
<tr>
<td>• No trailing cables.</td>
<td></td>
</tr>
<tr>
<td>• Flexible wheeling routes.</td>
<td></td>
</tr>
<tr>
<td>• Not radically different to shuttle cars/training.</td>
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<tr>
<td></td>
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<tr>
<td>Flexibility</td>
<td></td>
</tr>
<tr>
<td>Advantages</td>
<td></td>
</tr>
<tr>
<td>• Can handle variable seam conditions.</td>
<td>• Requires battery charge station.</td>
</tr>
<tr>
<td>• Flexible wheeling routes.</td>
<td>• Requires special ratio feeder.</td>
</tr>
<tr>
<td>• Materials transport.</td>
<td></td>
</tr>
<tr>
<td>• Outbye maintenance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Advantages</td>
<td></td>
</tr>
<tr>
<td>Proven technology - 20 years in USA.</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3. LITERATURE REVIEW

The literature review of this dissertation has two main objectives: First, it provides a background on underground coal mining haulage systems for the reader who might not be familiar with underground coal mining. Second, it reviews the previous research and methodologies pertaining to the characterization of mobile mining equipment in underground operations.

3.1 Brief Description of Underground Coal Mining

An underground coal mining operation consists of two main functions of coal production/excavation and coal haulage. The coal is produced at the “face” of entries and crosscuts. An underground coal mine panel, or section, depending on how big it is, might consist of several faces. Two major methods of coal mining are: 1. Longwall mining, which has one long face as shown in Figure 3-1; and 2. Room-and-pillar mining with multiple narrow faces as shown in Figure 3-2. There is an even split in the percentage of coal produced by each system in underground coal mining in the U.S. The mining operation is set up in panels, which would be the width of the face in a longwall mining or the width of the mining section in the room-and-pillar operation. In room-and-pillar operations the panel consists of several headings or entries, joined by cross cuts at certain intervals.
Mined coal is transported from the face to the surface through use of haulage units on the section, which dumps on a section belt conveyor that, in turn, connect to a mine-wide belt-conveyor system. In room-and-pillar mining and also in the development sections of longwall panels, mined coal is moved from the face to feeder breaker and panel/section conveyor by either batch or continuous haulage equipment. The feeder
breaker is the inlet to the conveyor belt; it breaks the coal into smaller pieces and it usually sits 100-150 m (300 to 500 feet) away from the face. This study focuses exclusively on coal mine shuttle cars utilized in such an operation.

3.1.1 Room-And-Pillar Mining

In the room-and-pillar mining method the pillars of coal are left behind the mined area to support the load above the openings (rooms) mined by the continuous miner (CM). Rooms are also called “entries” or “crosscuts.” Room width varies between 4.2-6.1 m (16 and 22 ft) in width. A 6-m (20-ft) room width is the most common size entry. Pillar sizes might be changed depending on roof conditions and the depth and/or thickness of the coal seam. Deeper mines require a bigger pillar size to support the overlying overburden. The height of the face varies with the height of the coal seam, although in thin-seam mining additional roof rock is often mined.

Room-and-pillar sections typically have as few as three or as many as fifteen parallel entries. Entries are connected at regular intervals, usually by perpendicular rooms called “cross cuts.” Pillar size can be determined by the spacing of entries and crosscuts. Entries and crosscuts are mined with a continuous miner in several small segments called “cuts.” Depending on roof conditions, each cut varies in depth from 1.5 to 12 m (5 to 40 ft). Deeper cuts generate more dust due to limited auxiliary ventilation to support the dead-end in the face. MSHA regulations must be met by dust control and ventilation requirements. A 25-foot cut is the most common cut depth. Haulage unit size is
determined based on the pillar size, the room width, the cut depth, and the height of the coal seam.

Figure 3-3 shows a typical cutting sequence for a 7-entry room-and-pillar mining section. The panel advances one lineal crosscut distance by completing 26 cuts. The section’s infrastructure, such as the conveyor belt and the power center, are moved forward regularly by advancing two to three cross-cut distances (depending on the width of the panel).

![Figure 3-3 Cutting sequence in room-and-pillar mining](image)

### 3.2 Shuttle Car Operation

The shuttle car is utilized to haul coal from the face to the feeder breaker. Coal is loaded into a shuttle car by the continuous miner (CM), and then it hauls coal to a dump point where a feeder breaker transfers it onto the panel conveyor belt. The number of shuttle cars in the haulage operation depends on the mine plan. Shuttle cars must periodically wait for each other a brief amount of time to make the haul path free because entry widths and car sizes make it impossible for cars to pass each other in the same entry. This limitation results in a change-out delays.
3.3 Previous Studies and Measurements

This section presents a review of the previous studies performed in the area of developing and characterizing the duty cycle of hauling equipment in an earthmoving operation.

3.3.1 CANMET Study

The Canada Centre for Mineral and Energy Technology (CANMET) has measured the duty cycle of four different mine vehicles (load-haul-dump, shuttle car (or coal hauler), battery-powered locomotive, and robotic vehicle) in seven different mines (Desrivères and Bétournay, 2002) for the future design of a fuel cell-powered underground mining haulage vehicle. The studied vehicles covered a mix of diesel fuel and electric-powered vehicles in different sizes. The developed duty cycles for coal haulers as well as the list of studied vehicles are provided in appendix A.

Each duty cycle case study includes real-time power requirements during different operations (e.g., loading, loaded tram, unloading, and empty tram). The mean power during each work segment, the mean power for the entire duty cycle, and the total energy are presented.

3.3.2 Southern Illinois University face haulage system time study

(Chugh et al., 2003) evaluated the performance of the three most common face haulage systems, 1. cable shuttle car, 2. diesel ram-car, and 3. battery ram-car, in eight different coal mines based on a time study in the Midwest coal seams of the Illinois Basin. The
result of this study is provided in appendix B. Among the eight studied coal mines, the characteristics of only two mines are provided in the published report, which are briefly discussed here.

3.3.2.1 Mine A
Mine A is a room-and-pillar super-section with two continuous miners per section and four battery ram-cars running in the haulage system. The panel consists of eleven entries on 60-foot centers, crosscuts on 60-foot centers, and a 20-foot entry width. It advances four crosscut distances between belt moves.

3.3.2.2 Mine B
Mine B is a longwall development operation running with two cable shuttle cars. The average coal seam height is 7 feet. The panel consists of three 16-foot-wide entries on 65-foot centers with crosscuts on 150-foot centers. The feeder and section belt are located in #3 entry. The average cut depth is 26 feet.

3.4 Measuring the Duty Cycles
A preliminary literature survey was conducted on both on-road and heavy-duty off-road vehicles in order to find reasonable solutions for determining the duty cycle. A torque-measuring flange could be mounted in the driveline between the engine and the transmission as a first, but not an easy solution. This method is expensive, difficult to implement, and needed significant drivetrain modification. Earthmoving and construction
machinery are usually difficult to access and equipment owners are usually reluctant to modify the vehicle. In mining applications, particularly, all modifications need to be approved and certified by the Mine Safety and Health Administration (MSHA), which is the mine safety regulatory agency in the U.S. This approval process usually takes a long time and needs frequent inspections, thereby delaying the production, which makes mining companies avoid this process and related downtime. However, there are other affordable options for duty-cycle measurement that will be reviewed in the following.

### 3.4.1 Developing Duty Cycle from the Driving Cycle on Non-mining Vehicles

The power and energy demand of urban and highway vehicles could be calculated from its driving cycle\(^2\) (O’Keefe, Simpson, Kelly, and Pedersen, 2007). The driving cycle of a highway vehicle could be found from its speed-versus-time profile. Calculations could be done based on the longitudinal-dynamics model of the vehicle (Gillespie, 1997). The rolling friction \(F_F\), the inertia force \(mdv/dt\), and the road grade force \(F_G\) are acting forces applied to the vehicle. Power consumption would be calculated from the acting forces and speed variation. The driving cycle and vehicle specifications could be imported in the vehicle system analysis simulators generating a fully-detailed view of the vehicle operation. The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy has listed highway duty vehicle system analysis simulators in its website. (NREL, 2012). Among them, ADVIAOR, which is a MATLAB/Simulink-

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\(^2\) the term “driving cycle” refers to speed-versus-time profile; whereas, “duty cycle” refers to power-versus-time profile
based simulation program, could be used for the performance and fuel-consumption analysis of light- and heavy-duty vehicles with conventional (gasoline/diesel), hybrid-electric, full-electric, and fuel-cell power-trains (ADVISOR® Software for Advanced Vehicle Energy Analysis, 2012).

Besides knowing the technical specifications and the driving cycle of the vehicle of interest, the test route condition and the components of the duty cycle, which could also be named as missions, should be given to the software in order to determine the power consumption through simulation.

3.4.1.1 Methodologies for Developing the Driving Cycles

The driving cycle is the speed history of the vehicle. Collecting the speed data through the vehicle on-board data port is a time-saving and affordable solution if this port is available. Currently, all vehicles are equipped with an on-board electronic speed measurement system and the speed data could be retrieved from the Engine Controller Unit (ECU) through the available data port provided in the vehicles. However, accessing the ECU information could be an issue for earthmoving vehicles. The available information on the ECU could be considered as confidential and is not released by the manufacturer because of the highly-competitive environment of this industry. In the case of not having access to the on-board speed measurements, additional devices could be used to measure the vehicle speed, as follows:
1. An encoder could be installed on the vehicle wheels to measure the rotation of the wheel through time (Montazeri-Gh and Naghizadeh, 2003).

2. An auxiliary ground-contacting wheel could be installed on the vehicle and then the rotational speed of the auxiliary wheel would be measured. This approach is not accurate since the auxiliary wheel underestimates the true ground speed due to slip between the tire and tractive surface (Al-janobi, 1996). This study has shown that the magnitude of this slip was inversely related to the firmness of the soil surface (Tompkins et al., 1985).

3. A global positioning system (GPS) unit could be mounted on a vehicle to capture the location of a vehicle in real-time. Several papers have focused on the speed measurement of a tractor in agricultural applications (Pexa et al., 2011) and urban electric vehicles (Shahidinejad et al., 2010) by implementing a GPS in the car. However, the GPS system is unsuitable for underground applications since no signal could be transmitted between the GPS unit and the satellite.

4. An inertial measurement unit (IMU) could be installed on a vehicle. An IMU is an electronic device that measures the craft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers.

Calculating the power consumption of earthmoving vehicles based on the driving cycles suffers from the flaw of underestimating the hydraulic power during the loading and unloading cycles. As earthmoving vehicles consume abundant power for running the hydraulic pump, the hydraulic pump power consumption should also be modeled and included in determining the duty cycle (Bradley, Huff, and Frank, 2005). Similar to vehicle speed data, the information related to a hydraulic pump motor, such as amp and voltage, plus pressures and flow rates in the valves are monitored and sent to the ECU for processing. In a case where retrieving the hydraulic pump data is not possible through the
ECU, the electric motor which drives the pump has to be instrumented. Power transducers are able to monitor the amount of power which an electric motor takes in. If the unit allows for monitoring the generated/consumed power through the ECU, then the total power consumption could be monitored and used for determination of the duty cycle.

3.4.2 Developing of Duty Cycle from the Accessible Parameters on Electric Control Unit

Nowadays, mechanically-injected fuel engines are replaced by electronically-controlled engines. The Electric Control Unit (ECU) controls diesel engines or electric motors in order to keep the system at its optimal performance point. As shown in Figure 3-4, an array of sensors and actuators communicates and transmits messages with the ECU via a communication line named the CAN bus. Utilizing the CAN bus intercommunication reduces the size and complexity of wiring. Aspects of the CAN bus message such as vehicle speed, fuel consumption rate, and door status might be displayed in the driver's cab. The other message in both high-and low-priority (i.e. engine performance message or suspension system parameters) might also be accessible through an assigned diagnostics port on the vehicle. In other words, the determination of duty cycles would require less effort with the growth of vehicle intercommunication technology and the availability of a CAN-bus interface plug on the vehicle.

3 Controller Area Network
3.4.2.1 CANbus on Heavy Duty Vehicles

The SAE\textsuperscript{4} J1939 CAN bus is a standard protocol adopted in heavy-duty diesel-powered vehicles for on-board diagnostics (SAEJ1939, 2012). The J1939 CAN bus can be configured to read RPM, engine load, throttle position, inlet fuel/air ratio and many other parameters. The reason for collecting information on these parameters is to optimize the control of the engine emissions for different applications. Logging CAN messages might be an easy solution; however, interpreting messages to a meaningful parameter value could be an issue. A scanner device could be attached to the CAN-bus interface port in order to monitor the messages. The device can be configured to capture the parameters of interest and save them in a specified format. Different types of commercial CAN-bus data loggers could either save data on a memory card or transfer it

\textsuperscript{4} Society of Automotive Engineers
via wifi to the laptop acquiring the real-time data. These units were used for measurement of the performance parameters of underground haulage units in the current study.
Chapter 4. DEVELOPMENT OF THE DUTY CYCLES FRAMEWORK

The goal of this research is to measure power and energy consumption of various shuttle cars working in different haulage operations in order to characterize the developed duty cycles based on the haulage operation features. To reach this goal, the following steps were taken to characterize the duty cycle of a shuttle car:

1. Determine the haul-road condition such as grades and rolling resistance.
2. Learn the haulage operational characteristics such as the utilization, number of haulage units in operation, capacity of the haulage units, number of haulage trips per cut, advancing rate, frequency of stops and starts during the haulage cycles, and the haulage distance.
3. Review the mine geometry such as the entry and crosscut spacing, the room width, the depth of cut, and the coal seam height.
4. Time the haulage cycle and waiting times.
5. Calculate the tramming speed, the loading rate, and the dumping rate.
6. Measure the power/energy consumption of the shuttle car and determine the status of the machine.

This chapter describes those parameters that affect shuttle car duty and timing cycles, and then it explains the methodology and case studies chosen to develop the duty cycles.
4.1 Determine Haulage Operation Condition

The haulage operational conditions change continually along the haul path. The parameters described below would change the haulage operational conditions and should be accounted for in the study.

4.1.1 Rolling Resistance

Rolling resistance (RR) is the most important haulage operational characteristic and a critical factor in determining power/energy consumption and travel time. RR of unpaved roadways is changing due to the softness of the roadway and the existence of water as well as the pressure of air in the tires. RR is a difficult parameter to measure in the field. A towing test on level ground at a constant speed is a simple test to determine RR. Estimation of RR by empirical approaches requires visual inspection of the road for corrugations, rutting, and gravel loss among other characteristics. The most common RR prediction method in earthmoving operations is based on an empirical approach offered in the Caterpillar Performance Handbook. The formula is given in Equation 1.

\[ RR = 2\% + 1.5\% \text{ per inch tire penetration} \]  

Equation 1

In addition to the empirical approach, researchers have developed on-board sensing systems employed in earthmoving equipment to predict the real-time RR. Thompson et.al. (2003) developed a monitoring system for mine trucks based on the GPS system and tri-axial vibration sensors detecting road defect vibration signatures.
Measured RR values would be used in commercial haul-road management software (e.g., Caterpillar’s Vital Information Management System (VIMS) and Truck Production Management System (TPMS)) to optimized the operation of haulage units.

