Mapping the Brake Energy in Articulated Haulers

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Abstract:
An energy recovery analysis method was developed for the F generation articulated haulers in the form of a MATLAB script. The method is based on the mapping of the peak brake power, brake energy and engine energy. The method was developed using adequate signals collected on haulers at customer sites and test tracks. A conceptual study was also carried out concerning the brake energy that may be stored in the Energy storage systems (ESS) and the results shows the actual amount of brake energy that can be accumulated in the ESS along with the accurate selection of the ESS for a particular work site. The developed method was implemented in a measurement system (M-LOG) and two test runs were made. Results revealed that the energy recovery analysis method was implemented successfully with minor issues. The method developed in this thesis was welcomed by Volvo CE after test run and is in use presently.

Keywords: Articulated hauler, MATLAB, Brake energy, Peak brake power, Engine energy, Energy storage system.
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Karlskrona, October 2013

Gaurav Chopra
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1 Notation

\(\text{BE}\) Brake energy
\(\text{E}\) Energy
\(\text{\(F_S\)}\) Sampling frequency
\(\text{P}\) Power
\(\text{R}\) Wheel radius
\(\text{\(T\)}\) Torque
\(\text{\(\omega\)}\) Angular frequency

Indices

\(\text{BP}_1\) Brake pressure front axle
\(\text{BP}_2\) Brake pressure rear axle
\(\text{ERT}\) Engine retarder torque
\(\text{ET}\) Engine torque
\(\text{MF}_{\text{BTBFA}}\) Multiplication factor for brake torque in bogie front axle
\(\text{MF}_{\text{BTFA}}\) Multiplication factor for brake torque in front axle
\(\text{MF}_{\text{BTBRA}}\) Multiplication factor for brake torque in bogie rear axle
\(\text{MF}_{\text{ET}}\) Multiplication factor for engine torque
\(\text{MF}_{\text{RT}}\) Multiplication factor for brake torque in retarder
Abbreviations

VEB    Volvo Engine Brake
VGT    Variable Geometry Turbo
EPG    Engine Pressure Governor
VCB    Volvo Compression Brake
CAN    Controller Area Network
GTA    Global Transport Application
GVW    Gross Vehicle Weight
ESS    Energy Storage System
2 Introduction

2.1 Background

The usage of construction equipment performing off-road transports varies greatly. In order to choose the best design solutions for such machines, it is crucial to understand the variability in machine usage among customers. This is especially the case when new concepts such as alternative drivetrains are introduced. With the increased amount of control systems in machines a large number of sensors signals are available that provides useful information regarding the machine usage. This information can be fed back to the product development offices, but given the mobile nature of the machines and that they are often used in remote locations, it is required to analyze the important signals from the collected data and the relevant information from collected data are fed back for study.

![Figure 2.1. An F-series articulated hauler.](image)

It is important to track the usage of machines, since they are built for a purpose and by collecting data from the machines describes the effective usage of machines and if there are some limitations that could be worked upon. At Volvo CE, Braås data is brought back from the various customer
sites to analyze various parameters that affect the performance of articulated haulers. An articulated hauler is a type of dump truck which is used over rough terrain to transport loads. A hauler is all-wheel drive and has two units: the front section, also known as tractor unit and the rear section containing the dump body, the trailer unit. Figure 2.1 provides an overview of an articulated hauler.

2.2 Aim

An energy recovery analysis method was developed for the F generation articulated haulers in form of a MATLAB script. The analysis method is based on the mapping of the peak brake power, brake energy and engine energy. Main purpose of this thesis was to develop an energy recovery analysis method based on mapping of the energy usage in articulated haulers. The analysis method should focus on mapping the total kinetic energy consumed in brakes as compared to energy generated in engine, peak brake power generated and energy consumed during braking by subsystems during brake events, energy usage in between brake events from engine. All these parameters are required to investigate the feasibility of recovering brake energy. Depending upon the results obtained possible hybrid solutions could be used to accumulate the brake energy in an Energy Storage System (ESS).

2.3 Method

Energy usage was studied in MATLAB first from raw data collected from haulers at different sites. A MATLAB code was made for this purpose. Once the energy recovery analysis method was developed it was implemented in a measurement system for acquiring data concerning energy usage directly from haulers. New data was collected from a hauler at test track with the developed method implemented in the measurement
system, for verification of implementation of the energy recovery analysis method.

3 Brake Subsystems

The F-series machines feature a hydraulically operated brake system. The system includes functions for service brakes, the hydraulic wheel brakes acting on six wheels, as well as engine brake, parking brake, load and dump brake and an emergency brake, which is software-controlled [1]. Figure 3.1 shows various subsystems in a brake system of machines.

![Figure 3.1. Braking Subsystems in a hauler.](image)

3.1 Wheel Brake

The wheel axles have fully sealed wet multi-disc brakes with external oil cooler. The hydraulic pump that supplies hydraulic pressure to the brake system also drives the circuit for radiator fan as well as circulation for brake cooling oil. The system is divided into two independent circuits, one for the tractor unit and one for the trailer unit. Front and rear brake circuits have separate accumulator banks. The accumulators are precharged with nitrogen gas and their function is to store energy and ensure good brake capacity. As a back-up, the accumulators provide brake
system pressure if the engine or hydraulic pump fail. If one circuit fails, braking capacity always remains in the other circuit.

### 3.2 Engine brake

The VEB (Volvo Engine Brake) is a Volvo–developed, patent protected engine brake. It is also known as engine retarder. It consists of two interacting braking functions, dependent on the engine variant, installed in the machine. VEB is available in several versions; the following describes the function for articulated haulers [2].

1. **Exhaust brake, VGT** – On stage IIIIB/Tier 4i engines, the variable geometry turbocharger functions as an exhaust brake.

   **Exhaust brake, EPG** – The EPG is controlled by solenoids “butterfly valve” (shutter), positioned in the exhaust outlet from the turbocharger. The shutter is used for redirecting the exhaust to the EPG and restricting their free outflow. The braking effect is achieved during the exhaust stroke when the exhaust flow is restricted and the back-pressure is formed between the engine piston and the EPG shutter.

2. **Compression brake, VCB** – The working principle of VCB is that during the compression stroke and the expansion stroke the opening of the exhaust valve is controlled in such a way that the excess pressure is created in the combustion chambers and this, in turn, creates a braking effect on the crankshaft.

**VEB function principle** – When VEB is activated, two out of four strokes of the engine are utilized for increasing the engine braking effect; the exhaust stroke and the compression stroke – see figure 3.2
A. The exhaust stroke is utilized in that the pressure governor shutter closes the outlet from the turbocharger. When the piston is on its way up, a high counter pressure is created in the cylinder and also a consequent braking effect, as the air cannot be blown out in the same way as during normal running of the engine.

B. The next stroke, which is utilized to increase the braking effect, is the compression stroke, when the piston compresses the gases in the engine cylinder. Also in this case the high pressure in the exhaust manifold, when the EPG shutter is closed, is utilized. Around the bottom dead center after the inlet stroke, the exhaust valves are opened for a short moment to allow the high pressure to enter and “charge up” the cylinder chamber. During the following compression stroke the braking effect is achieved because of increased resistance force applied to the piston.

C. At the end of the compression stroke the exhaust valves open again momentarily to release the compressed air from the cylinder.
(decompression). In this way the propelling effect during the power stroke is avoided, which otherwise would have reduced the engine braking.

3.3 Parking brake

Parking brake consists of a brake caliper that acts on a brake disc installed on the trailer unit’s propeller shaft. The brake caliper has automatic adjustment of the brake pads. The parking brake is applied by the spring force and released with compressed air controlled with parking switch on the instrument panel. When parking brake is applied, the longitudinal differential lock is engaged.

3.4 Load and dump brake

The load and dump brake function is integrated in standard wheel brake system. Its function is to reduce the wear of the parking brake by applying all wheel brakes in an easy way for loading and dumping.

3.5 Brakes relevant for energy recovery

The energy recovery analysis method developed in this thesis only consider wheel brakes and engine brake because parking, load and dump brakes works when machine is not moving and thus no brake torque cannot be obtained while machine is standing still.
4  Data measurement

4.1  Sites for data collection

4.1.1  Customer sites

In total there were three different customer sites used for data collection. The customer sites used were

1. Jaro – This customer site is situated in Poland. It is an open mine of clay. It had four different types of soil configurations – sand, gravel, stone and dirt and had very rough road conditions for driving. Site had hilly topographical conditions along with poor traction of tires with ground surface and very high rolling resistance.

