Monitoring energy efficiency of heavy haul freight trains with energy meter data

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Abstract

In this MSc thesis, it is investigated what parameters are relevant for describing energy consumption of heavy haul freight trains and how these can be used to develop key performance indicators (KPIs) for energy efficiency. The possible set of KPI is bounded by data available from energy meters used in electric IORE class locomotives hauling iron ore trains in northern Sweden. Furthermore, the analysis is only concerned with energy efficiency at the rolling stock level, excluding losses in the electric power supply network.

Based on a literature study, parameters of interest describing driver, operations and rolling stock energy efficiency have been identified. By means of simulation, a parametric study is performed, simulating a 30 ton axle load iron ore train with 68 wagons. Train modelling input is obtained from technical documentation or estimated through measurements and statistical analysis. A multi-particle representation of the train is used to calculate gradient resistance for the simulation, which is also applied to determine the curve resistance.

Results show that the motion resistance is simulated quite accurately, while the lack of a driver model in the simulation tool leads to overestimation of energy consumption. Taking this into account, the importance of the driver for energy efficiency can still clearly be showcased in the parametric study. Especially on long steep downhill sections, prioritising the electric brakes over mechanical brakes is demonstrated to have a huge influence on net energy consumption, as has the amount of coasting applied. With the same driver behaviour in all simulations, the savings in specific energy from increasing axle load to 32.5 tons is estimated. Moreover, a comparison of increased train length and axle load points towards higher savings for the latter.

In the end, parametric study results are used to recommend a structure for a monitoring system of energy efficiency based on a set of KPIs. With a sufficiently high sampling rate of energy meter data, it is adequate for calculating driver related KPIs and some additional KPIs. More KPIs can be tracked with access to additional data, e.g. cargo load.

Keywords

Energy consumption, Energy meter, Energy monitoring, Heavy haul freight train, Key performance indicator, Multi-particle model, Simulation
Sammanfattning

I detta examensarbete undersöks vilka parametrar som är relevanta för att beskriva energiförbrukning för tunga godståg och hur dessa kan nyttjas för att utveckla nyckeltal för energieffektivitet. Antalet möjliga nyckeltal avgränsas till sådana som kan beräknas med data från elmätare som används i elektriska littera IORE lok som drar tunga malmtåg i norra Sverige. Vidare så tar analysen endast hänsyn till energieffektivitet för rullande materiel, vilket utesluter förluster i elektriska kraftmatningsnätet.


Nyckelord

Energiförbrukning, Elmätare, Energiuppföljning, Tungt godståg, Nyckeltal, Flerpartikelmodell, Simulering
Zusammenfassung


Letztlich wurden die Resultate der Parameterstudie genutzt, um die Struktur eines Überwachungssystems für Energieeffizienz zu empfehlen, basierend auf einer Auswahl an Schlüsselindikatoren. Ausreichend hohe Messfrequenz der Energiezählerdaten ist genügend, um einige Schlüsselindikatoren zu ermitteln. Mit zusätzlichen Datenquellen können weitere Indikatoren berechnet werden.

Schlüsselwörter

Energieverbrauch, Energiezähler, Energieüberwachung, Schwerer Güterzug, Schlüsselindikator, Multi-Partikel-Modell, Simulation
Preface

Back when I started my studies at KTH with a Bachelor in Mechanical Engineering, I was not sure of what Master to choose later. I had an interest in aviation, but considering the climate change and impact aviation can have on it, any Master related to aviation did not feel right to me. Once the time had finally come when I had to make my choice of Master, the decision was not easy but after a tip from a fellow student I pursued a Master’s Degree in Rail Vehicle Engineering. Initially starting with basically zero knowledge of railways and no real expectations, today I have become a huge fan of railways, their complexity and strongly believe they are part of a sustainable future, considering how green, fast and safe this mode of transport can be. All in all, looking back, I couldn’t be happier with the choice of Master programme I made, so thank you fellow student for the tip back then!

This thesis marks the end of my studies at KTH and so I want to thank everyone that accompanied me along the way and helped me successfully finishing my studies and this thesis. Special thanks go to:

Christoph Domay, my supervisor at LKAB, for his efforts to support me as quickly as possible at all times, all interesting discussions and for having given me the chance to drive the, as of today, world’s strongest locomotive myself.

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The company Transrail, for providing coefficients of the Davis equation, which have been very important in this thesis.