### 4.1.2 Grade Resistance

Grades are measured in percent slope. The slope of a haul road changes within a coal seam. This parameter is determined from the mine map contour lines and the grade is determined by Equation 2, as follows:

\[
\text{Grade} = \frac{\text{vertical change in elevation (rise)}}{\text{corresponding horizontal distance (Run)}} \times 100\% \tag{Equation 2}
\]

### 4.1.3 Utilization

Utilization indicates the extent to which a machine is used when it is mechanically available. Mining equipment utilization is not only a vehicle usage indicator, but it also represents an overall production efficiency metric; therefore, mine operators usually keep track of their equipment utilization to monitor and improve the efficiency of their production. Utilization is calculated as the time a machine is producing, or utilized, times 100% divided by the total time available for production on a shift. In underground mining application, utilization may be measured by time studies using a stopwatch or it may be calculated by modern haulage fleet management software, which requires input data from studies. In this study, utilization is calculated as the time a
machine is utilized divided by machine availability. Machine availability is the amount of shift time, in percent, that the machine is available for production. The shuttle car pump switch is monitored to determine whether the equipment is able to run.

Shuttle car utilization varies between different mine operations. Shuttle car utilization is highly dependents on the haul road conditions, downtime characteristics on a given shift, and equipment age. At peak times, utilization is between 70% and 80%, while it could drop to 20% - 30% under extreme haul road conditions or inefficient operation. Lower utilization could result from low haulage efficiency due to:

1. Poor haul road condition due to inadequate road maintenance which may limit speeds and increase stop-start time frequency,
2. Poor condition of vehicles or inadequate driver skill,
3. Lack of efficient operational management,
4. Frequent inspection and/or maintenance, and
5. Extreme face conditions in terms of cutting and roof support, which adds more delays to the cutting sequence and limits the haulage operation.

4.2 Data Acquisition System and Sensor

In an attempt to collect the desired duty-cycle information from Joy shuttle cars and monitor the machine status, two different data acquisition systems (DAS) were employed. The first DAS unit was installed on the shuttle car electric controller module. This unit was recording the machine’s operating parameters such as motor voltage and current which were available on CAN. Another DAS unit was mounted
on the power center (or rectifier) to which the shuttle car is connected. This unit was measuring the power (or DC current) drawn by the shuttle car through the trailing cable. The measurement of two DAS units can be compared with each other to check the consistency of the results.

The summary of selected DAS units is offered below. Detailed information regarding the data acquisition systems are provided in following sections.

1. A Kvaser Memerator Pro CANbus data logger is connected to the shuttle car’s VFD master control box,
2. A DC current transducer and a DT82I data logger are installed inside the power center to monitor the trailing cable current.

4.2.1 DAS #1: Kvaser Memerator Pro CAN logger

The first DAS unit was selected based on the availability of the CAN port on the studied Joy shuttle car’s electric driving system. Joy shuttle cars were driven by a Saminco Variable Frequency Drive (VFD) system. The Saminco VFD system is equipped with the CAN-bus system which consists of 4 motor controller modules (Tram1, Tram2, conveyor belt, and pump), one diagnostic display, and a master control box. The master control box is an interface from customer controls and system control input. It distributes control signals to each motor controller and monitors several parameters in the system. For the monitoring purposes, the digital diagnostic display is also connected to the system. The handheld programmer is a tool used for troubleshooting and changing parameters of the
Available parameters on Saminco’s CAN bus, which are listed in Table 4-1, could be recorded by Kvaser Memerator CAN logger.

### Table 4-1 Available parameters on the Saminco’s CAN bus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tram/Pump/Conveyor Motors Armature Voltages</td>
<td>Bus Voltage</td>
</tr>
<tr>
<td>Tram/Pump/Conveyor Field Currents</td>
<td>Accelerator Pedal Position</td>
</tr>
<tr>
<td>Tram/Pump/Conveyor Output Currents</td>
<td>Conveyor Knob Position</td>
</tr>
<tr>
<td>Tram/Pump/Conveyor Heat Sink Temperatures</td>
<td>Pump Switch</td>
</tr>
</tbody>
</table>

The Kvaser unit was placed inside the shuttle car electric panel, where the VFD system and master controller box are located, and then it was wired to the master control box where digital display is connected (Figure 4-1 and Figure 4-2). The detailed wiring of the Kvaser data logger to the master controller module is provided in appendix H.
The Kvaser CAN logger was powered through the master controller module and it did not require driver interaction. The Saminco CAN protocol sends out the motor messages at a rate of 6Hz. The Kvaser logger was configured to record all data at the same rate of 6 Hz and time-stamped them. CAN messages were stored on a 4-Gigabyte SD card to be retrieved every two or three weeks by the author.
4.2.2 DAS #2: Trailing Cable Power data recorder

The second data acquisition system was installed at coal mine B. Shuttle cars are powered with 550VDC power at mine B. A high-voltage three-phase AC power was converted to 550VDC power by the rectifier where shuttle cars were plugged in; then, the 550VDC power was converted again to AC power inside the shuttle car to power up the shuttle car VFD system and four motors. As shown in Figure 4-3, a large-aperture DC Current Transducer with the model number of DT7-420-24U-U-DL was snapped to the DC line of the trailing cable inside the rectifier. The input range of the DC current transducer was 0-750A and the output was 4-20mA.
The programmable DT82I data logger was recording the DC current data with a sampling rate of 2Hz on a thumb drive to be easily retrieved every two or three weeks. The storage mechanism was chosen based on the changeable thumb drive and the SD card to reduce the equipment downtime. Figure 4-4 illustrates the installation of the data logger inside the rectifier.
Among six available shuttle cars in the face haulage operation of mine A and B, two similar 10SC32B types in mine A and two similar 21SC04 shuttle cars in mine B were selected and instrumented for this study. The model numbers of test case shuttle cars and their specifications are presented in Table 4-2.
4.4 Pre-Installation and Testing

The selected DAS units were tested outside of the coal mines before installation in order to evaluate their performance. The measured data was examined and was fine and compared to the benchmarks for verification.

4.4.1 Kvaser CAN Logger Testing

The Fairchild scoop utilized in mine A was driven by the similar Saminco VFD system installed on Joy shuttle cars coming with the same CAN messaging protocol. The programmed Kvaser CAN logger was connected to the CAN data port of the Fairchild scoop to test the logger. The port was located on the diagnostic display in an aluminum
enclosure inside the driver cabin (Figure 4-5). The scoop driving system was a 128V Battery / AC system consisting of a VFD tram drive and VFD pump drive in an explosion proof enclosure, a 75HP 80V AC traction motor and a 24HP 80V AC pump motor.

![Figure 4-5 Picture of Connecting Kvaser CAN data logger to a scoop](image)

The scoop driver was asked to perform different tasks for 5 minutes to verify the collected messages. Then, the collected messages were converted from binary to decimal numbers to represent a meaningful parameter. The results of this trial run are shown in Figure 4-6 and Figure 4-7.
Figure 4-6 Collected tram motor CAN parameters from Fairchild Scoop

Figure 4-7 Collected pump motor CAN parameters from Fairchild Scoop
4.4.2 Power Transducer Data Collecting System Testing

The pump station of mine A was instrumented to evaluate the power transducer data collection system (Figure 4-8).

![Barbara Mine Pump Station](image)

3CT power transducers were snapped to the three-phase AC lines of the pump motor inside the electric panel (Figure 4-9 and Figure 4-10). The 4-20mA signal wires and 24VDC power supply wires were wired to the data logger and AC-to-DC adapter, respectively.
The pump was switched on and off while DataTaker was recording power data. The plot of recorded pump power data is shown in Figure 4-11. The power consumption of the pump was also displayed on the electric panel LCD. The displayed power consumption on the LCD was approximately 140kW. As Figure 4-11 illustrates, there is a
good match between the measured power and what the LCD was displaying on the electric panel.

![Pump Station Power Consumption (KW)](image)

Figure 4-11 Power Transducer Data Collection Testing on Pump Station

### 4.5 Case Studies and Mine Layouts

#### 4.5.1 Mine A

Mine A is a room-and-pillar operation with a 7-entry standard section. The face haulage system consists of three JOY electricity-powered 10SC32B shuttle cars with a 15-tonne capacity. The mine operated with two production shifts and a maintenance shift per day, 10 working hours per shift, and 6 days per week.

Figure 4-12 presents two different scenarios of coal haulage (study area #1) and rock haulage (study area #2) examined in mine A. Mine A has been forced to cut through rock for almost 6 months due to the change in the geological condition of coal mine A from coal to rock. The mining plan and operation have been altered consequently.
4.5.1.1 Mine A - Study Area# 1 – July 15th through July 18th

Haulage cycle data were collected in four days from July 15th, 2013 through July 18th, 2013. The collected data covered 11 shifts and 35 shuttle car trips per shift on average. The study area #1 of mine A has 6-8 entries spaced at 55-foot centers from each other with crosscuts at 65-foot centers as shown in Figure 4-13. The entry width is 20...
feet. The panel was advancing three crosscut distances between belt moves. The feeder was located at #3 Entry. The average cut depth was 22 feet. Mine A employed two electricity-powered shuttle cars and had a third shuttle car as a spare haulage unit which may be used on the long haul paths. On average, the seam height was approximately 77 inches. The studied panel is angled around #4 Entry. This situation made the loaded shuttle car tram 10% uphill from the CM to the feeder breaker through the intake entries (Entries #1, #2, and #3) and tram 15% uphill through the intake crosscuts (Area B). On the other hand, the loaded shuttle car trammed 10% and 15% downhill through the return entries (Entries #4, #5, and #6) and return crosscuts, respectively (Area A). Since the thinner part of seam was encountered, the miners had to cut roof rock in Area C to get as much coal out of the panel as possible and make it compatible for further extension. Figure 4-12 provides the elevation contour lines in mine A that can help visualize the slopes for traveling in the panel.
4.5.1.2 Mine A - Study Area# 2 – July 22th through September 12th

In scenario #2, mine A was cutting through rock. The collected data covered 58 shifts and 798 shuttle car trips. The mining section has 3 entries spaced at 55-foot centers from each other and varying crosscut spacing depending on the roof condition as shown in Figure 4-14. The number of entries and crosscuts were decreased to minimize rock cutting in the roof as much as possible. The entry width was 20 feet. The feeder breaker was located at #2 Entry. The loaded shuttle car was tramming 15% - 17% uphill from the CM to the feeder breaker.
4.5.2 Mine B

Mine B is a room-and-pillar operation with standard section. The face haulage system consisted of three JOY electricity-powered 15SC shuttle cars with a 9-ton capacity.

Mine B produces 800K tonnes per annum. On average, the seam height was approximately 66 inches. The mine operated with two production shifts and one maintenance shift per day, 10 working hours per shift, and 6 days per week. Figure 4-15 shows three different areas studied in mine B. The handled material was coal for all three cases in Mine B.
4.5.2.1 Mine B - Study Area #1- September 19th through September 26th

Haulage cycle data were collected in one week from September 19th, 2013 through September 26th, 2013. The collected data covered 19 shifts and 475 shuttle car trips. The studied panel had 7-9 entries spaced at 55-foot centers with crosscuts on 65-foot centers. The entry width was 20 feet. The panel was advancing a four crosscut distance between belt moves. The feeder was located in #4 entry. The average cut depth was 24 feet. A typical cut sequence is shown in Figure 4-16 and the #1 studied area layout is shown in Figure 4-17.
4.5.2.2 Mine B - Study Area #2 – November 22th through December 19th

Data were collected for four weeks from November 22, 2013 through December 19, 2013. The collected data encompasses 21 shifts and 431 shuttle car trips. The mining operation faced a difficult situation during work in study area #2. The faces of the panel in #1 through #4 entries caved in and this incident trapped one of the continuous miners. The cooperating mine started mining from the other side of the panel to get to the trapped CM in order to recover it. The mining operation, roof condition and haul road condition deteriorated in this area. The feeder breaker location is shown by a green pin in
Figure 4-18. Shuttle cars had to tram 500ft to 700ft to get to the caved-in area. The cable length limitation was a big issue in this scenario. The haul road condition was extreme for the first 150 ft part of the road in front of the feeder breaker. The haul road condition along the two following crosscuts next to the feeder breaker, which is indicated as A1 area in Figure 4-18, was extremely muddy (10 inches of tire penetration). The roadway slope was about 3% uphill from the feeder breaker to the CM. The rolling resistance was estimated as 16% to 18% for this part of the haul road. After passing two muddy crosscuts, the haul road condition was still difficult to run the shuttle car. The severe bottom undulation and the bumpy road presented challenging conditions for the shuttle car to run in this area. The described situation of the #2 study area plus to the long distance of haul road pushed the cooperating mine to employ two shuttle cars with a scoop in series to haul coal from the face to the feeder breaker. The haulage operation was arranged so that the first shuttle car was hauling coal and then unloading coal to the second shuttle car midway, then the second shuttle car was dumping coal on the floor behind the A1 area in order for the scoop to collect it and rehandle the coal to the feeder breaker. The haul road in A2 area was still soft with dispersed spots where water had gathered. The tire penetration was observed as 4 to 6 inches in the wet spots. The rolling resistance was estimated as 12% to 15% for this part of the haul road. For the rest of the roadway up to the CM, the haul road bottom was firm with a 4% uphill slope.
4.5.2.3 **Mine B - Study Area #3**

The mine operation changed back to a normal operation in study area #3. Generally, the haul road slope was 3% uphill from the feeder breaker to the CM with 1% uphill slope in the #1, 2, 3, and 4 crosscuts and 5% uphill slope in the #5, 6, and 7 crosscuts. The layout of study area #3 is presented in Figure 4-19. The roadway was mostly firm for the entire haul path except for the two following crosscuts next to the feeder breaker which were bumpy and muddy (2-inch tire penetration). The shuttle car average tramming speed was reduced from 6.5 ft/s to 4.8 ft/s when it was travelling through these cross cuts. The average loaded and empty tramming speed was 5.4 ft/s and
7.7 ft/s, respectively. The maximum tramming speed of 8.6 ft/s was attained during empty tramming. The rolling resistance of 6% to 7% was estimated for the normal haul roads and 8% to 10% for the muddy/bumpy sections.

Figure 4-19 #3 study area layout – Mine B
Chapter 5. DATA ANALYSIS TOOLS

This chapter discusses the programming of the CANbus data collection system and the programs developed for the analysis of the collected data in MATLAB software.

5.1 Kvaser Memorator Professional Setup Tool

As mentioned before, Kvaser Memorator is a CAN device which communicates with the CAN bus on the shuttle car to receive CAN messages. The following section introduces the configuration procedure on Kvaser Memorator in order to record and interpret the messages to decimal values.