2. Kiruna – This customer site is situated in north of Sweden. It is an underground iron ore mine. But the haulers are used in open pit section. It had compacted soil road with smooth road conditions for driving. Topographical conditions were very hilly. Traction for tires varied from poor to fine and rolling resistance was low.

3. Abu Dhabi – This customer site is situated in U.A.E. (United Arab Emirates). It is a construction site with speed limits restricted to 20 km/h. Work site had sand mainly as soil configuration. Site had flat topographical conditions, good traction for tires and high rolling resistance.

Volvo Group has a standardized way for describing the Operating Environment, Vehicle Utilization and Transport Mission at different customer sites, by using GTA (Global Transport Application). GTA defines a number of parameters that help to specify differences in transport and driving conditions for haulage operations worldwide. For each hauler at customer site seven common GTA parameters were used which are described in Table 4.1.
Table 4.1. GTA parameters for customer tracks.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Jaro</th>
<th>Kiruna</th>
<th>Abu Dhabi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling resistance</td>
<td>40</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Load-bearing capacity</td>
<td>3</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>Topography</td>
<td>Hilly</td>
<td>Very Hilly</td>
<td>Flat</td>
</tr>
<tr>
<td>GVW</td>
<td>Normal</td>
<td>High</td>
<td>Normal</td>
</tr>
<tr>
<td>Operating Cycle</td>
<td>Local</td>
<td>regional</td>
<td>Local</td>
</tr>
<tr>
<td>Coefficient of traction</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.4</td>
<td>0.4 – 0.6</td>
</tr>
<tr>
<td>Road condition</td>
<td>Very rough</td>
<td>Smooth</td>
<td>Cross Country</td>
</tr>
</tbody>
</table>

For each site the GTA parameters were judged by test engineers according to the set standards. For Jaro, data measurements were taken on A25F, A30F and A35F haulers. For Kiruna, data measurement was done on an A40F hauler. For Abu Dhabi, data measurement was performed on an A35F hauler.

4.1.2 Test tracks

Total seven test tracks were used for the data collection. Measurements were carried out for loaded, unloaded and overloaded conditions of haulers at some of the tracks. An A35F FS hauler was used in for in the test track measurements. In total seven different test tracks were used for measurements. The test tracks used were as follows

1. Demo Track – This test track is situated behind the production unit at Braås. Soil configuration is mainly sand, dirt and stones. Topographical conditions for the track are flat for most of the section with a one big hill having high slope. Traction for tires is average but road conditions are mainly rough with low rolling resistance.

2. Camel Humps Track – This test track is also situated behind the production unit at Braås. Soil configuration, traction for tires, road
conditions and rolling resistance are similar to demo track. Track has very hilly topographical conditions throughout.

3. Braås 2 Track – This test track is also situated behind the production unit at Braås. This test track is also known as durability test track. Soil configuration and is similar to demo track described earlier but the road conditions are very severe and traction for tires is mainly poor. The track has flat topographical conditions throughout but the rolling resistance is very high.

4. Comfort Track – This test track is also situated behind the production unit at Braås. It is a road with hard surface and small humps having a height between 4 and 8 centimeters. Driving conditions are very rough due to these small humps but the rolling resistance is very low. Traction for tires is very high and the track is flat in terms of topographical conditions.

5. PT Update Track – This test track is situated in Målajord, 4 km from Braås. Soil configuration is mainly sand, soft gravel and stones, which results in average tire traction. Topographical condition in total can be defined as hilly. Rolling resistance is low and driving conditions are rough.

6. Målajord Off Road Track – This track is also situated in Målajord. The track is similar to Braås 2 track, but the topographical conditions are very hilly at some parts of it. Also the driving speed has to be low due to the features of the track.

7. Målajord Fuel Economy Track – This track is also situated in Målajord. Most of the track has flat topography and the rest of its features are similar to PT Update.

Table 11.1 in appendix A1 describes the GTA parameters for the test tracks.
For some measurements carried out at the test tracks data were acquired for driving on a combination of different tracks. Table 4.2 describes the combination of test tracks used for data measurements.

Table 4.2. Test track used in measurements.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Name of entire track</th>
<th>Test tracks used</th>
</tr>
</thead>
<tbody>
<tr>
<td>F15</td>
<td>Humps</td>
<td>Demo track + Camel hump track</td>
</tr>
<tr>
<td>F43</td>
<td>Braås 2</td>
<td>Braås 2</td>
</tr>
<tr>
<td>F75</td>
<td>Secret track</td>
<td>Demo track + Braås 2 + Comfort track</td>
</tr>
<tr>
<td>F79</td>
<td>PT Update</td>
<td>PT Update</td>
</tr>
<tr>
<td>F7F20</td>
<td>Terrain track</td>
<td>Målajord – off road track</td>
</tr>
<tr>
<td>EEHH</td>
<td>EEHH</td>
<td>Målajord – fuel economy track</td>
</tr>
</tbody>
</table>

4.2 Measurement systems

Two types of measurements systems were used for data collection. For the test track measurements, an eDAQ measurement system was used to collect data. Triggering for data collection was done manually at the test tracks. And data was stored directly into a computer hard drive while driving. The sampling frequency was set to 200 Hz and data collected was in S3 time series which is in .sif format and they were subsequently converted to .mat format using the software nCode GlyphWorks.

For the measurement at the customer sites the haulers were equipped with a M-LOG measurement system to measure the CAN data. Memory cards were used to store the data (the memory cards with the collected data were sent to Volvo CE, Braås). In the measurement at the customer sites the ignition was used to triggering the measurements, when ignition switch was turned on measurement system started to collect data. The sampling frequency was set to 100 Hz and collected data was in diadem time series which is in .dat format and they were converted to .mat format using the software nCode GlyphWorks. Figure 4.1 shows the eDAQ and M-LOG measurement systems.
The M-LOG measurement system is compact and it was placed under the instructor seat in driver cab. The eDAQ measurement system on the other hand is larger and it was instead placed on the instructor seat during the test track measurements. Figure 4.2 describes the installation of the measurement systems in the haulers.
4.3 Signals analyzed

During measurement a substantial number of signals were measured, but for the analysis only a fraction of these signals were used which are described in Table 4.3.

*Table 4.3. Signals used in analysis.*

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Name of signal</th>
<th>Actual parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Actual Retarder Percent Torque</td>
<td>% Retarder Brake torque</td>
<td>%</td>
</tr>
<tr>
<td>2.</td>
<td>Actual Engine Percent Torque</td>
<td>% Engine torque</td>
<td>%</td>
</tr>
<tr>
<td>3.</td>
<td>Output Brake Pressure Two</td>
<td>Brake pressure in rear axle</td>
<td>kPa</td>
</tr>
<tr>
<td>4.</td>
<td>Output Brake Pressure One</td>
<td>Brake pressure in front axle</td>
<td>kPa</td>
</tr>
<tr>
<td>5.</td>
<td>Vehicle Speed</td>
<td>Speed of Vehicle</td>
<td>km/h</td>
</tr>
<tr>
<td>6.</td>
<td>Engine Speed</td>
<td>Speed of shaft connecting engine – torque convertor</td>
<td>rpm</td>
</tr>
<tr>
<td>7.</td>
<td>Vehicle Inclination</td>
<td>Vehicle Inclination</td>
<td>‰</td>
</tr>
<tr>
<td>8.</td>
<td>Current Gear</td>
<td>Current Gear</td>
<td></td>
</tr>
</tbody>
</table>

The main signals used for most of the calculations were; the actual retarder percent torque, the actual engine percent torque, the output brake pressure two, the output brake pressure one, the vehicle speed and the engine speed. Vehicle inclination signal was used to study the peak power in some cases where it was of interest because of the topology at the site or track. The vehicle inclination signal does not directly provide the actual vehicle slope and thus cannot be used directly. A function called “inclination 2” previously developed at Volvo CE, Braås was used in MATLAB to get vehicle inclination correct in terms of slope. Inputs to the “inclination 2” function were the vehicle speed, vehicle inclination, current gear and sampling frequency. The output of the function was the inclination of the vehicle in percentage slope.
5 Energy recovery analysis method

The main focus of this thesis project was to develop an energy recovery analysis method based on the mapping of the peak brake power, brake energy and engine energy in articulated haulers. The aim was to deduce how much energy is consumed in total during braking compared to energy provided by engine with the aid of the developed method. In detail the method would address the brake events, when the brake events start and ends, the peak brake power and brake energy during brake events. Also in between the brake events energy usage from engine would also be mapped.