The teachers and staff at the KTH Railway Group, for having given us students an engaging, interesting and useful education.

My parents, for all their love and support throughout my studies.

Stockholm, July 2021
Philipp Geiberger
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<th>Description</th>
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<tbody>
<tr>
<td>ATC</td>
<td>Automatic Train Control</td>
</tr>
<tr>
<td>DAS</td>
<td>Driver Advisory System</td>
</tr>
<tr>
<td>EETC</td>
<td>Energy Efficient Train Control (driving strategy)</td>
</tr>
<tr>
<td>ERTMS</td>
<td>European Rail Traffic Management System</td>
</tr>
<tr>
<td>Fanoo</td>
<td>Class of iron ore wagons used by LKAB</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>IORE</td>
<td>Class of electric freight locomotives used by LKAB</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>KTH</td>
<td>KTH Royal Institute of Technology</td>
</tr>
<tr>
<td>LKAB</td>
<td>Luossavaara-Kiirunavaara Limited Company</td>
</tr>
<tr>
<td>MC</td>
<td>Maximum Coasting (driving strategy)</td>
</tr>
<tr>
<td>MTTC</td>
<td>Minimum Time Train Control (driving strategy)</td>
</tr>
<tr>
<td>RMS</td>
<td>Reduced Maximum Speed (driving strategy)</td>
</tr>
<tr>
<td>STAX</td>
<td>Maximum Axle Load Limit (Swedish abbreviation)</td>
</tr>
<tr>
<td>STEC</td>
<td>Simulation of Train Energy Consumption (simulation tool)</td>
</tr>
<tr>
<td>Wh</td>
<td>Watt-hour</td>
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Chapter 1

Introduction

Due to climate change and air pollution problems in densely populated areas, there has in recent years been a strong driving force within the transport sector to reduce emissions. One way of achieving this is by increasing the energy efficiency within the system.

From an energy point of view, rail transport has several advantages compared to other modes of transport that makes it highly energy efficient. Firstly, the fact that trains run with smooth, hard wheels on smooth, hard rails gives a low rolling resistance. Secondly, air drag is reduced by the fact that consecutive vehicles shield each other to at least some extent. Lastly, electric energy supply can be facilitated via a catenary above the tracks, giving no local emissions at the vehicle and allowing for energy recuperation during braking [1].

At the same time, there is still a lot of room for improving the energy efficiency of rail transports. This is especially true for freight trains, that often have an exterior shape that contributes to aerodynamic drag and use low-technology, inefficient rolling stock. Introducing several improvements such as low drag freight wagons, eco-driving and energy recovery is estimated to give energy consumption reductions of between 40-45% by 2050 [1].

The single, most effective means of reducing energy consumption, both from an emission and cost point of view, is in [1] pointed out to be the introduction of heavier freight trains. This approach is being exercised by the company LKAB, which is transporting iron ore from several mines in northern Sweden to the harbours in Narvik and Luleå using heavy haul freight trains. In this thesis, the energy consumption of these train operations is analysed.
1.1 Background

LKAB is a mining and mineral company that is excavating and processing iron ore at several mines in the north of Sweden, located in Kiruna, Malmberget and Svappavaara. The processed iron ore is transported from the mines to the harbours of Luleå and Narvik by heavy haul trains and some is shipped onward via boat to customers.

For the rail transports, LKAB’s own trains use the Malmbanan, which is an electrified railway stretching all the way from Riksgränsen at the border to Norway to Luleå in Sweden via Kiruna and Gällivare (close to Malmberget), see Figure 1.1. In Norway, Ofotbanen is used, running from Narvik to Riksgränsen at the border of Sweden. Due to the mountainous topography and harsh winter climate along these railways, the trains running there have to overcome a lot of resistance due to steep gradients (up to 1.7%), tight curves and tunnels respectively snow protection galleries around the track. Moreover, the fact that the railways are single track means the capacity for running multiple trains at the same time is limited.

Figure 1.1 – Overview of the railways used by LKAB: Ofotbanen in Norway (dark blue) and Malmbanan in Sweden (light blue). Source: LKAB Logistics
Due to limited line capacity, LKAB has optimised their rail transports towards carrying as much ore per train as possible, i.e. heavy haul trains. Today, LKAB runs trains with an overall length of 750 m, which is the limit the infrastructure allows for on the railways [2]. Also, the maximum allowed axle load limit (STAX) is the highest in Europe at 30 tons. Right now, the railways are in the process of being upgraded to the even higher STAX of 32.5 tons [3].