5.1.1 CAN Bus Parameters Configuration

To be able to record CAN messages, it is important that the CAN device is configured correctly to transmit and receive messages. The CAN-bus configuration parameters are:

- **Bus speed**: This parameter defines the bit rate at which messages are transmitted.
- **Sampling point position**: This parameter continuously synchronizes the CAN bit timing between different devices connected to the CAN bus.
- **Synchronization jump width (SJW)**: This parameter is used to adjust the CAN device bus clock. The CAN controller may change the length of a bit by an integral number between 1 and 4.
- **Number of samples per bit**: This property specifies the total number of samples available to the CAN channel.

- **Acknowledgement mode**: Defines whether the CAN device acts as only a receiver (Silent mode) or it transmits messages as well (Normal mode).

The bus speed on Kvaser Memorator must be configured to the same speed as the Saminco CAN bus bit rate. Usually mining products run at a bus rate of 250 Kbits/second. The position of the sampling point usually depends on what kind of CAN controller is used on the hardware. The sampling-point position is set at 60/40% of a bit and it becomes more critical if noise immunity is needed. SJW was also set to 1.

### 5.1.2 Define and Filter Messages

CAN messages are 0 - 8 byte messages in size. Depending on the equipment type, up to 20,000 messages/second could be broadcasted by the CAN bus. Therefore, received CAN messages were filtered based on the message identifiers to limit the number of recorded messages; otherwise, the SD card could be filled very quickly. After filtering the messages, binary CAN messages were converted to time-series signals using the protocol which Saminco engineers provided. In the last stage, the time series signals were saved as a Comma Separated Values (CSV) file format to be imported into the Matlab program for further analysis.
5.2 Duty Cycle Generation Tool

The Duty Cycle Generation tool was developed with MATLAB which generates the shuttle car duty cycles from the imported time-series signals explained in the previous section. The first part of the program takes the time-series signals, partitions them into a sequence of discrete segments, and then assigns labels to each segment. Each label represents one of four work segments of the shuttle car duty cycle; they are: 1. Empty tramming, 2. Loading, 3. Loaded tramming, and 4. Unloading.

Duty cycles were identified using the MATLAB change-point detection and algorithm. The change-point detection algorithm tries to identify changes in the characteristics of the signal, such as the mean value of the signal, the area underneath the signal, the root mean square (RMS) value, the variance, and peak-to-RMS.

Figure 5-1 illustrates a sample window of the driver reference input containing three signals of the accelerator pedal position (APP), conveyor knob position (CKP), and pump switch with explanations as given below:

- The blue line indicates the position of the driver accelerator pedal. The corresponding value changes from 0 (idle position) to 255 (full position),
- The red line represents the conveyor knob position (CKP) and the corresponding value changes from 0 to 125, and
- The green line represents the pump switch status with two values of 0 and 100.
CKP and APP signals were chosen to identify the components of the duty cycles. As Figure 5-1 presents, the CKP signal changes aggressively between zero and the maximum value during the loading cycles. In other words, the loading cycle encompasses several short durations and a spiked CKP signal. On other hand, the CKP signal changes as steps during the unloading cycles. Unloading cycles include longer-duration CKP signals with varying amplitudes. That said, the area underneath the CKP signal is selected as the change-point detection feature which classifies the loading and unloading cycles. Figure 5-2 illustrates how well loading cycles are classified from unloading cycles when the area underneath the conveyor position signal is used as the detection feature.
Figure 5-2 Plot of #1 Classifier: Area under conveyor signal during loading and dumping cycles

The mean-to-peak ratio of the CKP signal could also be used as a classifying feature. Figure 5-3 is represented in a format where the x-axis refers to the area under the signal, and the y-axis refers to the peak-to-mean ratio of the CKP signal.
Once the loading and unloading cycles are identified, the portions of the signal between the aforementioned two segments represents the tramming cycles. Based on the fact that the empty tramming cycle come after the unloading cycle, and similarly, the loaded tramming cycle follow the loading cycle, the cycle label assignment task can be completed.

5.3 **Duty Cycle Analysis Tool**

After labeling the various components of the entire work cycle, statistical analyses were performed on the cycles to provide the duty cycle parameters required for battery sizing. The duty-cycle analysis tool creates multiple plots that are used to explore the relationship between the duty-cycle parameters using visualization techniques such as

![Figure 5-3 Plot of #2 Classifier: Mean-to-peak ratio of conveyor signal during loading and unloading cycles](image-url)
scatter plots and histograms. The studied duty cycle parameters are discussed in the following sections.

5.3.1 Cycle Time

The cycle time is the first and most basic information needed for any subsequent analysis. The programs developed for identification of the cycle components allow for calculation of the time allocated for each component of the entire cycle and for the total cycle time, which was the sum of the loading, tramming, unloading, and return components.

5.3.2 Analysis of Energy Consumed in Each Cycle

5.3.2.1 Required energy (kWh) per haulage trip

Battery manufacturers need to have a clear understanding of the required energy for a haulage trip and the number for trips to size the capacity of the battery. The number of shuttle car haulage trips during a shift can be calculated based on the shift production, number of the active haulage units, the load-carrying capacity of each haulage unit and the geometry of the panel. This parameter can be also determined by field observation. The required energy per haulage trip depends on the shuttle car gross weight (loaded and unloaded), the haul road condition, the hauling distance, and the driver’s skill level, which makes this parameter hard to determine. The required energy needs to be measured by instruments installed on either the shuttle cars or the power center.
5.3.2.2 Required energy per haulage trip based on the haulage cycle timing

The haulage cycle time is another parameter that can be determined easily as discussed before. For this purpose the cycle time can be estimated from the recorded data. Alternatively, a simple stopwatch could be employed to time the cycles and the work segments of a haulage cycle (tramming, loading, unloading, etc.). The required energy per haulage trip was correlated to the duration of a haulage cycle by a linear model. The slope of the linear model (energy-time) represents the mean power throughout the cycle, which changes based on the haul road condition. This correlation helps engineers to time the shuttle car and then come up with a good estimation of the required power and energy.

5.3.3 Power Consumption Analysis

Studying the power consumption history helps to predict the required battery size and life as well as to optimize the electrical design for these haulage units. Because of the highly-dynamic nature of the power demand during haulage cycles, the power is measured as the average over time or RMS over a course of a cycle. The calculated power consumptions per haulage cycles are presented in related histograms that will be presented in the following section.

5.3.4 Peak Power Analysis

The battery must be able to handle the high momentary power demands during acceleration and uphill tramming without fear of over-drawing the battery and thus
reducing its lifespan. For the purpose of determining the peak power, local peak power demands in the time-series signal of total power consumption were detected using the MATLAB “peakfinder” algorithm. The MATLAB peakfinder algorithm calculates the peak power’s duration, peak-to-peak intervals, and the area underneath the peak powers, which translates to the required energy during the peak period.

5.3.4.1 MATLAB peak-finder algorithm

The MATLAB peak-finder algorithm works based on the following steps:

1. The first derivative of the signal is smoothed using the sliding average method.

2. Zero-crossings points with downward curve slopes are found.

3. The zero-crossing points are filtered out based on the slope threshold. The slope of the original signal at the zero-crossing points must exceed the "slope threshold."

4. The remaining points from step 3 must exceed the "amplitude threshold."

The performance of the MATLAB peak-finder algorithm in detecting the local peaks is presented in Figure 5-4. The length of the red lines laid on the detected peaks represents the peak duration.
5.3.5 Estimating Rolling Resistance (RR)

The Caterpillar empirical method described in previous chapters can be used to estimate RR for the surface haulage trucks; however this method seems to underestimate the RR for underground haulage units. Based on the time and the power study performed on the section R1 of mine B study area #3, the calculated RR for the case of loaded tramming obtained in the range of 9% to 14%, and for the case of empty tramming found in the range of 7% to 12%; while, the predicted RR by Caterpillar empirical method was obtained in the range of 6% to 8% for both cases of empty and loaded tramming. The Caterpillar empirical formula must be adjusted for tire pressure, tire deformation, the type of tire, and the gross weight of machine. To improve the accuracy of the Caterpillar empirical method in predicting RR for underground haulage vehicles, a MATLAB code was developed to estimate RR using the recorded tramming time, tramming power, and the haul road grade.

Figure 5-4 Plot of the recorded power consumption data and duration of detected peaks
The required power consumed by the shuttle car \( P_{\text{total}} \) to overcome external forces in order to tram with the average speed of \( \bar{v} \) can be written as Equation 3:

\[
P = \eta^{-1} \times \bar{v} \times (F_a + F_r + F_i + F_g)
\]

Equation 3

Where:

\[F_a: \text{aerodynamic force}\]
\[F_r: \text{rolling resistance force}\]
\[F_i: \text{inertia force}\]
\[F_g: \text{force required to overcome the grade resistance}\]
\[\eta: \text{efficiency}\]

The aerodynamic force is negligible due to the low tram speed of the shuttle car. The power required by the inertia force is estimated as 4\% to 8\% of the total power depending on the number of turns and stop-start times occurring during the tramming cycles. A study done by (Lineberry, 1986) proposes a linear model which estimates the power required by the inertia force due to the number of intermittent factors per tramming cycle. The number of intermittent factors per tramming cycle was found by the MATLAB code. \( F_r + F_g \) is substituted with total effective grade multiplied by gross weight, which changes Equation 3 to Equation 4:

\[
P = \eta^{-1} \times \bar{v} \times (F_r + F_i + F_g) = \eta^{-1} \times \bar{v} \left( \frac{m}{s} \right) \times \text{GW (kgf)} \times \text{TEG (\%)}
\]

Equation 4

where:

\[\text{GW: gross weight (kg)}\]
The Matlab code solved Equation 4 for RR in each haulage trip. In Equation 4, the tramming power and tramming time were known from the DAS records, GR was found from the mine contour map, and gross weight was estimated from the shuttle car capacity and its curb weight provided in the shuttle car specifications. Haul distances were not collected by DAS to obtain the average tram speed. Efficiency is also unknown. Thus, the ratio of the loaded-to-unloaded tramming power was calculated for each work cycle in order to cancel out the haul distance and efficiency in the calculation. For a haulage trip, the ratio of loaded-to-unloaded power was simplified as below:

\[
\text{Power Ratio} = \text{Weight ratio} \times \text{Tramming Time ratio}^{-1} \times \text{TEG ratio} \quad \text{Equation 7}
\]

The TEG ratio was computed for each work cycle knowing the power, the weight, the tramming time ratios, and the number of intermittent factors per tramming cycle. A TEG ratio greater than 1 means that a loaded shuttle car is tramming uphill; while, a TEG ratio lower than 1 means that a loaded shuttle car is tramming downhill. Equation 8 and Equation 9 are given to calculate RR depending on the order of TEG.

\[
\begin{align*}
\text{RR(\%)} &= \text{GR(\%)} \times \frac{1 + \text{TEG}}{1 - \text{TEG}} \\
&\quad \text{TEG} < 1
\end{align*}
\quad \text{Equation 8}
\]
This model does not present a good estimation of RR for TEG values found close to 1, which makes the calculation highly sensitive to the value of GR.

Figure 5-5 illustrates the TEG ratio calculated for study Area #1 in Mine A. Haulage cycles with a TEG ratio lower than 1, which are located inside the black box, represent a situation where a loaded shuttle car was tramping downhill. For the rest of haulage cycles, the loaded shuttle car was tramping uphill. Inconsistent TEG ratio values were obtained after 18th July in Figure 5-5 due to the transient change of operations from coal mining to rock cutting at the end of this part of the study, which presented a variant haul road condition. For illustration purposes, consider Figure 5-5, Equation 8, a GR of 9% to 11%, and a TEG ratio of 0.25, where RRs were obtained in a range of 15% to 18%, which is 30% higher than the RR determined by the Caterpillar empirical method.
5.3.6 Crest Factor Analysis

The crest factor is the other factor to look at when it comes to the battery or powersource sizing. The crest factor is the ratio of peak power to the RMS of the power signal. Non-linear load devices such as electric drive vehicles powered by variable frequency drives draw a high crest factor from a source of power. The source of power must handle high crest factors and supply the peak current desired by the load. If the source cannot handle this, then its output voltage and power factor will become distorted (Tolbert, Hollis, and Hale, 2008).
5.3.7 Intermittent Delays Analysis

Haulage cycles may experience intermittent delays during the course of a normal shift. A shuttle car is idle and does not haul coal during the intermittent delays. Intermittent delays could decrease the shuttle car utilization to below 50% (Hirschi, 2012). Intermittent delays could be due to the repetitive tasks when 1. The CM, feeder breaker, or shuttle cars undergo regular or unexpected maintenance; 2. The CM or roof bolter move to a new cut; 3. The scoop is cleaning the haul road; 4. The power center or conveyor belt is being moved; and 5. There is a change-out delay when the shuttle car arrives at a change-out point. In this list, items 1-4 are maintenance- or mining cycle-related delays considered as downtime where the shuttle car is down or switched off. Item 5 is the key element that reflects the operational delays and downtimes while mining is in progress, and thus is more important to study and minimize.

To minimize the change-out delay, the change-out points, near the CM and near the feeder breaker, should be kept as close as possible to each piece of equipment. The feeder breaker should be moved frequently with the maximum advancement of a 3 or 4 crosscut distance in the panel to keep the haul distance in an optimum range. According to (Chugh et al., 2003), the capacity of larger shuttle cars would offset the change-out delays.

Intermittent operation of shuttle cars not only affects the shuttle car utilization, but it also increases the shuttle car’s power demand due to adding more acceleration and deceleration to the cycles. Power demand could vary according to the intermittent factors such as stops at change-out points, turning in a sharp curve or blind corners, and passing
bridges or underpasses. A study done by (Lineberry, 1986) proposes a linear model which estimates the additional power requirement due to the number of intermittent factors per cycle. The result of this study is presented at Table 5-1.

Table 5-1 Estimation of additional power requirement due to the number of intermittent delay (factor) per cycle (Lineberry, 1986)

<table>
<thead>
<tr>
<th>Number of Mid-Cycle Intermittent Factors Per Cycle</th>
<th>Approximate Acceleration Factor</th>
<th>Approximate Additional Power Required (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>1-2</td>
<td>1.1</td>
<td>4</td>
</tr>
<tr>
<td>3-4</td>
<td>1.2</td>
<td>8</td>
</tr>
<tr>
<td>5-6</td>
<td>1.3</td>
<td>12</td>
</tr>
<tr>
<td>7-8</td>
<td>1.4</td>
<td>16</td>
</tr>
<tr>
<td>48</td>
<td>1.5</td>
<td>20</td>
</tr>
</tbody>
</table>

While intermittent operation of a shuttle car reduces the shuttle car utilization and increases its power demand, it could significantly improve the discharge performance of the battery (Castillo et. al., 2004). Intermittent operation provides a relaxation time for the battery such that the temperature returns towards the normal level. Because of this potential for a recovery during intermittent operation, the battery capacity drops less and the operating efficiency is higher compared to the continuous operation as is shown by the dotted line in Figure 5-6. In general, batteries operate more efficiently under interrupted operation, whereas internal combustion engines work efficiently with continuous steady loads. This is another reason why the battery-powered shuttle car is a preferred solution for the haulage operation subjected to intermittent factors.
Figure 5-6 Comparison of battery capacity between the intermittent and continuous discharge.