The analysis method was first developed in MATLAB, a script was developed which covers all the aspects described above. In reality the analysis method was developed for the measurement system (M-LOG), when the analysis method is implemented in the measurement system it logs data concerning brake power, brake energy and engine energy signals directly from the machines. This method was made universal for all the haulers equipped with the same braking system as the F-series presently have.

5.1 Assumptions

- Angular velocity is same for all wheels. The reason behind this assumption was that the vehicle speed has maximum limit of 60 km/h, so the working speed would be quite low during operation as compared to a car. While steering there will be a smaller difference in the angular velocity of the wheels due to low vehicle speed. There will a small error with this assumption which is acceptable.
• There is a uniformly distributed ± 10 % error in the measured brake pressure (front and rear axles) and measured percentage torque (engine and retarder) signals. This assumption is made because the signals collected cannot be 100% accurate and may have error and the true value could vary from -10% to +10% of the true value of the signal.

• There is a uniformly distributed ± 2 % error in engine rpm and vehicle speed signals. Error assumed here is small, because the engine rpm and vehicle speed signals can be trusted to be more accurate than the signals mentioned in previous assumption. This is a small error which can be neglected but when combined with previous error, the total error gets added and then it’s a matter of concern to study the error propagation of the total error in the calculations.

### 5.2 General Calculations

The main quantities to be calculated with developed method are torque, power and energy. Most of the calculations were similar for all haulers. Some parameters however differed between the machines and are given in Table 11.2 in appendix A1. Initially the calculations start with finding the torque. The input signals for engine and retarder percentage torque, ET signal(t) and ERT signal(t), were multiplied by the respective multiplication factors MF<sub>ET</sub> and MF<sub>RT</sub> and divided by 100 due to percentage and further by 1000 to get torque in kNm. Hence, the engine and retarder torque (T<sub>Engine(t)</sub> and T<sub>VEB(t)</sub>) were respectively produced as

\[
T_{\text{Engine}}(t) = ET \text{ signal} \times \frac{MF_{\text{ET}}}{100 \times 1000} \tag{5.1}
\]

\[
T_{\text{VEB}}(t) = ERT \text{ signal} \times \frac{MF_{\text{RT}}}{100 \times 1000} \tag{5.2}
\]
The signal for engine rpm \((rpm\ signal(t))\) was converted to angular velocity \((\omega_{\text{Engine}}(t))\) of the engine shaft as

\[
\omega_{\text{Engine}}(t) = \frac{2\pi \times \text{rpm signal}(t)}{60}
\] (5.3)

The angular velocity of the engine shaft \(\omega_{\text{Engine}}(t)\) and respective engine torque in Eq. 5.1 and retarder torque in Eq. 5.2 were used to produce the engine power \(P_{\text{Engine}}(t)\) and retarder power \(P_{\text{VEB}}(t)\) according to

\[
P_{\text{Engine}}(t) = \omega_{\text{Engine}}(t) \times T_{\text{Engine}}(t)
\] (5.4)

and

\[
P_{\text{VEB}}(t) = \omega_{\text{engine}}(t) \times T_{\text{VEB}}(t)
\] (5.5)

The engine energy \(E_{\text{engine}}(t)\) and brake energy in retarder \(BE_{\text{VEB}}(t)\) may respectively be produced as

\[
E_{\text{Engine}}(t) = \int P_{\text{Engine}}(t) dt
\] (5.6)

and

\[
BE_{\text{VEB}}(t) = \int P_{\text{VEB}}(t) dt
\] (5.7)

In Matlab numerical integration is used to calculate integrals. The brake torque acting on front and rear axle, \(T_{\text{Front Axle}}(t)\) and \(T_{\text{Rear Axle}}(t)\), during braking may be produced as

\[
T_{\text{Front Axle}}(t) = 2 \times BP_1(t) \times \frac{MF_{\text{BTFA}}}{14 \times 1000}
\] (5.8)

and

\[
T_{\text{Rear Axle}}(t) = 2 \times BP_2(t) \left[ \frac{MF_{\text{BTFA}}}{14 \times 1000} + \frac{MF_{\text{BTRBA}}}{14 \times 1000} \right]
\] (5.9)

Where \(BP_1(t)\) and \(BP_2(t)\) are pressure signals, \(MF_{\text{BTFA}}, MF_{\text{BTFA}}\) and \(MF_{\text{BTRBA}}\) are multiplication factors and the division with 1000 to get \(kN\text{m}\).
Rear axle is assumed as combination of front and back bogie axles together. The angular velocity of a wheel $\omega_{wheels}(t)$ may be calculated according to which the velocity should be in radians per second and wheel radius ($R$) and vehicle speed ($Vehicle speed signal$) were used to find it.

$$\omega_{wheels}(t) = \frac{Vehicle Speed Signal(t)}{3.6 \times R} \quad (5.10)$$

Here $R$ is the wheel radius.

Now the brake power for front and rear axle, $P_{Front Axle}(t)$ and $P_{Rear Axle}(t)$, may be calculated as

$$P_{Front Axle} = \omega_{wheels} \times T_{Front Axle} \quad (5.11)$$

and

$$P_{Rear Axle} = \omega_{wheels} \times T_{Rear Axle} \quad (5.12)$$

The brake energy generated by front and rear axle, $BE_{Front Axle}(t)$ and $BE_{Rear Axle}(t)$ are thus given by

$$BE_{Front Axle}(t) = \int P_{Front Axle}(t) \, dt \quad (5.13)$$

and

$$BE_{Rear Axle}(t) = \int P_{Rear Axle}(t) \, dt \quad (5.14)$$

### 5.3 Brake Energy and Engine Energy ratio

The percentage brake energy ($\% BE_{VEB}$) generated in retarder was defined as the ratio between total brake energy ($TBE_{VEB}$) from retarder and total energy ($TE_{Engine}$) from engine according to:
\[ \% \text{BE}_{\text{VEB}} = \frac{T\text{BE}_{\text{VEB}}}{T\text{E}_{\text{Engine}}} \times 100 \quad (5.15) \]

Correspondingly, the front axle percentage brake energy \( \% \text{BE}_{\text{FrontAxle}} \) and axle percentage brake energy rear \( \% \text{BE}_{\text{RearAxle}} \) were defined as

\[ \% \text{BE}_{\text{Front Axle}} = \frac{T\text{BE}_{\text{Front Axle}}}{T\text{E}_{\text{Engine}}} \times 100 \quad (5.16) \]

and

\[ \% \text{BE}_{\text{Rear Axle}} = \frac{T\text{BE}_{\text{Rear Axle}}}{T\text{E}_{\text{Engine}}} \times 100 \quad (5.17) \]

### 5.4 Peak brake power and brake events

To investigate the feasibility of recovering brake energy knowledge of the peak brake power and brake energy for each brake event, for each brake subsystem, is for instance required. The peak brake power and brake energy per brake event as well as the topology at a user site may affect the selection of energy conversions system and Energy Storage System (ESS).

An ESS may generally be specified for a certain power range, min to max input power, thus the mapping of the peak power generated in all subsystems is required.

Initially, the brake event was defined. The brakes can work in three combinations

1. VEB (Volvo Engine Brake)
2. Service Brakes (Front axle and Rear axle)
3. VEB and Service Brakes
In order to define a brake event, conditions were provided concerning the brake pressure signal levels from front and rear axle and engine retarder torque signal. The conditions defining the brake events are:

1. Brake pressure(front axle) > 65 kPa
2. Brake pressure(rear axle) > 65 kPa
3. |VEB| > 0 (the signal assume negative values)

When one or more of the three brake conditions are true a brake event is defined to start and it will continue until all three brake conditions are false.

Thus, the end point of a brake event is when neither of the above conditions is true. Figure 5.1 provides a clear description of the brake event definition. The brake pressure for front and rear axles is plotted along with percentage retarder torque signal (PRT) in Figure 5.1.

![Figure 5.1. Brake pressure for front and rear axle, and retarder torque.](image)

A retarder brake event is first observable to the left in Figure 5.1, start and of each brake event is indicated in the figure. Slightly later the second brake event appears in Fig. 5.1 and the retarder starts it and subsequent the service brakes are activated with retarder and this brake event ends.
with the retarder. The start and end points of each brake event have been stored.

After the conditions for a brake event were defined, the torque generated by the engine retarder was calculated with the aid of equation 5.2. To obtain the angular frequency of engine shaft equation 5.3 was utilized.