With complete trains weighing up to 8520 tons at STAX 30 tons, the amount of energy needed for propelling the trains is very high, especially considering the resistance from steep gradients, tight curves and tunnels the trains need to overcome. Approximately 15 trains per day are operated from the mines to the harbours. This results in enormous amounts of consumed energy, e.g. in 2019 LKAB required 84 GWh for all rolling stock in the train operations [4].

Energy consumption is measured in the traction units, i.e. the locomotives, using energy meters. These are owned by the Swedish infrastructure manager Trafikverket and record several parameters such as speed, position, consumed energy and regenerated energy. Every 5 min, accumulated energy consumption is sampled together with all other parameters and saved to an internal memory. Regularly, the data from the memory is then uploaded to a server using mobile network and forms the basis for Trafikverket’s billing of consumed energy [5].

Even though the energy meter data is available to LKAB via a web application of the energy meter supplier, there is as of today no regular monitoring and evaluation of the rolling stock performance from an energy point of view. Instead, energy performance has only been investigated in a few specific cases. The reason regular monitoring and evaluation is desirable is due to that it would make it possible to identify possible areas for energy/cost savings and monitor deviations from expected performance. Also, analysing consequences and verifying effects of operational or technical changes is enabled.

Therefore, a highly automated energy monitoring and performance follow-up is aimed for. But before such a system can be implemented, it is first necessary to attain sufficient knowledge about relevant values and conditions upon which the energy performance can be evaluated, which LKAB does not have today. In this thesis, it is investigated what parameters are relevant for describing energy consumption of heavy haul freight trains and how these can be used to develop key performance indicators (KPIs) for energy efficiency.
1.2 Purpose

This thesis has several purposes. The overall purposes can be formulated as increasing knowledge about the relationship between operational and technical parameters and the energy consumption of heavy haul freight trains. The overall purpose can then be broken down to three main purposes.

Firstly, the purpose of the work within the scope of this thesis can be seen from the perspective of the host company LKAB. For LKAB, the knowledge gained from this thesis is supposed to form a basis for being able to define the basic structure and functionality of a data tool that automatically and continuously can monitor and evaluate the energy consumption of the rolling stock. Looking even further ahead, the ultimate purpose of the data tool and interest of LKAB lays in being able to monitor energy efficiency performance of the rail transports continuously and increase the efficiency. As part of the results of this thesis, it is expected to be possible to already now give some recommendations towards how the energy efficiency of train operations at LKAB can be increased. Thus, this thesis work can contribute directly to the ultimate purpose of the work with energy monitoring at LKAB, though the work of this thesis has a more particular purpose.

All analysis done in this thesis is quite specific in the sense that it is tailored towards characteristics of operations and rolling stock of LKAB. Still, the work has a purpose for the general freight railway industry and research within that field too, since the operations and rolling stock of LKAB form a very typical case of heavy haul. As described in the beginning of this chapter, introducing heavy haul is desirable to reduce energy consumption of freight trains. Thus, through the activities of this thesis, it is possible to obtain a better understanding of the influence of several characteristic parameters, such as axle load, on heavy haul operation energy efficiency respectively reassure the findings of previous research. In the long term, with the help of these parameters, it could become easier to monitor energy performance, for both freight train operators and infrastructure owners, when introducing heavy haul.

Finally, this thesis also serves the purpose of demonstrating the author’s ability to work within the fields of engineering and academic research. By reaching goals set up to achieve the overall purpose of this thesis, the author is able to reinforce knowledge gained during the academic education and attain new skills useful for future work within the field of rail vehicle engineering.
1.3 Goals

To fulfil the purposes of this thesis, a number of goals have been defined that describe the steps required towards achieving the purposes. These goals can be summed up as follows:

- Give a proper review of previous research and findings within the relevant fields of study of this thesis
- Development of a simulation model that predicts energy consumption to a satisfactory extent
- Definition and validation of relevant values for analysis and KPIs for monitoring of the energy consumption
- Providing a summary of parameters significant for describing heavy haul energy consumption and what quantitative influence they have
- Specification of functionality, conditions and input data for an automatic and continuous monitoring of energy consumption
- Give suggestions for improvement of the energy efficiency of LKAB’s operations

Note that the developed simulation model forms the basis for reaching all goals stated thereafter. Hence, it is important that the simulation not only predicts energy consumption to a satisfactory extent, but must also depict the relevant aspects of reality to satisfactory extent, so that effects of all potentially relevant parameters can be studied properly.