Courtesy of (Lawson, n.d.)

In an attempt to study intermittent delays, two parameters of stop-start frequency per haulage trip and the duration of the stops have been studied and the results are reported in next chapter of this report.

5.4 Shift Utilization vs. Energy Consumption Analysis

Shift utilization is reported commonly by mining companies. The required energy during a course of a shift can also be estimated by utilization. For the purpose of correlating utilization and total energy consumption, the supervised shift analyzer tool extracts the shifts’ information from the duty-cycle analysis, and then provides a linear model for the total energy consumption during a course of a shift based on the shuttle car’s utilization.
Chapter 6. ANALYSIS OF COLLECTED FIELD DATA

6.1 Overview on Shifts Analysis

A general overview of shift information such as utilization, energy consumption and the total number of analyzed haulage cycles during a shift are presented in this section.

The average shuttle car utilization for mine A and mine B during coal haulage were 35% and 37%, respectively. This value dropped to 16% in Mine A during rock haulage due to the slow operation of rock cutting in the face. The box plots of energy consumption, utilization, and the number of haulage trips during a shift are presented in Figure 6-1, Figure 6-2, and Figure 6-3, respectively.

![Figure 6-1 Boxplot of energy consumption during a shift [kWh]](image-url)
Figure 6-2 Boxplot of shuttle car utilization % per shift

Figure 6-3 Boxplot of number of haulage trips during a shift

The boxplots of energy consumption, utilization, and the number of haulage trips during a shift for the 5 studied cases are provided in appendices C to H. As shown in Figure 6-1 through Figure 6-3, the second shift is the most-productive shift and the third shift, which is the maintenance shift, is the least-productive shift in a normal day. The first-shift utilization is less than or mostly equal to the second-shift utilization due to the regular inspections conducted on the first shift.
6.2 Haulage Cycle Timing

The histograms of the required times for completing a haulage cycle are presented in Figure 6-4, and the statistical information of histograms is presented in Table 6-1 and Table 6-2. Parts (e) through (g) of Figure 6-4 correspond to the study area A1, A2, and A3 at mine B, as described in section 4.5.2.2.

Figure 6-4 Histograms of haulage cycle timing for various working conditions
Table 6-1 Summary of statistical information for haulage cycle time [sec]

<table>
<thead>
<tr>
<th>Haulage Cycle Time</th>
<th>Hauling Coal</th>
<th>Hauling Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>301</td>
<td>260</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>111</td>
<td>155</td>
</tr>
<tr>
<td>Minimum</td>
<td>125</td>
<td>120</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>239</td>
<td>165</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>279</td>
<td>219</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>334</td>
<td>312</td>
</tr>
<tr>
<td>Upper Fence</td>
<td>381</td>
<td>386</td>
</tr>
<tr>
<td>Maximum</td>
<td>1442</td>
<td>1907</td>
</tr>
<tr>
<td>Sample Number</td>
<td>475</td>
<td>431</td>
</tr>
</tbody>
</table>

Table 6-2 Comparison of haulage cycle time [sec]

<table>
<thead>
<tr>
<th>Cycle Time [s]</th>
<th>Coal Haulage - Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</th>
<th>Rock Haulage - Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>280</td>
<td>354</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>120</td>
<td>148</td>
</tr>
<tr>
<td>Minimum</td>
<td>124</td>
<td>118</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>210</td>
<td>249</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>253</td>
<td>330</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>319</td>
<td>430</td>
</tr>
<tr>
<td>Upper Fence</td>
<td>374</td>
<td>520</td>
</tr>
<tr>
<td>Maximum</td>
<td>1418</td>
<td>1099</td>
</tr>
</tbody>
</table>

Unloading coal from the 15-ton-capacity shuttle car to the feeder breaker took 64±14 seconds; while it took 87±39 to unload rock to the feeder breaker. The process of unloading rock took more time to not overload the feeder with big chunks of rock. For a 8-ton-capacity shuttle car, the unloading cycle took 47±20 seconds.
6.3 Mean Power Consumption

Figure 6-5 illustrates the mean power consumption of the components of the duty cycle for the five studied cases at mines A and B. It is emphasized that the upper fence of the box plots in Figure 6-5 does not represent the maximum power observed during that operation, but it refers to the upper limit of the mean power consumption during each work segment. The results of the peak power analysis are discussed in the following sections.

Figure 6-5 Boxplots of Mean power consumption of duty cycle components [kW]
The mean power consumption during the loading and unloading cycles is associated with the power usage of the conveyor motor. For a 8-tonne-capacity shuttle car, the mean power of the shuttle car during the unloading cycle is 62% higher than the mean power of loading cycle. This value decreased to 20% for a 14-tonne-capacity shuttle car because the conveyor system of the higher-capacity shuttle car was used more often during the loading cycle in order to receive load from the CM and distribute it along the shuttle car.

For a relatively flat-lying coal seam where the mine’s haul road grades varied in a range of -2% and 2%, the ratio of loaded-to-unloaded mean power consumption was obtained in a range of 1.1 to 2.3. For steeper-grade mines, this ratio ranged between 2.3 and 5 for the 15%-grade road, and ranged between 1.8 and 4.8 for the 12%-grade road. In the case where the loaded shuttle car trammed 12% downhill and the empty shuttle car trammed 12% uphill, the ratio of loaded-to-unloaded mean power dropped to the range of 0.35 to 0.7.

The statistical information of the mean power consumption calculated for the four components of the duty cycle is presented in Table 6-3 and Table 6-4. Besides the five common statistical descriptive values, the first and third quartile of the data set are also provided in the statistical information tables presented.
Table 6-3 Descriptive statistical evaluation of values of mean power consumptions [kW] during tramming cycles

<table>
<thead>
<tr>
<th>Mean Power [kW]</th>
<th>Empty Tram</th>
<th></th>
<th></th>
<th>Loaded Tram</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
</tr>
<tr>
<td></td>
<td>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</td>
<td>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</td>
<td>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</td>
<td>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Nov-Dec</td>
<td>Sep</td>
<td>July</td>
<td>July-Aug</td>
<td>Aug-Sep</td>
<td>Nov-Dec</td>
</tr>
<tr>
<td></td>
<td>37.3</td>
<td>27.9</td>
<td>38.7</td>
<td>27.6</td>
<td>23.9</td>
<td>39.1</td>
</tr>
<tr>
<td>Mean</td>
<td>10.2</td>
<td>8.8</td>
<td>18.9</td>
<td>12.3</td>
<td>20.0</td>
<td>10.6</td>
</tr>
<tr>
<td>Mean</td>
<td>10.5</td>
<td>13.1</td>
<td>15.0</td>
<td>12.3</td>
<td>12.3</td>
<td>10.5</td>
</tr>
<tr>
<td>Mean</td>
<td>29.4</td>
<td>20.8</td>
<td>23.2</td>
<td>19.0</td>
<td>19.0</td>
<td>31.8</td>
</tr>
<tr>
<td>Mean</td>
<td>38.2</td>
<td>25.8</td>
<td>33.3</td>
<td>24.2</td>
<td>23.0</td>
<td>38.1</td>
</tr>
<tr>
<td>Mean</td>
<td>45.9</td>
<td>34.0</td>
<td>51.6</td>
<td>33.3</td>
<td>27.1</td>
<td>46.5</td>
</tr>
<tr>
<td>Mean</td>
<td>54.1</td>
<td>40.6</td>
<td>65.8</td>
<td>40.4</td>
<td>31.2</td>
<td>53.8</td>
</tr>
<tr>
<td>Mean</td>
<td>65.1</td>
<td>51.5</td>
<td>81.6</td>
<td>77.8</td>
<td>51.7</td>
<td>70.1</td>
</tr>
</tbody>
</table>

Table 6-4 Descriptive statistical evaluation of values of mean power consumptions (loading and unloading cycles)

<table>
<thead>
<tr>
<th>Mean Power [kW]</th>
<th>Loading</th>
<th></th>
<th></th>
<th>Unloading</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
</tr>
<tr>
<td></td>
<td>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</td>
<td>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</td>
<td>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</td>
<td>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Nov-Dec</td>
<td>Sep</td>
<td>July</td>
<td>July-Aug</td>
<td>Aug-Sep</td>
<td>Nov-Dec</td>
</tr>
<tr>
<td></td>
<td>20.7</td>
<td>16.7</td>
<td>25.1</td>
<td>23.0</td>
<td>20.9</td>
<td>28.0</td>
</tr>
<tr>
<td>Mean</td>
<td>4.9</td>
<td>2.8</td>
<td>4.3</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Mean</td>
<td>11.4</td>
<td>11.4</td>
<td>17.2</td>
<td>15.6</td>
<td>15.4</td>
<td>15.9</td>
</tr>
<tr>
<td>Mean</td>
<td>19.6</td>
<td>16.3</td>
<td>24.4</td>
<td>22.4</td>
<td>19.1</td>
<td>24.3</td>
</tr>
<tr>
<td>Mean</td>
<td>23.3</td>
<td>18.3</td>
<td>26.8</td>
<td>26.0</td>
<td>23.7</td>
<td>31.1</td>
</tr>
<tr>
<td>Mean</td>
<td>43.0</td>
<td>31.4</td>
<td>59.3</td>
<td>49.6</td>
<td>38.9</td>
<td>41.0</td>
</tr>
</tbody>
</table>

The regression line shown in Figure 6-6 describes how the mean power consumption of tramming cycles, the weight of shuttle car, and the total grade of the haul road are related. The y-axis in Figure 6-6 represents the ratio of mean power [kW] to
gross weight [tonne] as calculated in Table 6-5, and the x-axis represents the total grade averaged along the haul road.

Table 6-5 Information of mean power, total grade, and weight ratio

<table>
<thead>
<tr>
<th></th>
<th>Empty Tram</th>
<th>Loaded Tram</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
</tr>
<tr>
<td></td>
<td>Shuttle Car) (10%</td>
<td>Shuttle Car) (20%</td>
</tr>
<tr>
<td></td>
<td>- 15% Total Grade)</td>
<td>30% Total Grade)</td>
</tr>
<tr>
<td>Mean Power [kW]</td>
<td>37.3</td>
<td>27.9</td>
</tr>
<tr>
<td>SD Power [kW]</td>
<td>10.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Weight (tonnes)</td>
<td>18</td>
<td>8.8</td>
</tr>
<tr>
<td>Power-to-weight ratio [kW/tonnes]</td>
<td>2.07 1.55</td>
<td>1.55 1.11</td>
</tr>
<tr>
<td>Averaged total grade %</td>
<td>21</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 6-6 Correlation between power density and haul road total grade [kW/tonne/grade/cycle]
The mean power consumption can be derived from the total grade by using the regression line presented in Figure 6-6. Using Equation 10, the following calculation estimates the mean power consumption of a 21-tonne shuttle car with a 11-tonne capacity tramming on a 15% total grade haul road:

\[
\text{Power [kW]} = \text{GW(tonne)} \times (0.0367 \times \text{GR} + 1.114)
\]

Equation 10

where:

\[
\text{GR} = \text{Grade ratio (%)}
\]

\[
\text{GW} = \text{Gross weight (tonne)}
\]

Loaded tramming mean power = (21 tonnes+11 tonnes) \times (0.0367 \times 15\% + 1.114) = 53 kW

6.4 Peak Power Consumption

The peak powers of haulage cycles are detected using a Matlab peak-finder algorithm. The maximum observed peak power for each segment of a haulage cycle is chosen as the maximum peak power. Figure 6-7 illustrates the box plots of the maximum peak power observed in different components of the duty cycle for the five studied cases at mines A and B.
Since two studied shuttle cars are different in terms of weight and capacity, the boxplots of the maximum peak power are divided by the gross weight of shuttle car during the tramming cycles and presented in Figure 6-8 for a better comparison between loaded and empty tramming cycles.
The results indicate that a higher range of peak power density can be obtained during the empty tramming cycles in the case of utilizing a lower-capacity shuttle car because of the two following reasons:

1. The empty shuttle car was tramming uphill, and

2. The empty shuttle car reached higher tramming speeds (7.5 ft/s) compared to the loaded tramming speed (5.5 ft/s).

Yet the overall graph of normalized power or power density shows that the amount of power consumed by the vehicle is more or less constant given the weight and road conditions as explained in the theories.
6.4.1 Peak Power Duration

The duration of peak power consumptions for the work cycle in the operations monitored in this study was calculated and is presented in this section. Figure 6-9 illustrates the 2D scatter plot of the peak powers greater than 150kW and Figure 6-10 illustrates the peak powers between 100kW and 150kW. In the figures’ plots, the x-axis represents the peak power and the y-axis represents the corresponding peak duration.

Figure 6-9 Plot of peak power duration against recorded peak power (peak powers > 150KW) a) Mine A, coal haulage  b) Mine A, rock haulage  c) Mine A, rock haulage  d) Mine B, coal haulage  e) Mine B, coal haulage
Figure 6-10 Plots of peak power duration against recorded peak power (peak powers < 150KW) a) Mine A, coal haulage  b) Mine A, rock haulage  c) Mine A, rock haulage  d) Mine B, coal haulage  e) Mine B, coal haulage

Around 88% of the peak durations took less than 1 second. In both cases of coal haulage and rock haulage, the maximum observed peak duration was around 7.4 seconds at the peak power of approximately 125kW. The results of the peak power durations are given in Table 6-6.
Table 6-6 Peak power duration [s]

<table>
<thead>
<tr>
<th>Peak Power Duration [s]</th>
<th>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</th>
<th>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal Hauling</td>
<td>Rock Hauling</td>
</tr>
<tr>
<td></td>
<td>Nov - Dec</td>
<td>Sep</td>
</tr>
<tr>
<td>Mean</td>
<td>0.62</td>
<td>0.36</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.46</td>
<td>0.21</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>0.50</td>
<td>0.33</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>0.71</td>
<td>0.44</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.30</td>
<td>2.19</td>
</tr>
<tr>
<td>Peak Duration &gt;1s</td>
<td>11%</td>
<td>1.62%</td>
</tr>
<tr>
<td>Peak Duration &gt;2s</td>
<td>2.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Peak Duration &gt;3s</td>
<td>0.5%</td>
<td>0%</td>
</tr>
</tbody>
</table>

6.4.2 Energy Demand at Peak Power

The area underneath the peak power signal represents the energy demand. The summary of the statistical analysis of energy demand during peak power is provided in Table 6-7.