The brake power versus time generated by each sub-subsystem and brake event was calculated using equations 5.5, 5.11 and 5.12. Thus, the brake power was calculated between the start and end points of each brake event for all sub-subsystem, for each measurement and for all the involved sites.

### 5.5 Brake Energy during brake events

To investigate the feasibility of an Energy Storage System for recovery of the kinetic energy wasted during brake events knowledge concerning e.g. the amount of kinetic energy consumed during brake events is required.

The brake power during brake events was estimated and used to calculate brake energy during brake events in each sub-system numerically. The brake energy was calculated based on equation 5.7 for the retarder and equation 5.13 and 5.14 for the front and rear axle in combination with information regarding the start and end points of respective brake events.

### 5.6 Energy usage between brake events

The energy used by an articulated hauler between brake events is consumed by its engine. In the investigation concerning the feasibility of an energy recovery system, in addition to knowledge on the kinetic energy wasted by brake events, also the knowledge on the energy used in between brake events is a key component. This enables the understanding
of the energy requirements in between the brake events. The engine torque was calculated numerically based on equation 5.1 and the angular velocity for the engine shaft, equation 5.4 was used directly to calculate the power generated by the engine in combination with the start and end points for brake events. The engine energy consumption was calculated in between the brake events with the aid of equation 5.6.

5.7 Concepts for brake energy accumulation

After the calculation of peak brake power and brake energy during the brake events and the energy usage in between the brake events, a conceptual study for an Energy Storage System (ESS) was carried out. Each ESS has an upper limit for the maximal brake power it can handle (total brake power from all subsystems) and a limit energy storage capacity. Table 5.1 give the power and energy limits for three different energy storage systems that can be implemented in haulers [3].

Table 5.1. ESS with power and energy limits.

<table>
<thead>
<tr>
<th>Energy storage system (ESS)</th>
<th>Power Limit (kW)</th>
<th>Energy Limit (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESS 1</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>ESS 2</td>
<td>60</td>
<td>2000</td>
</tr>
<tr>
<td>ESS 3</td>
<td>120</td>
<td>3000</td>
</tr>
</tbody>
</table>

Two different concepts related to an ESS with power and energy limits were studied. For both the concepts a general case of ESS was used having $P_L$ (power limit) as maximum power it can handle and $E_L$ (energy limit) as maximum energy it can accumulate.
5.7.1 Concept C1

In this concept energy storage systems with different power and energy limits were studied with the assumption that the energy in the ESS is completely consumed by the engine between the brake events, i.e. the ESS is assumed to be empty before a brake event starts. Hence, assuming that the ESS is empty before a brake event starts will put limitation on the accuracy of the study. This assumption, however, reduces the computational load.

The brake power generated by each sub-system during brake events was calculated based on equations 5.5, 5.11 and 5.12, and summed to produce the total brake power \( P(t) \) for each brake event. A power limit \( P_L \) was applied to the total brake power produced during a brake event and brake power exceeding \( P_L \) was replaced by \( P_L \) and the values below \( P_L \) remained unchanged during the brake event, according to:

\[
P_{LT}(t) = \text{Minimum} \left( P(t) \text{ (at each brake event)}, P_L \right)
\]

where \( P_{LT}(t) \) is new total limited power

Then the new total limited power, \( P_{LT}(t) \), produced based on equation 5.18 was subsequently integrated to obtain the limit brake energy \( B_{E_n} \), \( 1 \leq n \leq N \), at each brake event \( n \). Now an energy limit \( E_L \), defined by ESS alternative considered in the calculations was applied and the energy values exceeding \( E_L \) was replaced with \( E_L \) and the energy values below \( E_L \) remained unchanged, in accordance with:

\[
E_{LT(n)} = \text{Minimum} \left( B_{E_n} \text{ (at each brake event)}, E_L \right)
\]

where \( E_{LT(n)} \) is new limited brake energy

The limited brake energy, \( E_{LT(n)} \), was calculated for each brake event assuming that the energy is stored in the ESS and the ESS is empty before a brake event starts.
5.7.2 Concept C2

As in concept C1 the energy storage systems with three different power and energy limits were studied, however, in the C2 concept no simplifying and limiting assumptions were made. Thus, if the brake energy in the ESS is not completely consumed between brake events it will be included in the energy accumulation calculation during brake events.

The total limited brake power, $P_{LT}(t)$, was calculated in the same way as in concept C1, thus by using equation 5.18. This total limit power was integrated to produce the brake energy $B_{En}$, $1 \leq n \leq N$, at each brake event. The energy consumed between the brake events was $E_{En}$, $1 \leq n \leq N-1$.

In concept C2 focus was on: The amount of brake energy accumulated up to and including brake event $n$, $B_{Es(n)}$, and the amount of brake energy only accumulated from brake event $n$, $B_{En}(n)$. For a general case of the $n^{th}$ brake event the total accumulated brake energy accumulated up to and including brake event $n$, $B_{Es(n)}$, is given by:

$$B_{Es(n)} = \min (B_{En} + \max (B_{Es(n-1)} - E_{En-1}, 0), E_{L}) \quad (5.20)$$

Initial conditions are $B_{Es(0)} = 0$ and $E_{E0} = 0$. From the expression $[\max (B_{Es(n-1)} - E_{En-1}, 0)]$ the energy left from previous brake event is calculated. $B_{Es(n-1)}$ is the energy accumulated by the ESS up to and including the $(n-1)^{th}$ brake event and $E_{En-1}$ is energy used in between the $(n-1)^{th}$ and $n^{th}$ brake events. If the value of the difference $B_{Es(n-1)} - E_{En-1}$ is positive there will be some energy left in the ESS from brake event $n-1$ and if the value is negative or zero no energy will be left from previous brake events in the ESS.

For the case of energy left in the ESS from previous brake events; the brake energy produced during the $n^{th}$ brake event, $B_{En}$, will be added to the ESS energy up to the energy limit $E_{L}$. Thus, if the sum of ESS energy and $B_{En}$ is greater than $E_{L}$, $B_{Es(n)}$ is assigned the value of $E_{L}$ and if the
sum of ESS energy and $B_E$ is lower than $E_L$, $B_{ES(n)}$ is assigned the value of this sum.

For a general case of the $n^{th}$ brake event the brake energy accumulated during brake event $n$, $B_{EA(n)}$, is given by:

$$B_{EA(n)} = \text{minimum}(B_{En}, E_L - \text{maximum}(B_{ES(n-1)} - E_{En-1}, 0)) \quad (5.21)$$

Initial conditions are $B_{ES(0)} = 0$ and $E_{E0} = 0$. If the ESS is considered as a bucket, as shown in Figure 5.2, in which energy can be accumulated in. It has an energy accumulation limit $E_L$ and the expression $[\text{maximum}(B_{ES(n-1)} - E_{En-1}, 0)]$ gives the energy that is left from the previous brake event and thus if the expression $[E_L - \text{maximum}(B_{ES(n-1)} - E_{En-1}, 0)]$ yields a positive value as result that will equal the remaining space left in bucket to be filled with energy during next brake event.

![Figure 5.2. Energy accumulation during the $n^{th}$ brake event in ESS (Concept C2).](image)

For the first brake event the values of $B_{ES(1)}$ and $B_{EA(1)}$ are given by

$$B_{ES(1)} = \text{minimum}(B_{E1}, E_L) \quad (5.22)$$
\[ BE_{A(1)} = \text{minimum} \left( BE_1, E_L \right) \]  

(5.23)

For the first brake event it is obvious that there will not be any previously accumulated energy in the ESS and thus \( BE_{S(1)} = BE_{A(1)} \).

\( E_{LT(n)} \) (Concept C1) and \( BE_{A(n)} \) (Concept C2) were calculated for a number of different combinations of ESS power and energy limits. In these calculations 49 different power limits from 20 kW to 500 kW with an increment of 10 kW were considered and 30 different energy accumulation limits from 500 kJ to 15000 kJ with an increment of 500 kJ were considered.

Thus, \( E_{LT(n)} \) (Concept C1) and \( BE_{A(n)} \) (Concept C2) were calculated for the 1470 possible combinations of ESS power and energy limits.

Concept C1 assumes that the ESS is empty before a brake event starts will yield results that may differ to corresponding results produced with concept C2. Hence, in concept C2 if the brake energy in the ESS is not completely consumed between brake events it will be included in the energy accumulation calculation during brake events.

The accuracy of concept C1 has to be checked to clarify the impact of the assumption that the ESS is empty before a brake event starts on its results.

The relative error between \( E_{LT(n)} \) and \( BE_{A(n)} \) in percentage was calculated as

\[
\% \text{Error} = \frac{(E_{LT(n)} - BE_{A(n)})}{BE_{A(n)}} \times 100
\]
5.8 Results

5.8.1 Results for Total (kinetic) brake energy

Energy recovery of the kinetic energy of a hauler via its the three brake sub-systems is considered. The percentage of brake energy contributed by each sub-system was plotted in a stacked bar plot, shown in Figure 5.3. From this figure it is clear that the hauler used at the site in Kiruna has largest percentage of total brake energy and the hauler used at U.A.E. site has the lowest percentage of total brake energy. At the Jaro site the maximum percentage of total brake energy was obtained for the A35F hauler and the lowest percentage of total brake energy was for the A30F.

![Figure 5.3. Percentage of brake energy available for reuse at customer sites.](image)

Ideally under same GTA parameters, the total brake energy for A25F should be less as compared to A30F. But for the A30F machine the amount of available data was substantially lower as compared to other machines, which may be one explanation for such result. Another possible reason could be that drivers of A25F more frequently use the brakes compared to A30F drivers. The results in figure 5.3 were clearly
influenced by the topographical conditions of the sites. At sites with very hilly topographical conditions the percentage brake energy available for reuse was greatest and at the Kiruna site the percentage brake energy available for reuse was the highest obtained. On the other hand, at sites with very flat topographical conditions the percentage brake energy available for reuse was lowest, with low speed driving and flat sand surface the results from U.A.E. site demonstrated the lowest percentage brake energy available of all the sites in this study.

Also if the result is viewed in terms of sub-systems, for the Jaro site all of the sub-systems provide approx. the same amount of re-usable energy for all the machines. At the U.A.E. site the usage of the retarder was low. In Kiruna the greatest part of brake energy was obtained from the rear axles of the haulers.

Results showing how the percentage brake energy is distributed between the three brake sub-systems for the different test tracks are given in appendix A3.

5.8.2 Results for Peak power during brake events

![Figure 5.4. Peak brake power generated in front axle as a function of accumulated number of brake events/hour.](image)
In Figure 5.4 front axle peak brake power versus accumulated number of brake events per hour for A25F, A30F and A35F at Jaro, and A40F at Kiruna respective A35 U.A.E. are shown.

![Graph showing peak brake power versus accumulated number of brake events per hour for different haulers at Jaro and Kiruna.](image)

**Figure 5.5. Peak brake power generated in rear axle during accumulated number of brake events/hour.**

In Fig. 5.5 the rear axle Peak brake power results are shown and they are fairly consistent with the front axle peak power results shown in Fig. 5.4. From Figs. 5.4 and 5.5 it follows that the A30F hauler used at Jaro provided the lowest peak power for both front and rear axles.
Figure 5.6. Peak brake power generated in retarder as a function of accumulated number of brake events/hour.

The retarder peak power results are shown in Figure 5.6 and it follows that the Kiruna machine generally produced the highest retarder peak power. However, the A25F used at Jaro site produce the highest retarder peak power, of all haulers at the different sites, during a few brake events, see Fig. 5.6. The results also indicate that the service brakes were applied more aggressively at Jaro site. Also, the results shown in Figs. 5.4, 5.5 and 5.6 indicates that the total peak power provided by the three subsystems is approx. 500 kW at 10 brake event/hour for the Kiruna machine. Thus, the power limits suggested in table 5.1 for the ESS:s may basically be reached by most of the brake events.
Figure 5.7. Peak brake power versus the mean slope of the driving surface for A25F (Jaro).

To provide more information concerning a hypothesis of aggressive usage of machine, the total combined peak brake power for all subsystems for each site were plotted with respect to mean percentage slope of the driving surface. Figure 5.7 clearly indicates that the highest total peak brake power values for all subsystems occur in a close range of zero percent slope of the driving surface for A25F machine at Jaro.
Figure 5.8. Peak brake power versus the mean slope of the driving surface for A30F (Jaro).

For the A30F hauler at the Jaro site; the higher values for total peak brake power for all subsystems display a distinct offset towards a negative slope of the driving surface, as illustrated in Figure 5.8.

The highest total peak brake power values for all subsystems of the A35F hauler at the Jaro site are, on the other hand, in a close range of zero percent slope of the driving surface, shown in Fig. 5.9. However in this case increased total peak brake power values are also observable in approximate range of -10% to -15 % driving surface slope. The case when high values for the brake subsystems total peak brake power occur in a close range of zero percent slope of the driving surface is likely to indicate aggressive usage of the brakes of a machine.
Figure 5.9. Peak brake power versus the mean slope of the driving surface for A35F (Jaro).

Figure 5.10. Peak brake power versus the mean slope of the driving surface for A35F (U.A.E.)
For the A35F hauler at the U.A.E. Site; the values for the total peak brake power of the brake subsystems versus mean slope of the driving surface is shown in Figure 5.10.

Now for the A40F used at the Kiruna site, the results for total peak brake power of the brake subsystems shown in Figure 5.11 indicate high magnitudes in the region of negative surface slope. This may indicate an effective usage of the brakes.

![Figure 5.11. Peak brake power versus the mean slope of the driving surface for A40F (Kiruna).](image)

In terms of the usage percentage of each brake subsystem; the peak power for each brake subsystem divided with the total peak power of the brake subsystems were plotted as a function of the percentage of total number of brake events for each customer site.

Figure 5.12 shows percentage of peak power contributed by the front axle to total peak power (all subsystems) as a function of the percentage of the total number of brake events.
For the A35F machine at the Jaro site; in approx. 25% of the brake events there is no brake peak power provided by the front axle and for approx. 1% of the brake events more than 90% of peak power is provided by the front axle.

From Figure 5.12 it follows that the A30F machine at the Jaro site that the front axle provide approx. 30% of the peak brake power during approx. 20% of brake events and for ca. 40% of the brake events about 35% of the peak brake power is provided by the front axle. Similarly for other machines (A25F, A30F and A35F from Jaro and A35F from U.A.E.) results could be interpreted.

![Graph showing percentage of peak brake power generated by front axle as a function of the percentage of the total number of brake events.](image)

**Figure 5.12. Percentage of peak brake power generated by front axle as a function of the percentage of the total number of brake events.**

The results concerning the Percentage of peak brake power generated by rear axle and retarder as a function of the percentage of the total number of brake events are given in appendix A2.1.
5.8.3 Results for Brake energy during brake events

Figure 5.13. Brake Energy generated in front axle as a function of the number of brake events/hour.

Figure 5.14. Brake Energy generated in rear axle as a function of the number of brake events/hour.
The graphs displaying the highest levels of brake energy generated by the front axle and by the rear axle as a function of number of brake events/hour originates from the machine used at the Kiruna site, see Figure 5.13 and 5.14. Furthermore, for the A40F Kiruna and the A35F Jaro haulers the graphs for the brake energy generated by the rear axle as a function of number of brake events/hour display higher levels as compared to the values for the front axle.

![Graph showing brake energy generated in retarder as a function of brake events/hour](image)

*Figure 5.15. Brake Energy generated in retarder as a function of the number of brake events/hour.*

Figure 5.15 shows the brake energy generated in the retarder as a function of the number of brake events/hour and it displays a pattern similar to the results for the front and rear axles in Figs. 5.13 and 5.14.

In appendix A2.2 results can be seen for the percentage of brake energy generated by front axle as a function of the percentage of the total number of brake events.
5.8.4 Results for Engine energy in between brake events

Figure 5.16. Energy consumed by engine as a function of the number of brake events/hour.

Energy used in between the brake events by the engine, was plotted using a log scale for the x axis in Figure 5.16.

5.8.5 Results for the Concepts for brake energy accumulation

Concept C1

In this concept energy storage systems, ESS, with power limits between 20 kW to 500 kW and energy limits between 500 kJ to 15000 kJ were considered with the assumption that the ESS is empty before each brake event starts. Figure 5.17 shows percentage of energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit for concept C1 and Kiruna data. The
corresponding results for the haulers at the other customer sites using concept C1 are given in appendix A2.3.

Figure 5.17. Percentage of brake energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit using Concept C1 for the A40F hauler, Kiruna.

The scale for the z-axis is confidential and is removed from figure 5.17. The corresponding results for the haulers at the other customer sites using concept C1 are given in appendix A2.3.

Concept C2

In this concept energy storage systems, ESS, with power limits between 20 kW to 500 kW and energy limits between 500 kJ to 15000 kJ were considered. In this case no simplifying and limiting assumptions were made. Thus, if the brake energy in the ESS is not completely consumed between brake events it will be included in the energy accumulation calculation during brake events. Figure 5.18 shows a surface plot for the
percentage of brake energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit for the Kiruna site using concept C2.