Table 6-7 Peak power energy [kWh]

<table>
<thead>
<tr>
<th>Peak Power Energy [kWh]</th>
<th>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</th>
<th>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal Hauling</td>
<td>Rock Hauling</td>
</tr>
<tr>
<td></td>
<td>Nov - Dec</td>
<td>Sep</td>
</tr>
<tr>
<td>Mean</td>
<td>0.023</td>
<td>0.013</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.019</td>
<td>0.009</td>
</tr>
<tr>
<td>Min</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>0.013</td>
<td>0.008</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>0.018</td>
<td>0.011</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>0.026</td>
<td>0.015</td>
</tr>
<tr>
<td>Max</td>
<td>0.234</td>
<td>0.100</td>
</tr>
</tbody>
</table>
6.5 Energy Consumption of Haulage Trips

The histograms of energy consumption during haulage trips are provided in Figure 6-11.

Figure 6-11 Histograms of energy consumption of haulage trips for various working conditions
The statistical information of the histograms is provided in Table 6-8. On average, energy consumption of haulage trips in mine A was 1.025 kWh higher than mine B due to the higher grade resistance of haul roads in mine A and the size of the shuttle car.

Table 6-8 Summary of statistical analysis of energy consumption per haulage trip [kWh]/trip

<table>
<thead>
<tr>
<th>Energy Consumption [kWh]/trip</th>
<th>Mine B (18 tons Shuttle Car) (10% - 15% Total Grade)</th>
<th>Mine A (25 tons Shuttle Car) (20% - 30% Total Grade)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal Hauling</td>
<td>Rock Hauling</td>
</tr>
<tr>
<td></td>
<td>Nov - Dec</td>
<td>Sep</td>
</tr>
<tr>
<td>Mean</td>
<td>2.86</td>
<td>2.93</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.35</td>
<td>0.83</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.4</td>
<td>1.03</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>2.14</td>
<td>2.43</td>
</tr>
<tr>
<td>Median</td>
<td>2.42</td>
<td>2.79</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>3.3</td>
<td>3.29</td>
</tr>
<tr>
<td>Maximum</td>
<td>10.5</td>
<td>9.95</td>
</tr>
<tr>
<td>Samples Number [cycles]</td>
<td>475</td>
<td>431</td>
</tr>
<tr>
<td>&gt;3 kWh/trip</td>
<td>32%</td>
<td>35%</td>
</tr>
<tr>
<td>&gt;4 kWh/trip</td>
<td>10%</td>
<td>9%</td>
</tr>
<tr>
<td>&gt;5 kWh/trip</td>
<td>5.6%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

Table 6-9 Comparison of haulage cycle energy consumption

<table>
<thead>
<tr>
<th>Energy Consumption [kWh]/trip</th>
<th>Mine B 18-tonne Shuttle Car (Coal Hauling)</th>
<th>Mine A 25-tonne Shuttle Car (Rock Hauling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.89</td>
<td>3.89</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.10</td>
<td>1.09</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.22</td>
<td>1.55</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>2.28</td>
<td>3.20</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>2.60</td>
<td>3.71</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>3.30</td>
<td>4.44</td>
</tr>
<tr>
<td>Maximum</td>
<td>10.24</td>
<td>10.19</td>
</tr>
</tbody>
</table>
Figure 6-12 and Figure 6-13 represent the correlation between the energy consumption of haulage trips and the number of trips over the course of an 8-hour shift in mine A and mine B, respectively. Parts (a) and (b) of Figure 6-12 refer to rock haulage and part (c) refers to coal haulage. There is a consistency between the slopes of the lines drawn in Figure 6-12 and Figure 6-13, and the mean values of haulage trips’ energy consumption are found in Table 6-8 and Table 6-9.
The energy consumption of the duty cycle components is shown in Figure 6-14.

![Boxplot of energy consumption of duty cycle components][1]

**Figure 6-14 Boxplot of energy consumption of duty cycle components [kWh]**

### 6.6 Energy Density

The developed haulage cycles’ energy consumptions have been divided by the gross weight of the shuttle car to obtain the energy density of haulage cycles. The gross weight of the shuttle car is changing during a haulage cycle as the shuttle car loads and dumps coal. Although the curb weight of the shuttle car does not impact the energy and power consumption during the unloading cycles, the curb weight of the shuttle car must be chosen in order to calculate energy density for the whole work cycle. Plus, the shuttle

[1]: https://via.placeholder.com/150
car did not remain stationary by the CM during the loading cycles. The shuttle car was moving (up, back and at angles) by the CM trying to help its own conveyor system to distribute the load on the shuttle car. Thus, an average weight between two modes of free and fully loaded was assigned to the shuttle car’s gross weight during the loading and unloading cycles. In order to calculate the energy density accurately, the energy consumption of each work segment is divided by the corresponding gross weight as presented in Table 6-10.

Table 6-10 Selected gross weight for calculating the energy density

<table>
<thead>
<tr>
<th>Haulage Cycle Operation</th>
<th>Gross Weight</th>
<th>Low capacity shuttle car</th>
<th>High capacity shuttle car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty tramming</td>
<td>Curb weight</td>
<td>18 tonne</td>
<td>22 tonne</td>
</tr>
<tr>
<td>Loaded tramming</td>
<td>Curb weight + Load weight</td>
<td>26 tonne</td>
<td>37 tonne</td>
</tr>
<tr>
<td>Loading</td>
<td>Curb weight + 0.5 × Load weight</td>
<td>22 tonne</td>
<td>30 tonne</td>
</tr>
<tr>
<td>Unloading</td>
<td>Curb weight</td>
<td>22 tonne</td>
<td>30 tonne</td>
</tr>
</tbody>
</table>

Calculation of the energy density where the energy consumption is normalized by machine weight during the given component of a cycle has narrowed down the spread of the variables, as can be seen in Figure 6-15. The narrow values of normalized energy consumption allow for estimation of the required power by units of various sizes and capacities in other mining operations.
Figure 6-15 Histograms of haulage cycle energy density

The energy density histograms are represented in a format where the x-axis refers to the energy density per haulage cycle in kilo-watt-hour/tonne, and the y-axis refers to the frequency of occurrence of a certain energy density.

A summary sheet of haulage cycle energy density is shown in Table 6-11 and Table 6-12.
Table 6-11 Energy density of haulage cycles [kWh]/tonne/cycle

<table>
<thead>
<tr>
<th>Energy Density [kWh]/Tonne/Cycle</th>
<th>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</th>
<th>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Hauling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.075</td>
<td>0.068</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.53</td>
<td>0.47</td>
</tr>
<tr>
<td>Rock Hauling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.07</td>
<td>0.068</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.03</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Table 6-12 Comparison of haulage cycles energy density [kWh]/tonne/cycle

<table>
<thead>
<tr>
<th>Energy Density [kWh]/Tonne/Cycle</th>
<th>Mine B (Coal)</th>
<th>Mine A (Coal)</th>
<th>Mine A (Rock)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.15</td>
<td>0.10</td>
<td>0.143</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.093</td>
<td>0.08</td>
<td>0.068</td>
</tr>
</tbody>
</table>

The mean energy density during coal hauling in mine A was 0.1 ± 0.08 kWh/tonne. This value increased by 40% to 0.14 ± 0.068 kWh/tonne when the shuttle car was hauling rock. Despite the tougher coal haul condition in mine A, the energy density of haulage cycles in mine B was 0.05 ± 0.013 kWh/tonne higher than mine A during coal haulage while the energy required by shuttle cars in mine A was 1.00 ± 0.001 kWh higher than mine B. It can be concluded that it is more efficient to employ a high-capacity shuttle car in the haulage operation to consume less energy per tonne of production.
6.6.1 Estimating the energy required by haulage trips considering the panel geometry and haul road conditions

The information of energy density obtained from study area #2 at Mine B was divided into three sections corresponding to areas A1, A2, and A3 as described in section 4.5.2.2 and presented in parts (b) through (d) of Figure 6-16. The results were compared to the energy density of study area #1 at mine B, which is shown at part (a) of Figure 6-16, in order to discover an experimental formula relating the average energy consumption of a haulage trip to: 1. Average total grade of haul roads, 2. Pillar dimensions, 3. Number of entries, 4. Shuttle car curb weight, and 6. Shuttle car load capacity.

Figure 6-16 Energy density per haulage cycle for study area #1 and #2 at mine B
(a) Study area #1, (b) Study area #1-A1, (c) Study area #1-A2, (d) Study area #1-A3

Figure 6-17 The correlation between normalized energy and maximum hauling distance in panel

The average required energy of a shuttle car hauling in a panel with a specific geometry can be derived from the regression line presented in Figure 6-17 and presented in Equation 11.

\[
E \text{ [kWh]} = 0.0223 \times 10^{-3} \times \left[ N_E \times \left( \frac{P_w}{2} + 10 \right) + N_c \times (P_l + 20) \right] \times \text{TEG} \times W \quad \text{Equation 11}
\]

where:

- \( E \) = Mean required energy [kWh]
- \( N_E \) = Number of entries
- \( N_c \) = Number of advanced crosscuts
- \( P_w \) = Pillar width (ft)
- \( P_l \) = Pillar length (ft)
TEG = Total effective grade (%)  

W = Shuttle car average mass (tonne) = curb mass + 0.5 × load capacity  

For example, the mean required energy of a 23-tonne shuttle car with a 14-tonne capacity tramming on a road with a 25% total grade through a panel with 3 entries, advancing at a two-crosscut distance, with pillar dimensions of 45ft x 45ft can be calculated as follows:

\[
E = 0.0233 \times 10^{-3} \times \left[ 3 \times \left( \frac{45}{2} + 10 \right) + 2 \times (45 + 20) \right] \times 25 \times (23 + \frac{11}{2}) = 3.975 \text{ kWh}
\]

which is 2% higher than the average energy required per trip obtained from measurements.

### 6.7 Intermittent Delays

Intermittent delays are found based on the shuttle car idle time. The idle times of shorter than 2 seconds are ignored and those longer than 2 seconds are defined as intermittent delays occurring during the haulage trips. Three sets of analyses were performed on the detected intermittent delays. First, the frequency of intermittent delays (or stop-start frequency) during a haulage trip was calculated. Second, the detected idle times during a haulage trip were added together and then divided by the cycle time to provide the ratio of intermittent delays to cycle time. Finally, the delay-to-delay intervals for each haulage trip were calculated and divided by cycle time to find the delay-to-delay intervals to cycle time ratio. These parameters help in the determination of the discharging cycle of the batteries and thus aids in sizing their capacity.
6.7.1 Mid-cycle Stop-start Frequency

Figure 6-18 illustrates the mid-cycle stop-start frequency during a haulage trip at two studied mines. The figures are represented in a format where the x-axis refers to the number of stop-starts and the y-axis refers to the frequency of occurrence of the stop-start number in a percentage format. The stop-start frequency of zero means that no delay occurred during the tramming cycle. Haulage cycles with zero or less stop-start frequency during the tramming cycles are more favorable in haulage operation. In order to calculate the average stop-start frequency per haulage trip, the weighted average of stop-start frequency was calculated and used in subsequent analysis.

Figure 6-18 Stop-start frequency during haulage trips – Mine A - (a) Aug – Sep, rock hauling, (b) July - Aug, rock hauling, (c) July, coal hauling
As Figure 6-18 (a) and (b) illustrate, the loaded shuttle car hauls the rock without any intermittent delays in 80% of the cases. In the case of rock haulage, on average, 0.3 stops occurred during loaded tramming cycles; while, empty tramming cycles experienced 2.5 stops on average. This is due to the right of way given to the loaded shuttle cars at intersections. A higher stop-start frequency not only results in a longer haulage cycle, but it also increases the mean power consumption of haulage cycles by 5% compared to the cycles experiencing 1 stop-start delay. The most frequent stop-start numbers during empty tramming cycles are 1 and 3. Figure 6-18 (c) provides the stop-start frequency for the coal haulage cycles at mine A. Comparing the coal haulage with rock haulage cycles at mine A, the percentage of zero stop-start frequency dropped from 80% during the rock haulage cases to 60% for the coal haulage cases. The average of stop-start frequency during loaded and empty tramming cycles increased to 0.95 and 2.15, respectively.

Figure 6-19 (a) and (b) provide the stop-start frequency for the coal haulage cycles at mine B. Comparing the coal haulage cycles between the two mines, the percentage of zero stop-start frequency during loaded tramming cycles dropped from 60% at mine A to 30% at mine B. The average of stop-start frequency during the loaded and empty tramming cycles increased to 2.2 and 2.3, respectively.
Figure 6-19 Boxplot of tramming cycles stop-start frequency – Mine B – (a) September, coal hauling, (b) Nov - Dec, coal hauling

6.7.2 Ratio of Mid-cycle Intermittent Delay to Cycle Time

The mid-cycle delays occurred in each haulage cycle and were added and then divided by the whole cycle duration to obtain the ratio of intermittent delays to cycle time. The results are presented as a histogram plot in Figure 6-20 and Figure 6-21.
As shown in Figure 6-20, an average of 10% - 40% of coal haulage cycle time was lost to mid-cycle intermittent delays. Haulage cycles with longer hauling paths (part (a) and (c) of Figure 6-20), where the shuttle car passes 2-3 crosscuts to get to the face, have experienced more intermittent delays compared to the shorter paths (part (b) of Figure 6-20) where the shuttle car passes 1 crosscut to get to the face. In the case of rock haulage, the ratio of mid-cycle delays to cycle time was extended to 10% to 70% due to the slow process of rock cutting in the face.
Figure 6-21 Histogram of the ratio of mid-cyle delays to cycle time (rock haulage)

Figure 6-22 and Figure 6-23 present the box plot of the duration of intermittent delays that happened during the loaded and empty tramming cycles for different distances of the face from the feeder breaker. Seventy-five percent of the stop times during empty tramming were found to be less than 60 seconds, associated with the waiting times at the change-out point. Longer stop times could be referred to waiting for the CM to move to a new cut or when the scoop was cleaning up the haul road and/or face area.
In the case of rock haulage, both loaded and empty tramming cycles experienced longer intermittent delays.

The results of intermittent delay analysis emphasize the fact that the feeder breaker should be placed at an optimum distance from the face in order to minimize the intermittent delays occurring during long haulage cycles.
6.7.3 Delay-to-delay Intervals

The intervals between the occurrence of two delays were calculated and presented in this section. The ratio of delay-to-delay intervals to haulage cycle time is presented in Figure 6-24.

![Histograms of ratio of delay-to-delay intervals to haulage cycle time](image)

Figure 6-24 Histograms of ratio of delay-to-delay intervals to haulage cycle time

The summary of the statistical analysis for delay-to-delay intervals is presented in Figure 6-25.
Figure 6-25 Summary of statistical analysis delay-to-delay intervals

<table>
<thead>
<tr>
<th>Delay-to-delay Intervals [s]</th>
<th>Coal Haulage</th>
<th>Rock Haulage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>77.4</td>
<td>171.9</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>79.1</td>
<td>144.2</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>26.9</td>
<td>56.6</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>48.2</td>
<td>129.2</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>94.4</td>
<td>245.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>680.2</td>
<td>598.8</td>
</tr>
</tbody>
</table>

6.7.4 Crest Factor

Crest factors (CF) were found within the range of 1.1 to 8.8. The maximum observed CF is 8.8 which occurred during the empty tramming and loading cycles at mine A. The average of CFs during the empty tramming cycles is 2.76 which is approximately 0.5 higher than the average of CF in three other operations. Likewise, loading cycles present higher CF values because of the momentary back and forth movement of the shuttle car while receiving coal from the continuous miner. The statistical information of crest factors is summarized in Table 6-13 and Table 6-14.

<table>
<thead>
<tr>
<th>Power Crest Factor</th>
<th>Empty Tram Hauling Coal</th>
<th>Empty Tram Hauling Rock</th>
<th>Loaded Tram Hauling Coal</th>
<th>Loaded Tram Hauling Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.5</td>
<td>2.7</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>SD</td>
<td>0.8</td>
<td>1.0</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.4</td>
<td>1.3</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>1.8</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>2.3</td>
<td>2.6</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>3.0</td>
<td>3.2</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Upper Fence</td>
<td>3.6</td>
<td>3.7</td>
<td>3.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.6</td>
<td>8.0</td>
<td>6.5</td>
<td>8.8</td>
</tr>
</tbody>
</table>
Table 6-14 Statistical analysis of power crest factor (loading/unloading cycles)

<table>
<thead>
<tr>
<th>Power Crest Factor</th>
<th>Loading</th>
<th>Unloading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hauling Coal</td>
<td>Hauling Rock</td>
</tr>
<tr>
<td>Mean</td>
<td>2.2</td>
<td>2.8</td>
</tr>
<tr>
<td>SD</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>2.1</td>
<td>2.6</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Upper Fence</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>8.7</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Table 6-15 presents the average of CF calculated over the five studied cases.

Table 6-15 Summary of statistical analysis of averaged power crest factor

<table>
<thead>
<tr>
<th></th>
<th>Empty Tram</th>
<th>Loaded Tram</th>
<th>Loading</th>
<th>Unloading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.8</td>
<td>2.2</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.9</td>
<td>0.6</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.4</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>2.1</td>
<td>1.8</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>50th Percentile</td>
<td>2.6</td>
<td>2.0</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>3.2</td>
<td>2.4</td>
<td>2.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Upper Fence</td>
<td>3.7</td>
<td>2.6</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Max (average)</td>
<td>7.7</td>
<td>5.8</td>
<td>7.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>8.8</td>
<td>7.3</td>
<td>8.8</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 6-16 is the summary of the occurrence of CF beyond a certain threshold.

The table shows that on average 15.5% of the total analyzed cycles experienced a crest factor higher than 3, 4.3% for CFs higher than 4, and 1.5% for CFs higher than 5.
Table 6-16 Summary of crest factors over a certain threshold (percentage of haulage cycles)

<table>
<thead>
<tr>
<th></th>
<th>Mine B (18-tonne Shuttle Car) (10% - 15% Total Grade)</th>
<th>Mine A (25-tonne Shuttle Car) (20% - 30% Total Grade)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nov - Dec</td>
<td>Sep</td>
<td>Jul</td>
</tr>
<tr>
<td>Crest Factor &gt; 3</td>
<td>14%</td>
<td>19%</td>
<td>14%</td>
</tr>
<tr>
<td>Crest Factor &gt; 4</td>
<td>4%</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>Crest Factor &gt; 5</td>
<td>1.2%</td>
<td>2%</td>
<td>1%</td>
</tr>
</tbody>
</table>

6.8 Energy Consumption vs. Utilization Analysis

Figure 6-26 depicts the correlation between utilization and energy consumption of the shuttle car during an 8-hour shift. Parts (a) and (b) of Figure 6-26 refer to rock haulage and part (c) refers to coal haulage in mine A. The average of this ratio in the case of rock haulage is 2.5 and in the case of coal haulage it is 3. This means that for a 25-tonne shuttle (15-tonne capacity) and utilization of 50% working in a coal mine where the total effective grade of the haul road is between 25% and 30%, the total energy consumption during a shift would be approximately 150 kWh. It should be emphasized that all calculations were made based on an 8-hour shift. The final number must be multiplied by 1.25 in case of estimating total energy consumption for a 10-hour shift.
Figure 6-26 Energy-utilization (Mine A)

Figure 6-27 illustrates the relationship between utilization and the energy consumption of a 18-tonne shuttle car (8-tonne capacity) during an 8-hour shift in mine B. The total effective grade resistance of the haul road was estimated in the range of 12% to 15% for these two cases. In part (a) of Figure 6-27, a higher energy-to-utilization ratio is obtained due to the lower haulage operational efficiency and utilization in that course of study. The average of energy-to-utilization ratio was 2.23. For instance, a 18-tonne shuttle (8-tonne capacity) and a utilization of 70% working in a coal mine where the total effective grade of the haul road was 12%, the total energy consumption during a 10-hour shift would be 89 kWh multiplied by an adjustment factor of 1.25 (to change an 8-hour shift to a 10-hour shift), which equals to 111.25 kWh.
6.9 Energy Difference of Haulage Trips between Various Travel Paths

The energy difference between following two haul paths, when the shuttle car moves to the next cut, involving one or two intersections, was calculated and presented here. A shorter haul path requires less energy for the shuttle car haulage trips. The histogram of the energy difference between following two haul paths involving a one- or two-intersection distance from the feeder breaker is shown in Figure 6-28. Figures are given in which x-axis represents the energy in kWh and the y-axis represents the occurrence. A negative energy difference value means that the shuttle car moved from side entries, which is considered as a long haul path, to the center entries which give shorter haul paths. The standard deviation of histogram data could be taken as a parameter that indicates the change in energy consumption of haulage cycles if an extra entry would be added to the panel. The change in energy demand differs in the cases of short and long hauling paths. When the panel has advanced three crosscuts where the shuttle car passes 5 to 7 intersections to get to the CM, adding one entry to the room-and-
pillar panel would increase the average energy consumption of haulage trip by 18%. In the case where a panel has advanced 1 or less than 2 crosscuts, the average energy consumption of haulage trips would increase by 10%.

Figure 6-28 Histogram of energy difference of haulage trips between two following entries
Chapter 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Research Summary

In this study, the duty cycles and timing of cycles of two different models of JOY coal shuttle cars in different haul road conditions and haulage operations in two coal mines in central PA were assessed. The outcome of the study will be used as the basis for verification of the required energy and power of coal shuttle cars for the purpose of sizing suitable batteries. The measurement of the duty cycles for the two shuttle cars was mostly performed by recording the available machine information from the master controller module of vehicles through the CANbus interface, and field data such as haul road conditions, hauling distances, and haulage operation were measured through the field observation. A MATLAB program was developed in order to analyze and visualize the duty cycles and timing of cycles. At the end, the generated duty cycles were correlated with field observations in order to characterize the duty cycles.

7.2 Conclusions

The following conclusions are made regarding the results and outcomes of this study:

1. The average shuttle car utilization was found to be 36% and 16% for the coal haulage operation and the rock haulage operation, respectively. The
shuttle car utilization is lower due to the slow operation of rock cutting in the face and higher delay and waiting times.

2. The second shift is the most-productive shift and the third shift (maintenance shift) is the least-productive shift in a normal day. The first-shift utilization is less than or mostly equal to the second-shift utilization due to the regular inspections conducted on the first shift.

3. Unloading coal from a 15-ton-capacity shuttle car to the feeder breaker took 64±14 seconds; while it took 87±39 to unload rock on the feeder breaker. The process of unloading rock took more time to not overload the feeder breaker with big chunks of rock. For an 8-tonne-capacity shuttle car, the unloading cycle took 47±20 seconds.

4. For an 8-tonne-capacity shuttle car, the mean power of the shuttle car during the unloading cycles is 62% higher than the mean power of the loading cycle. This value decreased to 20% for a 14-tonne-capacity shuttle car because the conveyor system of the higher-capacity shuttle car was employed more during the loading cycle in order to receive the load from the CM and distribute it along the shuttle car.

5. The mean power consumption during tramming cycles can be estimated from the total grade of a haul road and the gross weight of the machine by using the following formula:

\[ \text{Tramming Mean Power} = \text{Gross Weight} \times (0.0367 \times \text{GR(%) + 1.114}) \]
6. The required power density for each duty cycle operation can roughly be summarized as follows:

For low-capacity shuttle cars:

unloading > loading > tramming empty > tramming loaded

For high-capacity shuttle cars:

unloading > loading > tramming loaded > tramming empty

7. Peak power density and peak power is summarized in the table below:

<table>
<thead>
<tr>
<th></th>
<th>Low capacity shuttle car</th>
<th>High Capacity shuttle car</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Empty Tramming</td>
<td>Loaded Tramming</td>
</tr>
<tr>
<td>Peak Power Density kWh/tonne</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Maximum observed peak duration</td>
<td>6.2 sec at 120kW</td>
<td>7.4 sec at 125kW</td>
</tr>
</tbody>
</table>

8. Haulage cycles with longer hauling paths, where shuttle cars passed 2-3 crosscuts to get to the face, experienced more intermittent delays compared to the shorter paths where shuttle cars pass 1 crosscut to get to the face.

9. Twenty-five percent of coal haulage trip time was lost to mid-cycle intermittent delays. In the case of rock haulage, 40% of haulage trip time was lost to mid-cycle intermittent delays due to the slow process of rock cutting in the face.
10. The crest factor for each work segment of the duty cycle can be shown as follows:

empty tram > loading > loaded tram > unloading

11. Empty tramming and loading cycles present higher CF values because of the frequent acceleration and deceleration during the cycles. On average, 15.5% of haulage cycles experienced a crest factor of higher than 3, 4.3% for CFs higher than 4, and 1.5% for CFs higher than 5.

12. The maximum observed CF was 8.8 made by a high-capacity shuttle car in mine A during both empty tramming and loading cycle.

13. An experimental formula is offered relating the average energy consumption of a haulage trip to the average of the haul road’s total grade, panel geometry, and shuttle car weight:

\[ E \, [\text{kWh}] = 0.0223 \times 10^{-3} \times \left[ N_E \times \left( \frac{P_w}{2} + 10 \right) + N_C \times (P_t + 20) \right] \times \text{TEG} \times W \]

14. An experimental formula is offered relating the total energy consumption of a shuttle car during a course of an 8-hour shift with the total number of haulage trips per shift and shuttle car maximum weight:

Total Energy per shift = 0.1028 \times \text{Max Weight}_{\text{shuttle car}} \times N_{\text{haulage trips}}

15. An experimental formula is proposed correlating the total energy consumption of a shuttle car during the course of an 8-hour shift with shuttle car utilization and its maximum weight:

For the case of the coal haulage operation:

Total Energy per shift = 0.1028 \times \text{Max Weight}_{\text{shuttle car}} \times \text{Utilization}
For the case of the rock haulage operation:

\[
\text{Total Energy per shift} = 0.0972 \times \text{Max Weight}_{\text{shuttle car}} \times \text{Utilization}
\]

### 7.3 Recommendations for Future Work

In the performed study, the data-logging system was incapable of recording hauling distances and haul-road grades. Adding a positioning system for locating the shuttle car between the feeder and face would be a great achievement in the follow-up studies. The positioning system would enable the study group to measure the hauling distances and determine the panel advancement. The huge problem with employing a positioning system is that most of them work based on GPS, which is not an option in underground applications. Instead, a very accurate IMU\(^5\) sensor could be utilized to back-calculate the shuttle car speed and position from the acceleration measurements made by the IMU sensor.

\(^5\) Inertial Measurement Unit
References


Haulage Systems Product View. Retrieved from Joy Global:


   http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Cable-reel+Shuttle+Cars+vs.+Battery+Shuttle+Cars#0


Appendix A: CANMET Duty Cycle Study
<table>
<thead>
<tr>
<th>Minesite</th>
<th>Vehicle</th>
<th>Duty Cycle Component</th>
<th>Time (s)</th>
<th>Distance Traveled (meters)</th>
<th>Grade Traveled (%)</th>
<th>Duty Cycle Mean Power (kw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dome</td>
<td>Massha 4.5 ton Battery Locomotive (three 4-ton cars)</td>
<td>Tram to loading Loading Tram to dump dump</td>
<td>407</td>
<td>1,200 x 2</td>
<td>variable</td>
<td>7.07</td>
</tr>
<tr>
<td>Dome</td>
<td>Massha 4.5 ton Battery Locomotive (four 4-ton cars)</td>
<td>Tram to loading Loading Tram to dump dump</td>
<td>537</td>
<td>1,200 x 2</td>
<td>variable</td>
<td>7.27</td>
</tr>
<tr>
<td>Mouska</td>
<td>Clayton 5.5 ton Battery Locomotive (six 4-ton cars) (2 locos 1 track)</td>
<td>Tram to loading Wait Tram to loading Loading Tram to dump dump</td>
<td>395</td>
<td>1,050 x 2</td>
<td>+0.5%</td>
<td>6.84</td>
</tr>
<tr>
<td>Mouska</td>
<td>Clayton 5.5 ton Battery Locomotive (six 4-ton cars)</td>
<td>Tram to loading Loading Tram to dump dump</td>
<td>412</td>
<td>1,050 x 2</td>
<td>+0.5%</td>
<td>8.37</td>
</tr>
<tr>
<td>Laurel Alma</td>
<td>JOY AH 10SC32B Electric AC Coal hauler with DC drive</td>
<td>Tram to loading Loading Tram to dump dump</td>
<td>112</td>
<td>N/A</td>
<td>0%</td>
<td>43.45</td>
</tr>
<tr>
<td>Black Beauty</td>
<td>JOY AH 1200 Battery powered Articulated coal hauler</td>
<td>Dump Tram to loading Loading Tram to dump</td>
<td>43</td>
<td>N/A</td>
<td>0%</td>
<td>35.45</td>
</tr>
<tr>
<td>Shoal Creek</td>
<td>JOY 10SC32B Electric AC coal hauler</td>
<td>Tram to loading Loading Tram to dump dump</td>
<td>108</td>
<td>N/A</td>
<td>0%</td>
<td>87.4</td>
</tr>
<tr>
<td>Louvicourt</td>
<td>Wagner ST8-B Diesel powered LHD (level and ramp load delivery)</td>
<td>Loading Tram flat loaded Dump Tram flat unloaded Tram up ramp fully loaded Tram down ramp unloaded Idle miscellaneous</td>
<td>52</td>
<td>500</td>
<td>0%</td>
<td>130.12</td>
</tr>
<tr>
<td>Bell Allard</td>
<td>Wagner ST1010 Diesel powered LHD (on level, remote slope delivery)</td>
<td>Tram to loading Loading Tram flat Stop Tram flat Dump Tram flat stop</td>
<td>34</td>
<td>26</td>
<td>0%</td>
<td>118.9</td>
</tr>
<tr>
<td>Bell Allard</td>
<td>Wagner ST1010 Diesel powered LHD (ramp load delivery)</td>
<td>Tram to loading Loading Tram flat-down ramp-flat Dump Tram flat-up ramp-flat</td>
<td>24</td>
<td>21</td>
<td>0%</td>
<td>138.0</td>
</tr>
</tbody>
</table>
Figure A- 1 List of studied mine sites and vehicles by CANMET