![Graph](image)

**Figure 5.18. Percentage of brake energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit using concept C2 for the A40F hauler, Kiruna.**

The corresponding results for the haulers at the other customer sites using concept C2 are given in appendix A2.4. In figure 5.18 the scale of the z-axis has been removed, it is confidential.

**Percentage Error in Concept C1**

Using the assumption that the ESS is empty before each brake event starts introduce errors and the calculated Percentage of brake energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit may differ from the actual value. The error is given by $E_{LT(n)} - BE_{A(n)}$. Figure 5.19 shows the percentage error for the
calculated brake energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit for the Kiruna site when concept C1 is used instead of concept C2. The errors obtained were highest for low energy limits and very high power limits.

**Figure 5.19.** Percentage of error for the calculated Percentage of brake energy that can be accumulated as a function of brake power generation limit and brake energy accumulation limit using concept C1 for the A40F hauler, (Kiruna).

Concept C1 results in high errors for high peak power limits and low energy accumulation limits. From the figure 5.19 it can be observed that errors involved using concept C1 may be neglected for a range of power limits and energy accumulation limits that are described in table 5.1. Thus, the concept C1 may be considered for data logging.

The corresponding error results for the haulers at the other customer sites using concept C1 are given in appendix A2.5. The error in using concept C1 for the other sites basically displays a similar error pattern as the Kiruna site.
6  Accuracy in results

6.1  Errors in measurements

In the initial study of the measured and recorded signals from the different haulers at the different sites errors were found in them. Each single measurement from respective site was studied in detail for possible errors. In a normal measurement the signals would appear in a manner shown in Figure 6.1

![Figure 6.1. Measured and recorded signals that are considered to be without errors.](image)

A typical error found in the signals was high level spikes with short time duration. In Figure 6.2 error spikes in the measured signals are illustrated. In the figure it can be seen that there are three high peaks in engine rpm signal, and for both the brake pressure signals the spikes appears at different times as compared to the rpm signal.
However, for the vehicle speed signal the signal spikes appears at the same time as for the both brake pressure signals. Another error case is when a signal's level is high and constant for short or long interval, and may continue for entire measurement. Figure 6.3 shows examples of incorrect signals with high and constant level throughout the measurements.

This type of error appears when the CAN bus provide a signal that not represents a valid sensor signal. Such error may appear with different time duration and may appear at different times.

Figure 6.2. Measured signals with short interval spike errors.
Figure 6.3. Incorrect signals with constant level.

6.2 Error removal

Before the calculations of brake power, brake energy, engine power and engine energy were made the errors were removed from the measurement and recorded data. A MATLAB program was developed and implemented for removal of errors in all recorded signals. To detect and remove spike errors in the recorded signals by the MATLAB program the following procedure was used.

If either of the below conditions is true the data samples for the time segments where the “true” condition is valid will be removed from the six measured signals.
“Or” conditions for removing remove spike errors:

- |Engine percentage torque| > 250 %
- |Engine Retarder percentage torque| > 100 %
- |Brake pressure front axle| > 20000 kPa
- |Brake pressure rear axle| > 20000 kPa
- |Vehicle speed| > 100 km/h
- |Engine rpm signal| > 5000 rpm

Figure 6.4 illustrates the removal of spike errors from the engine rpm signal.

![Figure 6.4. Example: Spike error removal from engine rpm signal.](image)

The data samples having errors were removed from the entire measurements by using the conditions described above. In the same way the errors in the other signals were also removed and the calculations concerning the feasibility of an Energy Storage System for recovery of
kinetic energy from a hauler were carried out subsequently. In some of the measurements one of the signals was zero but the other signals were carrying information, in such cases the measured data were discarded.

6.3 Error Propagation

In addition to the extreme errors described above, random errors in the signals have to be considered since a measurement cannot be carried out with 100% accuracy. So before analysis method was worked upon a uniform distribution of ±10% error was assumed in engine percentage torque, engine retarder torque and brake pressure signals. The ±10% error means that the true value of the signal lies in the range of -10% and +10% of the signal value.

In vehicle speed and engine rpm signal ±2% error was assumed with uniform distribution which is quite less as compared to ±10%. Here also the ±2% error means that the true value of the signal lies in the range of -2% and +2% of the signal value. Propagation of these uncertainties needs to be studied in term of addition, subtraction, multiplication and division.

Addition and Subtraction

In a general calculation that involves pure addition, where measured quantities with respective uncertainty are \(x \pm \delta_x\) and \(y \pm \delta_y\). Here \(\delta_x\) and \(\delta_y\) are the real and positive uncertainties for the measured quantities \(x\) and \(y\). If the measured quantities \(x\) and \(y\) are added, \(f = x + y\) we get that

\[
f = (x + y) \pm (\delta_x + \delta_y)
\]

This implies a possible error in addition of \(\delta_f = (\delta_x + \delta_y)\), and a similar analysis for the case subtraction measured quantities will give an identical result. So basic rule applies for propagation of error in addition and subtraction is that the absolute error in result is the sum of absolute uncertainties of quantities used in calculations [4].
**Multiplication by a Constant Coefficient**

If a calculation of form \( f = ax + y \) is supposed, where \( a \) is a positive real constant, \( \delta_f \) will result in the uncertainty

\[ \delta_f = a \delta_x + \delta_y \]

**Multiplication and Division**

If the product of two measured quantities, \( f \pm \delta_f = (x \pm \delta_x) \times (y \pm \delta_y) \) is considered, the extreme values of \( f \) that can be obtained are:

\[ f_{\text{max}} = (x + \delta_x) \times (y + \delta_y) = xy + x\delta_y + y\delta_x + \delta_x\delta_y \]

And

\[ f_{\text{min}} = (x - \delta_x) \times (y - \delta_y) = xy - x\delta_y - y\delta_x + \delta_x\delta_y \]

Since the uncertainties are assumed to be small fraction of the measured quantities, the term \( \delta_x\delta_y \) is substantially smaller as compared to the other terms in the equations above and may be neglected and it will result in the uncertainty:

\[ \delta_f = x\delta_y + y\delta_x \]

Divide by \( f \)

\[ \frac{\delta_f}{f} = \frac{x\delta_y}{f} + \frac{y\delta_x}{f} = \frac{x\delta_y}{xy} + \frac{y\delta_x}{xy} \]

\[ \frac{\delta_f}{f} = \frac{\delta_y}{y} + \frac{\delta_x}{x} \]

This shows that the sum of relative errors in measured quantities is the relative error in the result.

If the quotient between two measured quantities, \( f \pm \delta_f = (x \pm \delta_x) \div (y \pm \delta_y) \) is considered, the extreme values of \( f \) that can be obtained are:

\[ f_{\text{max}} = (f + \delta_f) = (x + \delta_x) \div (y - \delta_y) \]
And
\[ f_{\text{min}} = (f - \delta_f) = (x - \delta_x) + (y + \delta_y) \]

These equations may be rewritten as
\[
\begin{align*}
(x + \delta_x) &= (f + \delta_f)(y - \delta_y) = fy - f\delta_y + y\delta_f = x - f\delta_y + y\delta_f \\
(x - \delta_x) &= (f - \delta_f)(y + \delta_y) = fy + f\delta_x - y\delta_f = x + f\delta_y - y\delta_f 
\end{align*}
\]

Where \( \delta_f \delta_y \) has been neglected. Thus, resulting in
\[
\delta_x = y\delta_f - f\delta_y
\]

which may be rewritten as
\[
\delta_f = \frac{\delta_x}{y} + f\delta_y
\]

Dividing by \( f \) gives
\[
\frac{\delta_f}{f} = \frac{\delta_x}{x} + \frac{\delta_y}{y}
\]

This gives a similar result as in the case of multiplication. Hence, for multiplication or division the relative error in the product or quotient is given by the sum of the relative uncertainties in the quantities used in calculation.

With combination of rule for addition, subtraction, multiplication and division it can be said that extreme uncertainty for energy could be \( \pm 12\% \) since it involves multiplication of two signals with one signal having error \( \pm 10\% \) and other \( \pm 2\% \). This means, that the relative error of \( \pm 12\% \) is the sum of relative errors of \( \pm 10\% \) and \( \pm 2\% \) during multiplication. Since a large number of measurements were carried out at each site, a general approach was followed by using functions \( \xi_1(n) \) and \( \xi_2(n) \) in MATLAB for studying the error propagation. The functions \( \xi_1(n) \) and \( \xi_2(n) \) are given by:

\[
\xi_1(n) = 1 + \frac{x(n) - 0.5}{5} \quad (6.1)
\]
With its value ranging \(0.9000 \leq \xi_1 \leq 1.1000\)

\[
\xi_2(n) = 1 + \frac{X(n)-0.5}{25} \tag{6.2}
\]

With its value ranging \(0.9800 \leq \xi_2 \leq 1.02\)

Here \(X(n)\) in Eq. 6.1 and 6.2 is a MATLAB function rand. The functions \(\xi_1(n)\) and \(\xi_2(n)\) create uniformly distributed random processes.

Both functions are multiplied with the engine energy signal \((EE(n))\) to get the engine energy signal with an artificial random error \((EE_{\text{Error}}(n))\) given by equation 6.3 as

\[
EE_{\text{Error}}(n) = EE(n) \times \xi_1(n) \times \xi_2(n) \tag{6.3}
\]

Similarly with front axle brake energy \((BE_{FA}(n))\), rear axle brake energy \((BE_{RA}(n))\) and retarder brake energy \((BE_{\text{Retarder}}(n))\) signals the functions \(\xi_1(n)\) and \(\xi_2(n)\) were multiplied to get front axle \((BE_{FA(\text{Error}}(n))\), rear axle \((BE_{RA(\text{Error}}(n))\) and retarder brake energy \((BE_{\text{Retarder(\text{Error}}(n))\) signals with an artificial error respectively by equations 6.4, 6.5 and 6.6 as:

\[
BE_{FA(\text{Error}}(n) = BE_{FA}(n) \times \xi_1(n) \times \xi_2(n) \tag{6.4}
\]

\[
BE_{RA(\text{Error}}(n) = BE_{RA}(n) \times \xi_1(n) \times \xi_2(n) \tag{6.5}
\]

\[
BE_{\text{Retarder}(\text{Error}}(n) = BE_{\text{Retarder}}(n) \times \xi_1(n) \times \xi_2(n) \tag{6.6}
\]

The brake energy signals with an artificial random obtained by equations 6.4, 6.5 and 6.6 were added to get a total brake energy signal with artificial random error by equation 6.7 as:

\[
BE_{\text{Total}(\text{Error}}(n) = BE_{FA(\text{Error}}(n) + BE_{FA(\text{Error}}(n) + BE_{\text{Retarder}(\text{Error}}(n) \tag{6.7}
\]

When the quantities independent of each other with uniform distribution are added in Eq. 6.7, they approach to normal distribution (by Central limit theorem). According to the Central limit theorem, if sufficiently
large numbers of independent and identically distributed random variables are added under general conditions, their sum approximates to normal distribution [5].

The percentage of total brake energy available with artificial random error ($%BE_{Error}$) will be given by equation 6.8 as:

$$%BE_{Error} = \frac{\sum_{n=1}^{N} BE_{Total(Error)}(n)}{\sum_{n=1}^{N-1} EE_{Error}(n)} \times 100$$

A normal probability plot for $%BE_{Error}$ was plotted for each customer site. Figure 6.5 shows the normal probability plot for $%BE_{Error}$ for data collected by A40F hauler used at the Kiruna site. In figure 6.5 it can be observed that the plot for percentage brake energy is linear between values of 12.5% – 14.9%, so these two values can be stated as extreme lowest and maximum true values for percentage brake energy with mean value for percentage brake energy as 13.7%.

![Figure 6.5. Normal Probability Plot for Percentage of Total Brake Energy available with artificial error in the case of A40F (Kiruna)](image_url)
Normal probability plots for percentage of total brake energy available with artificial random error for rest of the customer sites can be seen in appendix A2.6.
7 Implementation

After the development of the analysis method in the form of a MATLAB script, log proposals were made to implement the analysis method in the M-LOG measurement system. In total five different proposals were made to implement the analysis method in measurement system: total brake energy, peak power during brake events, brake energy during brake events, engine energy in between brake events and Total brake energy during brake events with power limits of 30, 60, 120 (kW). Table 7.1 highlights the proposals made and the different inputs required and desired outputs.

Table 7.1. Log proposals

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Proposal Name</th>
<th>Inputs Required</th>
<th>Desired Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Total Brake Energy</td>
<td>1. All the equations mentioned in section 5.2.</td>
<td>1. Brake energy in front axle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Brake energy in rear axle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. Brake energy in retarder</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4. Engine Energy</td>
</tr>
<tr>
<td>2.</td>
<td>Peak Power during brake events</td>
<td>1. Calculation of start and end points for each brake event</td>
<td>2-D histograms of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Peak Power front axle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Peak Power rear axle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. Peak Power retarder</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(All results vs. Number of brake events)</td>
</tr>
<tr>
<td>3.</td>
<td>Brake Energy during brake events</td>
<td>1. Entire procedure explained in section 5.5.</td>
<td>2-D histograms of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Brake Energy front axle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Brake Energy rear axle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. Brake Energy</td>
</tr>
</tbody>
</table>
For all the proposals; the main input requirement was to remove the error from the input signals before performing any calculations. The methods given in section 6.2 were used to remove error in input signals in all the proposals. Also, for the brake pressure in front and rear axle another condition was added, i.e. when the brake pressure goes below 65 kPa the brake pressure values were set to zero in advance of all the calculations. These two input conditions were common for each proposal.

For the first proposal all the calculations given in section 5.2 were used to estimate engine energy, brake energy from retarder, front and rear axle. In the second proposal the brake events were defined and start and end points for brake events were used to find peak power as discussed in section 5.4. In third proposal the brake energy during the brake events in all sub-systems was calculated using the methods presented in section 5.5. In the fourth proposal the engine energy used in between the brake events was calculated using the methods given in section 5.6. In the fifth proposal, the brake energy with limits applied on the total power from all sub-systems was calculated using the methods given in section 5.7 up to
equation 5.18. Application of the limits for the energy storages is considered as post-processing and thus will be carried out subsequent on the data processed by the measurement system with our methods implemented. This will reduce the computations as the calculations for the total brake energy with energy limits are required.

The required output from the first proposal was the total engine energy and total brake energy from all subsystems. But for rest of the proposals the output required was in the form of 2-D histograms, with number of brake events on one axis and required parameter on other axis. In histograms data was supposed to be stored in bins, with number of bins and width of each bin was set according to 5% acceptable error. Number of bins and width of bins were mentioned in each proposal by using the data from customer for each hauler respectively.

The output in form of 2-D histograms would consume less space for storage. Two separate test runs were made to implement the analysis method as suggested in log proposals. An A35F hauler was used at Målajord PT Update test track to get the two test run measurements. Sampling Frequency of 100 Hz was used for data collection.

First test run was made to check the correct implementation of the first log proposal. New signals for total engine energy and total brake energy for all the braking subsystems were measured. The input signals used were also measured and calculations were repeated in the MATLAB script. Results from Figure 7.1 reveals that the values for the measured percentage brake energy were slightly different compared to the calculated percentage brake energy. The calculated retarder brake energy was slightly more than the measured value for retarder brake energy. This difference occurred due to slight change in sampling frequency of the data when it was converted into .mat format in the software ncode GlyphWorks. It was observed that the GlyphWorks interprets the sampling frequency of 100 Hz as 100.000033 Hz. For the case of front and rear axle the difference was very small for the measured and calculated values of percentage of total brake energy. In total the results were acceptable.
Second test run was made to implement the remaining four proposals of analysis method because the output for all these proposals was required in form of histograms. Number of bins and bin width were mentioned in proposals after checking for 5% error from customer data. But while receiving output from second test run for proposal second to fifth, measurement system was unable to provide it in form of 2-D histograms directly. So the results were saved in Microsoft Excel Worksheets and then histograms were plotted from excel data. Calculations were repeated in MATLAB script and then histograms were plotted to compare the results with the measured results from proposals (second to fifth).
For peak power during brake events, results can be seen in Figure 7.2, 7.3 and 7.4.

**Figure 7.2.** Measured and calculated peak brake power for the front axle during brake events.

**Figure 7.3.** Measured and calculated peak brake power for the rear axle during brake events.
Figure 7.4. Measured and calculated peak brake power for the retarder during brake events.

The comparison results for measured and calculated values of brake energy during brake events, engine energy in between the brake events and total brake energy during the brake events obtained by having cutoff limits of 30, 60 and 120 kW can be seen in Appendix A4.