Figure A- 2 CANMET study: JOY 10SC32B DC drive coal hauler duty cycle

Table A- 1 CANMET study: JOY 10SC32B DC drive coal hauler duty cycle

<table>
<thead>
<tr>
<th>Operation Event</th>
<th>Time sec</th>
<th>Cumulative Time sec</th>
<th>Time over mean power %</th>
<th>Power Low peak Kw</th>
<th>Power Mean Kw</th>
<th>Power High peak Kw</th>
<th>Energy Kw-hr</th>
<th>Cumulative Energy Kw-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tram to loading</td>
<td>112</td>
<td>112</td>
<td>35</td>
<td>19.51</td>
<td>42.15</td>
<td>133.67</td>
<td>1.31</td>
<td>1.31</td>
</tr>
<tr>
<td>Loading</td>
<td>32</td>
<td>144</td>
<td>36</td>
<td>19.82</td>
<td>39.98</td>
<td>116.30</td>
<td>0.36</td>
<td>1.67</td>
</tr>
<tr>
<td>Tram to dump</td>
<td>63</td>
<td>207</td>
<td>32</td>
<td>19.93</td>
<td>40.65</td>
<td>111.47</td>
<td>0.71</td>
<td>2.38</td>
</tr>
<tr>
<td>Dump</td>
<td>38</td>
<td>245</td>
<td>96</td>
<td>21.94</td>
<td>64.76</td>
<td>99.13</td>
<td>0.58</td>
<td>2.96</td>
</tr>
<tr>
<td>Time over mean power whole cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Power throughout whole cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>43.45</td>
</tr>
</tbody>
</table>
Figure A-3 CANMET study: JOY AH1200 duty cycle

Table A-2 CANMET study: JOY AH1200 duty cycle

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time</th>
<th>Cumulative Power</th>
<th>Time over mean power</th>
<th>Power</th>
<th>Cumulative Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sec</td>
<td>Time sec</td>
<td>%</td>
<td>Low peak Kw</td>
<td>Mean Kw</td>
</tr>
<tr>
<td>Dump</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>5.57</td>
<td>28.41</td>
</tr>
<tr>
<td>Tram to loading</td>
<td>149</td>
<td>192</td>
<td>29</td>
<td>0.00</td>
<td>27.15</td>
</tr>
<tr>
<td>Loading</td>
<td>21</td>
<td>213</td>
<td>9</td>
<td>5.44</td>
<td>11.73</td>
</tr>
<tr>
<td>Tram to dump</td>
<td>129</td>
<td>342</td>
<td>64</td>
<td>0.00</td>
<td>51.17</td>
</tr>
<tr>
<td>Time over mean power whole cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Power throughout whole cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure A- 4 CANMET study: JOY 10SC32B AC drive coal hauler duty cycle

Table A- 3 CANMET study: JOY 10SC32B AC drive coal hauler duty cycle

<table>
<thead>
<tr>
<th>Operation Event</th>
<th>Time sec</th>
<th>Cumulative Time sec</th>
<th>Time over mean power %</th>
<th>Power</th>
<th>Energy Kw-hr</th>
<th>Cumulative Energy Kw-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tram to loading</td>
<td>108</td>
<td>108</td>
<td>60</td>
<td>30.56</td>
<td>90.23</td>
<td>1382.14</td>
</tr>
<tr>
<td>Loading</td>
<td>34</td>
<td>142</td>
<td>21</td>
<td>29.96</td>
<td>54.64</td>
<td>127.66</td>
</tr>
<tr>
<td>Tram to dump</td>
<td>65</td>
<td>207</td>
<td>98</td>
<td>106.48</td>
<td>129.26</td>
<td>301.82</td>
</tr>
<tr>
<td>Dump</td>
<td>53</td>
<td>260</td>
<td>0</td>
<td>30.85</td>
<td>51.10</td>
<td>83.50</td>
</tr>
</tbody>
</table>

Time over mean power whole cycle: 52%
Mean Power throughout whole cycle: 87.40
Appendix B: Southern Illinois University Face Haulage System Time Study
Table B-1 Southern Illinois University face haulage system time study

<table>
<thead>
<tr>
<th>Mine Name</th>
<th>Type of Mining Unit</th>
<th>Haulage Type</th>
<th># of Haulage Units</th>
<th>Capacity of Haulage Units</th>
<th>Loading Rate (tpm)</th>
<th>Tram Speed (fpm)</th>
<th>Dump Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinios Basin Mines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>WBSS</td>
<td>Battery Ramcar</td>
<td>6</td>
<td>(DBT810) 10</td>
<td>(14/15) 20</td>
<td>13</td>
<td>174</td>
</tr>
<tr>
<td>B</td>
<td>LW Gate</td>
<td>Shuttle Car</td>
<td>2</td>
<td>(Joy10SCc) 20</td>
<td>(12/12) 25</td>
<td>12.69</td>
<td>367</td>
</tr>
<tr>
<td>C</td>
<td>WBSS</td>
<td>Shuttle Car</td>
<td>3</td>
<td>(Joy10SCa) 10</td>
<td>(14/15) 20</td>
<td>9.92</td>
<td>388</td>
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<tr>
<td>C</td>
<td>&quot;</td>
<td>Battery Ramcar</td>
<td>4</td>
<td>(StmBH10) 10</td>
<td>(14/15) 20</td>
<td>6.5</td>
<td>300</td>
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<tr>
<td>C</td>
<td>&quot;</td>
<td>Battery Ramcar</td>
<td>4</td>
<td>(StmBH20) 12</td>
<td>(14/15) 20</td>
<td>9.5</td>
<td>300</td>
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<tr>
<td>D</td>
<td>WBSS</td>
<td>Diesel Ramcar</td>
<td>4</td>
<td>(Jeff4110) 14</td>
<td>(14/15) 20</td>
<td>13</td>
<td>115</td>
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<tr>
<td>E</td>
<td>Single Miner</td>
<td>Shuttle Car</td>
<td>3</td>
<td>(Joy10SCb) 16</td>
<td>(Eimico) 25</td>
<td>21.4</td>
<td>255</td>
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<tr>
<td>E</td>
<td>&quot;</td>
<td>Shuttle Car</td>
<td>3</td>
<td>(Joy10Scna) 8</td>
<td>(14/15) 20</td>
<td>7.53</td>
<td>275</td>
</tr>
<tr>
<td>Appalachian Mines</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>F</td>
<td>Single Miner</td>
<td>Shuttle Car</td>
<td>3</td>
<td>(Joy10SCb) 16</td>
<td>(14/15) 20</td>
<td>13.6</td>
<td>225</td>
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<tr>
<td>F</td>
<td>&quot;</td>
<td>Freedom Car</td>
<td>1</td>
<td>(FC12) 20</td>
<td>(14/15) 20</td>
<td>15.88</td>
<td>229</td>
</tr>
<tr>
<td>G</td>
<td>Single Miner</td>
<td>Shuttle Car</td>
<td>2</td>
<td>(Joy10SCa) 8</td>
<td>(14/15) 20</td>
<td>8</td>
<td>400</td>
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<tr>
<td>G</td>
<td>WBSS</td>
<td>Shuttle Car</td>
<td>2</td>
<td>(Joy10SCb) 16</td>
<td>(Eimico) 25</td>
<td>15.9</td>
<td>300</td>
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<tr>
<td>H</td>
<td>WBSS</td>
<td>Shuttle Car</td>
<td>2</td>
<td>(Joy21SC) 6</td>
<td>(14/10aa) 12</td>
<td>6</td>
<td>375</td>
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Appendix C: Developed Duty Cycles - Mine B, Study Area #2 & #3

December Analysis - Coal Haulage
Figure C-1 Mine B, study area #2 and #3 shifts utilization/total energy consumption/total number of haulage trip information
Figure C-2 Empty tramming power consumption [kW] and Energy consumption [kWh] at mine B, Study area #2 and #3
Figure C- 3 Loaded tramming power consumption [kW] and Energy consumption [kWh] at mine B, Study area#2 and #3
Figure C-4 Loading power consumption [kW] and Energy consumption [kWh] at mine B, Study area#2 and #3
Figure C-5 Unloading power consumption [kW] and Energy consumption [kWh] at mine B, Study area #2 and #3
Appendix D: Developed Duty Cycles - Mine B - Study Area #1

September Analysis - Coal Haulage
Figure D-1 Mine B, study area #1, shifts utilization/total energy consumption/total number of haulage trip information
Figure D- 2 Loaded tramming power consumption [kW] and Energy consumption [kWh] at mine B, Study area#1
Figure D-3 Empty tramming power consumption [kW] and Energy consumption [kWh] at mine B, Study area#1
Figure D-4 Loading power consumption [kW] and Energy consumption [kWh] at mine B, Study area#1
Figure D-5 Unloading power consumption [kW] and Energy consumption [kWh] at mine B, Study area#1
Appendix E: Developed Duty Cycle - Mine A - Study Area #2

July – August Analysis – Rock Haulage
Figure E-1 Mine A, study area #2, July-August Analysis, shifts utilization/total energy consumption/total number of haulage trip information
Figure E-2 Loaded tramming power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, July-August Analysis
Figure E-3 Empty tramming power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, July-August Analysis
Figure E-4 Loading power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, July-August Analysis
Figure E-5 Unloading power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, July-August Analysis
Appendix F: Developed Duty Cycle - Mine A - Study Area #2

August – September Analysis, Rock Haulage
Figure F-1 Mine A, study area #2, August-September Analysis, shifts utilization/total energy consumption/total number of haulage trip information
Figure F-2 Loaded tramming power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, August-September Analysis.
Figure F- 3 Empty tramming power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, August-September Analysis
Figure F-4 Loading power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, August-September Analysis
Figure F-5 Unloading power consumption [kW] and Energy consumption [kWh] at mine A, Study area#2, August-September Analysis
Appendix G: Developed Duty Cycle - Mine A - Study Area #1

July Analysis - Coal Haulage
Figure G-1 Mine A, study area #1, shifts utilization/total energy consumption/total number of haulage trip information
Figure G-2 Loaded tramming power consumption [kW] and Energy consumption [kWh] at mine A, Study area #1
Figure G-3 Empty tramming power consumption [kW] and Energy consumption [kWh] at mine A, Study area#1
Figure G-4 Loading power consumption [kW] and Energy consumption [kWh] at mine A, Study area#1
Figure G-5 Unloading power consumption [kW] and Energy consumption [kWh] at mine A, Study area#1
Appendix H: Monitoring Equipment Technical Information
The CAN channel 1 has the following pin configuration.
(Auto-reset fuses protect Pins 2, 3, 4, 7 and 9.)

<table>
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<tr>
<th>D-SUB pin number</th>
<th>Color code</th>
<th>Function HS</th>
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<tbody>
<tr>
<td>1</td>
<td>N/A</td>
<td>Not connected.</td>
</tr>
<tr>
<td>2</td>
<td>Green</td>
<td>CAN_L</td>
</tr>
<tr>
<td>3</td>
<td>Brown</td>
<td>GND</td>
</tr>
<tr>
<td>4</td>
<td>Orange</td>
<td>External trigger input</td>
</tr>
<tr>
<td>5</td>
<td>Black</td>
<td>Shield</td>
</tr>
<tr>
<td>6</td>
<td>N/A</td>
<td>Not connected.</td>
</tr>
<tr>
<td>7</td>
<td>Red</td>
<td>CAN_H</td>
</tr>
<tr>
<td>8</td>
<td>N/A</td>
<td>Not connected.</td>
</tr>
<tr>
<td>9</td>
<td>Yellow</td>
<td>Power supply to the device.</td>
</tr>
</tbody>
</table>

Figure H-1 Wiring guide of Kvaser logger to Saminco ECU guide
Kvaser Memorator Professional is a two-channel, high-performance, CAN bus interface and standalone Datalogger. Standalone mode logs data to an expandable SD card slot; interface mode connects to the PC with USB2.0. With the combined functionality of a standalone Datalogger and USB Interface, the Memorator Professional contains an advanced set of features: Message Filtering, Triggers, Error Detection Mode, Battery Backup, an expandable SD Card slot, Link J1587 compatible, Auto Transmit, Galvanic Isolation, and much more. Configurable using Kvaser’s included Memorator Tools software.

As a data logger, the Kvaser Memorator Professional is the perfect tool to capture irregular faults in the field or perform remote diagnosis. A great advantage is that all configurations are made with a user-friendly configuration program and are stored on the flash disk, making it both easy and convenient to set configurations with the PC and download it to Kvaser Memorator Professional for use in the field. The Kvaser Memorator Professional has a USB connection and can be used as a powerful USB CAN bus interface (like our Kvaser USBcan Professional).

Functions in Kvaser Memorator Professional

- Triggers and Data Logger capabilities
  - Kvaser Memorator can log continuously, or logging can be triggered by creating advanced triggers based on messages, data signal values, error messages, external trigger’s falling or rising edge, and I/O signals.
  - Pre- and post-triggers are available without buffer size restrictions, limited by disk space only.
  - Handles up to 20,000 msgs/s in standalone logger mode.
  - Transmit messages to the bus network.
• External digital output that can drive a LED or a buzzer.
• < 250 ms boot up time.
• Supports Silent Mode - log bus traffic safely without interfering and "listen-only" mode for bus analysis tools.

Filters

• Kvaser Memorator Professional can filter out selectable messages and/or signals to be logged. The identifiers can be picked from a database, or all messages can be logged.
• Support for pass as well as stop filters.
• Create a counting pass filter to have a message logged at enumerated occurrence.

Memory cards and functions

• Standard MMC or SD type flash memory cards can be used - up to 2GB.
• Support for 16GB SDHC cards. Larger SDHC cards supported in the future - up to 32GB.
• Set up several devices in a daisy chain for larger logging capacity.
• Transfer recorded data over the USB interface at 1.4 MB/s or an SD card reader at 15 MB/s.

Configuration software in the PC

• Easy to use graphic configuration tool - Kvaser Memorator Professional Setup Tool.
• Configuration of the CAN controller, i.e. bit rate and filters.
• Configuration of the trigger conditions.
• Configuration of filter for messages to be stored.
• Configuration upload and download via USB.
• Using the included Kvaser Dispatcher software, a complete measurement setup can be turned into a self-installing package that is sent to a remote location to carry out a specific logging task.