For all the results, in the bins with low values there were some differences between measured and calculated values. The differences were caused by the software “nCode GlyphWorks”, when the data was converted into .mat format in this software the sampling frequency was read as 100.00033 Hz instead of 100 Hz. But the difference was caused at bins for lower values and the bins with higher values gave exactly similar results for measured and calculated values. So the measured results were more accurate than the calculated results due to slight change in sampling frequency.
8 Conclusions

By analyzing the results produced by the implementation of the analysis method following conclusions can be drawn:

The developed analysis method enables the energy usage in articulated haulers to be mapped. The method can be used for all the different models of the F-generation haulers at any work site. The implementation of the analysis method in the M-LOG measurement system was successful; however, further work has to be carried out in order to get the results in the form of 2-D histograms from the measurement system.

The results concerning the percentage brake energy for the different customer sites indicate that at one of the sites, the Kiruna site, the level of brake energy might motivate the usage of brake energy recovery systems (see Figure 5.3).

The main reason for having a high percentage of brake energy produced by the hauler at the Kiruna site is probably because of the very hilly driving conditions and high loads during the working cycle there. For the other customer sites the brake energy did not reach a level motivating brake energy recovery, although there were cases with very high peak brake power at Jaro site which may be related to aggressive driving.

The analysis method can also be used to analyze how the machines are used by the customers. In case of machines used at the Jaro site, there are some parts which are hilly but not sufficient to provide adequate level of brake energy. In U.A.E. the driving conditions were predominantly flat which even restricted the usage of retarder.

It can be concluded that availability of the brake energy for reuse is mostly dependent upon topographical conditions from hilly to very hilly. With the help of GTA parameters in future it would be possible to analyze the potential availability of brake energy for reuse for a site.
9 Future work

During the work with this thesis project a number of studies that may be carried out subsequent were identified. For instance, a further development of the software we developed within the project to enable 2-D histogram presentation of results. This is probably not difficult to solve but may be time consuming.

The problem of change in sampling frequency discovered in software “nCode GlyphWorks” during data conversion in .mat format, should be solved to increase the accuracy of the calculated results for the implementation of the analysis method.

It might also be of importance to record more data regarding the brake energy at the customer sites to obtain a greater understanding on the reasons for the variations in brake usage. Also the influence of variations in GTA parameters on brake energy can be studied.

Energy usage in the subsystems that were not considered in the present project might also be of interest to study during work cycles. Such subsystems are for instance hydraulics, pumps, and fans etc. which consume energy from the engine.

Furthermore, possible technologies for the accumulation of energy need to be considered. Possible technologies might be; flywheels, batteries, electrical hybrids, ultra capacitors or accumulators (hydraulic/pneumatic).

A similar kind of energy recovery analysis method could be developed for other machines developed by Volvo Group for which aspects other than brake energy may be interesting to study.

It is a recommendation from the authors of this thesis work to Volvo CE, to standardize the names for the signals collected in the data in order to enable transparency between different machines in the Volvo CE product line concerning the application of the developed analysis method. Also
for the units of the parameters standardization would be beneficial to avoid confusions in understanding units for the signals in a collected data.
10 References


11 Appendix

11.1 Appendix A1

Table 11.1. GTA parameters for test tracks.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Demo track</th>
<th>Camel humps</th>
<th>Braås 2</th>
<th>Comfort track</th>
<th>PT update</th>
<th>Målajord Off road</th>
<th>Målajord Fuel Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling resistance</td>
<td>5</td>
<td>5</td>
<td>40</td>
<td>2</td>
<td>5</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>Topography</td>
<td>Hilly</td>
<td>Very Hilly</td>
<td>Flat</td>
<td>Flat</td>
<td>Hilly</td>
<td>Very Hilly</td>
<td>Predominantly Flat</td>
</tr>
<tr>
<td>Coefficient of traction</td>
<td>0.4 – 0.6</td>
<td>0.4 – 0.6</td>
<td>0.1 – 0.4</td>
<td>0.8</td>
<td>0.4 – 0.6</td>
<td>0.1 – 0.4</td>
<td>0.4 – 0.6</td>
</tr>
<tr>
<td>Road condition</td>
<td>Rough</td>
<td>Rough</td>
<td>Cross Country</td>
<td>Very Rough</td>
<td>Rough</td>
<td>Cross Country</td>
<td>Rough</td>
</tr>
</tbody>
</table>

Table 11.2. Multiplication factors for different machine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A25F</th>
<th>A30F</th>
<th>A35F</th>
<th>A40F/A40F FS</th>
<th>A35F FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$MF_{ET}$</td>
<td>2000</td>
<td>2080</td>
<td>2619</td>
<td>2763</td>
<td>2575</td>
</tr>
<tr>
<td>$MF_{RT}$</td>
<td>1280</td>
<td>1280</td>
<td>1000</td>
<td>1000</td>
<td>1300</td>
</tr>
<tr>
<td>$MF_{BTF}A$</td>
<td>40.45</td>
<td>40.45</td>
<td>66.34</td>
<td>66.34</td>
<td>66.34</td>
</tr>
<tr>
<td>$MF_{BTBFA}$</td>
<td>24.27</td>
<td>32.36</td>
<td>33.17</td>
<td>44.22</td>
<td>33.17</td>
</tr>
<tr>
<td>$MF_{BTBRA}$</td>
<td>24.7</td>
<td>24.27</td>
<td>33.17</td>
<td>44.22</td>
<td>33.17</td>
</tr>
<tr>
<td>$R (m)$</td>
<td>0.770</td>
<td>0.770</td>
<td>0.830</td>
<td>0.890</td>
<td>0.830</td>
</tr>
</tbody>
</table>
11.2 Appendix A2

A2.1

Figure 11.1. Percentage of peak brake power generated by rear axle during percentage brake events.

Figure 11.2. Percentage of peak brake power generated by retarder during percentage brake events.
A2.2

Figure 11.3. Percentage of brake energy generated by front axle during percentage brake events.

Figure 11.4. Percentage of brake energy generated by rear axle during percentage brake events.
Figure 11.5. Percentage of brake energy generated by retarder during percentage brake events.

A2.3

Figure 11.6. Percentage of brake energy that can be accumulated using Concept C1 in case of A25F (Jaro).
Figure 11.7. Percentage of brake energy that can be accumulated using Concept C1 in case of A30F (Jaro).

Figure 11.8. Percentage of brake energy that can be accumulated using Concept C1 in case of A35F (Jaro).
Figure 11.9. Percentage of brake energy that can be accumulated using Concept C1 in case of A35F (U.A.E.).

A2.4

Figure 11.10. Percentage of brake energy that can be accumulated using Concept C2 in case of A25F (Jaro).
Figure 11.11. Percentage of brake energy that can be accumulated using Concept C2 in case of A30F (Jaro).

Figure 11.12. Percentage of brake energy that can be accumulated using Concept C2 in case of A35F (Jaro).
Figure 11.13. Percentage of brake energy that can be accumulated using Concept C2 in case of A35F (U.A.E.).

A2.5

Figure 11.14. Percentage of error involved in usage of concept C1 in case of A25F (Jaro).
Figure 11.15. Percentage of error involved in usage of concept C1 in case of A30F (Jaro).

Figure 11.16. Percentage of error involved in usage of concept C1 in case of A35F (Jaro).
Figure 11.17. Percentage of error involved in usage of concept C1 in case of A35F (U.A.E.).

Figure 11.18. Normal Probability Plot for Percentage of Total Brake Energy available with artificial error in the case of A25F (Jaro).
Figure 11.19. Normal Probability Plot for Percentage of Total Brake Energy available with artificial error in the case of A30F (Jaro).

Figure 11.20. Normal Probability Plot for Percentage of Total Brake Energy available with artificial error in the case of A35F (Jaro).
Figure 11.21. Normal Probability Plot for Percentage of Total Brake Energy available with artificial error in the case of A35F (U.A.E.).
11.3 Appendix A3

Figure 11.22. Percentage of brake energy available for reuse at test tracks.

11.4 Appendix A4

Figure 11.23. Measured and calculated brake energy for the front axle during brake events.
Figure 11.24. Measured and calculated brake energy for the rear axle during brake events.

Figure 11.25. Measured and calculated brake energy for the retarder during brake events.
Figure 11.26. Measured and calculated engine energy during events in between the brake events.

Figure 11.27. Measured and calculated brake energy (power limits 30kW) during brake events.
Figure 11.28. Measured and calculated brake energy (power limits 60kW) during brake events.

Figure 11.29. Measured and calculated brake energy (power limits 120kW) during brake events.