Major features of Kvaser Memorator

• One device for desktop and laptop.
• Functionality of a standalone CAN bus data logger and a USB CAN bus interface in a single device.
• Support for Kvaser Lib3 J1587.
• Driver support for major operating systems.
• Quick and easy plug-and-play installation.
• Supports both 11-bit (CAN 2.0A) and 29-bit (CAN 2.0B) identifiers.
• CAN messages are time-stamped with 2 microseconds resolution.
• Large on-board RAM buffer for CAN messages.
• 100% compatible with applications written for Kvaser Leaf, LAPcan, PCcan, PCcan, USBcan, etc., with Kvaser’s CANlib.
• Two CAN connections ISO-11898-2 high-speed, 10 kbit/s up to 1 Mbit/s.
• Galvanic isolation to protect the hardware.
• 130mA current consumption.
• Operating temperature range from -40 to + 85°C
• Power from CAN bus or from the USB side.
• Built-in real time (calendar) clock with battery backup
• Logger status is indicated with five externally visible LEDs.
• Plastic housing with dimension W*L*H about 50*90*25 mm (circa 2 x 3.5 x 1 inch)

Additional software and documentation

• **Kvaser CANLIB SDK**, which includes everything you need to develop software for the Kvaser CAN boards. Includes full documentation and many program samples, written in C, C++, C, Delphi, and Visual Basic. All Kvaser CAN interface boards share a common software API. Programs written for one board type will run without modifications on the other board types.
• J2534 Application Programming Interface
• RP1210A Application Programming Interface
• On-line documentation in Windows HTML-Help and Adobe Acrobat format.
• Documentation, software and drivers can be downloaded for free at www.kvaser.com or purchased separately on CD if preferred.

### Technical Data

<table>
<thead>
<tr>
<th>Kvaser Memorator Professional HS/HS</th>
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<tbody>
<tr>
<td>Galactic Isolation</td>
<td>Yes</td>
</tr>
<tr>
<td>Bitrate</td>
<td>10-1000 kbps</td>
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<tr>
<td>Silent mode</td>
<td>Yes</td>
</tr>
<tr>
<td>Error frame generation</td>
<td>Yes</td>
</tr>
<tr>
<td>Error frame detection</td>
<td>Yes</td>
</tr>
<tr>
<td>Weight</td>
<td>150g</td>
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<tr>
<td>Timestamp resolution</td>
<td>2 s</td>
</tr>
<tr>
<td>On-board buffer</td>
<td>Yes</td>
</tr>
<tr>
<td>Maximum message rate, send</td>
<td>20000</td>
</tr>
<tr>
<td>Maximum message rate, receive</td>
<td>20000</td>
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<tr>
<td>Sound</td>
<td>No</td>
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<td>Clock synchronization</td>
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<tr>
<td>Dimensions (HxWxD)</td>
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<td>Temperature range</td>
<td>-40°C to +85°C</td>
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<td>Order number</td>
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The information herein is subject to change without notice.
DT SERIES, LARGE APERTURE

Current Transducers

DT Series, Large Aperture Current Transducers combine a Hall effect sensor and signal conditioner into a single package for use in DC current applications up to 1200A. The DT Series has factory set and calibrated ranges and industry standard 4-20 mA, 0-5VDC or 0-10VDC outputs. Available in solid case DIN rail mounted enclosure.

Applications

Battery Banks
- Monitor load and charging currents.
- Verify operation.

Transportation
- Measure traction power or auxiliary loads.

Wind and Solar Generated Power
- Measure the current produced or consumed.
- Detect mechanical problems before failure occurs.

Monitor DC Powered Motors
- Monitor current of cranes, saws, sizers and positioning equipment.

Battery Charging System

Features

Factory Set and Calibrated Ranges
- No need for field calibration.
- Eliminates zero and span pots.

Isolation
- Output is magnetically isolated from the input for safety.
- Eliminates insertion losses, no added burden.

Internal Power Regulation
- Works well, even with unregulated power.
- Cuts installation cost.

DIN Rail Mounted Enclosure
- Makes installation a snap.
- No drilling or screws to lose.
- Optional DIN Rail kit available for chassis mounting.*

*For information on the DIN Rail accessories kit, see page A85.

For additional Sample Output/Power Supply or Application Examples, see Supplemental Illustrations on page A87.

For more information contact us at 800.959.4014 or visit our website at www nktechnologies com. Sales@ nktechnologies com.
**DT SERIES, LARGE APERTURE**

**Dimensions**

**Connections**

**Specifications**

<table>
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<th>Parameter</th>
<th>Specification</th>
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<tr>
<td></td>
<td>0-5VDC: 2.75VDC</td>
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<tr>
<td></td>
<td>0-10VDC: 11.5VDC</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±2% FS</td>
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<tr>
<td>Repeatability</td>
<td>±1.0% FS</td>
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<tr>
<td>Response Time</td>
<td>100ms (90% of span change)</td>
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<tr>
<td>Frequency Range</td>
<td>DC</td>
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<tr>
<td>Power Supply</td>
<td>24VAC/DC, isolated from output 120VDC</td>
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<td>Power Consumption</td>
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<td>Loading</td>
<td>4-20 mA: 6.5000 maximum</td>
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<tr>
<td></td>
<td>0-5VDC: 2500 minimum</td>
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<tr>
<td></td>
<td>0-10VDC: 5000 minimum</td>
</tr>
<tr>
<td>Isolation Voltage</td>
<td>3KV [recommended line to output]</td>
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<td>Linearity</td>
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<td>Current Ranges</td>
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<td>UL 308 Industrial Control Equipment (panning), CE</td>
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**Ordering Information**

Sample Model Number: DT6+420/24VAC/0:0.2%
Solarized DC current transducer, 0-500A range, 24VAC/DC powered, 4-20 mA, unipolar output.

```
(1) DT - (2) ___ - (3) ___ - (4) ___ - (5) D L
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<tr>
<td>8</td>
<td>___</td>
<td>___</td>
<td>1000</td>
<td>___</td>
<td>___</td>
</tr>
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<td>9</td>
<td>___</td>
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<td>1200</td>
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<td>4-20 mA</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>DL</td>
</tr>
<tr>
<td>0-5VDC</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>___</td>
</tr>
<tr>
<td>0-10VDC</td>
<td>___</td>
<td>___</td>
<td>___</td>
<td>___</td>
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**Notes:**
- Deadfront captive screw terminals.
- 12-22 AWG solid or stranded.
- Observe polarity.
- Unipolar Output: Signal with current flowing in one direction only.
**ENERCEPT® H804X SERIES**

4-20mA Output kW Transducers

**CAUTION**

**HAZARD OF ELECTRIC SHOCK, EXPLOSION, OR ARC FLASH**
- Follow safe electrical work practices. See NFPA 70E in the USA, or applicable local codes.
- This equipment must only be installed and serviced by qualified electrical personnel.
- Read, understand and follow the instructions before installing this product.
- Turn off all power supplying equipment before working on or inside the equipment.
- Use a properly sized voltage sensing device to confirm power is off.
- **DO NOT DEPEND ON THIS PRODUCT FOR VOLTAGE INDICATION**
- Only install this product in insulated conduits.
- Failure to follow these instructions will result in death or serious injury.

**RISK OF EQUIPMENT DAMAGE**
- Enercept series are used for use at 50-60Hz. Do not connect this product to circuits with high harmonics energy, such as variable speed drives (a.k.a. variable frequency drives, adjustable frequency drives) or similar sources, as these may permanently damage the product.
- Failure to follow these instructions can result in overheating and permanent equipment damage.

**NOTICE**
- This product is not intended for life or safety applications.
- Do not install this product in hazardous or classified locations.
- The installer is responsible for conformance to all applicable codes.
- Mount this product inside a suitable fire and electrical enclosure.

**FCC PART 15 INFORMATION**
NOTE: This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense. Modifications to this product without the express authorization of Veris Industries nullify this statement.

For use in a Pollution Degree 2 or better environment only. A Pollution Degree 2 environment must control conductive pollution and the possibility of condensation or high humidity. Consider the enclosure, the correct use of ventilation, thermal properties of the equipment, and the relationship with the environment. Installation category CAT 3 or CAT 4.

**Installer’s Specifications**

- **Input Voltage:** 208 to 480 VAC
- **Number of Phases Monitored:** 1 or 3
- **Frequency:** 50/60 Hz
- **Maximum Primary Current:** 2400 A continuous per phase
- **C case isolation:** 600 VAC
- **Internal isolation:** 2400 VAC rms
- **Operating temp. range:** 0°F to 60°F (17°C to 12°F) (<15%RH non-condensing)
- **Storage temp. range:** -40°F to 150°F (-40°C to 150°C)
- **Accuracy:** ±1% of reading from 10% to 100% of the rated current

**Output Type:** 4-20mA

**Power Input (typical):** 10 VA to 30VA

**DIMENSIONS**

**SMALL**
- **100/300 Apm:**
  - A = 3.8” (96mm)
  - B = 1.7” (43mm)
  - C = 1.5” (38mm)
  - D = 1.2” (30mm)
  - E = 4.0” (102mm)
  - F = 4.0” (102mm)

**MEDIUM**
- **400/800 Apm:**
  - A = 4.8” (122mm)
  - B = 3.5” (89mm)
  - C = 2.5” (64mm)
  - D = 1.7” (43mm)
  - E = 5.2” (132mm)
  - F = 5.9” (150mm)

**LARGE**
- **800/1600 Apm:**
  - A = 4.9” (125mm)
  - B = 5.3” (135mm)
  - C = 2.3” (60mm)
  - D = 1.7” (43mm)
  - E = 7.0” (178mm)
  - F = 6.0” (152mm)
Applications include:

- Research & Development
- Process Monitoring
- Fault Identification
- Machine Down Time
- Energy Monitoring

Strain Gauges
Pressure
Flow
Load Cells
GPS

Vehicle Testing
CAN gate (optional)
- CAN bus
- J1939
- OBDII

FREE Software & Technical Support

The Smarter Solution
The dataTaker DT821 smart data logger provides an extensive array of features that allow it to be used across a wide variety of applications. The DT821 is a robust, stand-alone, low power data logger featuring USB memory stick support, 18 bit resolution, extensive communications capabilities and a built-in display. The dataTaker DT821’s Dual Channel concept allows up to 4 isolated or 6 common referenced analog inputs to be used in many combinations. With support for Modbus sensors and SCADA systems, FTP and Web interface and switchable 12V and 9V regulated outputs to power sensors, the DT821 is a totally self-contained solution.

Versatile Measurement
Connect an array of sensors through the versatile analog and digital channels, high-speed counter inputs, photo-encoder inputs, programmable serial sensor channels and the optional CAN gate interface (available for CAN bus applications). Temperature, voltage, current, 4-20mA loops, resistance, bridges, strain gauges, frequency, digital, serial and calculated measurements can all be scaled, logged and returned in engineering units or written statistical reporting. Set up sampling, logging, alarm and control tasks to suit your own requirements while interfaces for smart sensors, GPS and other intelligent devices expand the DT821 flexibility.

Superior Data Storage & Communications
With this standard unit able to store up to 10 million data points (expandable) you can log as much or as little as you need. Over write or stop logging once allocated memory is full, archive data on alarm event, copy to USB memory or transfer via FTP, the choice is yours. Communications features include RS232 and Ethernet, connect to the DT821 locally, remotely through a modem or over the Internet. The web interface allows users to configure the DT821, access logged data and see current measurements as min, max or in a list using a web browser. FTP provides data to your office over the Internet or mobile phone network, without the need for polling or specific host software.

www.datataker.com

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Analog Channels

- 1 analog input channel

Each channel is independent and supports: one isolated 3-wire or 4-wire input, or three isolated 2-wire inputs, or three common referenced 2-wire inputs.

The following configurations apply:
- Two-wire with common reference terminal
- 6 two-wire isolated
- 4 three and four wire isolated: 2

Fundamental Input Ranges

The fundamental inputs that the 8530A can measure are voltage, current, resistance, and temperature. All other measurements are derived from these:

- Voltage: 0 to 2500V
- Current: 0 to 20mA
- Resistance: 10 ohm to 20G ohm
- Temperature: -50°C to 150°C

Number of Channels: 4

- Current input range: 0 to 20mA
- Voltage input range: 0 to 2500V
- Resistance input range: 10 ohm to 20G ohm
- Temperature input range: -50°C to 150°C

Specifications

- Resolution: 16 bits
- Accuracy: ±0.05% of reading ±0.025% of full scale

Sampling

Integrates over 500/600Hz line period for accuracy and noise rejection

- Maximum sample speed: 25kHz
- Effective resolution: 18 bits
- Linearity: ±0.01%
- Common mode rejection: ±0.08%
- Line series mode rejection: ±0.08%

Inputs

- Input Channel Isolation: 150V (relay switching)
- Accel/Sensor: 100V (non-isolated)
- Input Impedance: 100kΩ, ±0.06%
- Common mode rejection: ≥80 db or 25G ohm, whichever is higher

Sensors

- Accelerometer: ±100 mV/g
- Gyroscope: ±150 °/s
- Temperature: ±1°C

Analog Sensors

- Supports a wide range of sensors including, but not limited to, those listed below.
- A wide range of sensor carrier including linearizing facilities such as polynomials, cross functions, and functions.

Thermocouples

- Types: B, E, J, K, R, S, T
- Standard calibration: 0°F to 100°F

RTDs

- Materials: Pt, Ni, Cu
- Resistance range: 100 to 1000 ohm

Monolithic Temperature Sensors

- Types: NTC, PTC, TCV, DTM, LMTD

Strain Gauge and Bridge Sensors

- Configurations: 1, 4, 5, 6, 9, 12, 16
- Excitation voltage: current

- Digital Channels

Digital Inputs/Outputs

- 4-channel digital inputs

- Output Types: 4-channel digital

- Output Type: 4-channel digital

- Output Type: 4-channel digital

- Relay Output

- 1 relaying relay contacts (max. 30V, 1A)

Counter Channels

- Low Speed Counters

- Counter type: 32-bit

- Count rate: 10 kHz

- Dedicated Counter Inputs

- 4-counter high-signal or 2-phase encoder (quadrature) inputs

- Input size: 32 bits

- Max count rate: 100 kHz

- Serial Channels

- Generic Serial Sensor

- Relays: Options to allow data to be logged from a wide range of serial sensors and data streams


- Data rate: 300 to 115,200

- Calculated Channels

- Combines values from analog, digital, and serial sensors using expressions involving variables and functions.

- Functions: An extensive range of arithmetic, trigonometric, relational, logical, and statistical functions are available.

Alarms

- Condition: High, low, within range and out of range
- Delay: optional time period for alarm response

- Actuator: A digital output, transmit a signal, execute any data logger command.

Scheduling of Data Acquisition

- Number of schedules: 11
- Schedule rates: 180s to 10s

Data Storage

- Internal Storage

- Capacitor: 128MB, approx. 10,000,000 data points.

- Larger storage available with technical support.

- Optional accessory:

- Network (TCP/IP) Services

- Operating System:

- Supported: Windows 7 (32-bit), Windows 8 (64-bit), Windows 10 (64-bit), Linux (32-bit, 64-bit), Mac OS X (10.7 or later)

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- Operating System:

- Supported: Windows 7 (32-bit), Windows 8 (64-bit), Windows 10 (64-bit), Linux (32-bit, 64-bit), Mac OS X (10.7 or later)