While the first two goals serve all purposes of this thesis, the points thereafter are mainly relevant for fulfilling the purpose and interests of the host company. The fourth point, i.e. providing a summary of parameters significant for describing heavy haul energy consumption, is however formulated to cover the interests and purpose of this thesis for the broader perspective of the general freight railway industry and research within that field. By accomplishing all goals stated above, the purpose of demonstrating the authors abilities within the fields of engineering and academic research is also fulfilled.
1.4 Delimitations

The analysis of energy consumption in this thesis will be limited to the operations and rolling stock used by LKAB, i.e. heavy haul freight trains, and also only be concerned with energy consumption at the rolling stock level. This includes the energy transfer from pantograph to the wheels and all other systems of the rolling stock. Losses and limitations in the electric power supply network from well up until and including the catenary and infrastructure-related energy consumption are thus excluded from the analysis. Stabled trains are not considered either, i.e. the analysis is limited to the energy consumption of trains in transit.

While the development of the necessary specifications for calculation of the defined values within a suitable data system for energy monitoring is one goal of this thesis, the implementation of the tool itself is not within the scope of this work. Therefore, such a data system will also not be available during the course of this thesis and so all analysis will have to be performed manually to some extent, which limits the amount of data that can be processed given the time frame of the thesis.

1.5 Structure of the thesis

The following chapters of this report are structured based on the goals stated in this chapter. First, a literature review of current research and findings in the fields of interest for this thesis is given in Chapter 2. Thereafter, based on the insights of the literature review, in Chapter 3 the methodology and process used for the work is developed and described. In the following Chapter 4, the modelling of train and track and their respective input is presented. Chapter 5 finally describes the results obtained from the applied methods and discusses these analytically. In addition, recommendations for improvement of energy efficiency and suitable KPIs for energy monitoring are described here. To sum up the work and its findings, in Chapter 6 a conclusion is given and an outlook for future work is provided.
Chapter 2

Literature review

One essential part in the work of this thesis is to perform academic research. To be able and do this properly, a literature review of previous research and theories in the relevant fields of study for this thesis is required. This serves the purpose of providing a basis of knowledge for developing an appropriate methodology for the following thesis work, taking established methods and theories in the relevant fields of study into consideration.

The findings from the performed literature review are presented in this chapter and the most useful parts for the work of this thesis are summarised at the end. Relevant literature was selected using Google Scholar [6] and the online search tool provided by KTH Library [7]. The choice of what literature is relevant and what fields of research are relevant for this thesis is decided upon mainly from the perspective of LKAB as heavy haul freight train operator. Hence, the number of research papers found during literature search far exceeds the amount of literature finally selected to be included in this review. As a direct consequence of this, the literature review does not cover all research fields within railway energy usage, but mainly only the fields relevant for freight train energy usage and energy simulations of freight trains. Since this thesis will only be concerned with trains powered by electricity via catenary, any trains with alternative sources of power, such as diesel or hydrogen trains, will not be considered.

Still, before getting specific, a more general overview of energy flow in the railway system is first given. Following that, the review is narrowing down to cover freight train energy and potential savings, energy consumption simulation and driving style optimisation for this type of train. Furthermore,
estimation methods for running resistance and some relevant research on key performance indicators are presented, which will be useful for reaching some of the goals set up for the thesis. It is worth mentioning that no previous, internal studies relevant to train energy were found that LKAB has undertaken.

2.1 Energy flow in the railway system

Before one can study how energy can be saved in the operation of railways in general and freight trains especially, one first needs to have an overview of the energy flows in the railway system as a whole and in the rolling stock to understand where losses occur.

Both Douglas et al. [8] and González-Gil et al. [9] provide a good general overview of the energy flow in the railway system, which starts with the infrastructure losses. These occur while electricity is transferred and converted on its way from well to the catenary (or third rail). The energy the trains then receive from the catenary is called traction energy and can be divided up in three main areas. Firstly, there is auxiliary consumption, which not only powers comfort system such as heating, ventilation, air-conditioning (HVAC) but also cooling fans and pumps for the power circuits and brake air compressors. Secondly, drive chain losses while transforming the electric energy into kinetic and potential energy will occur. Auxiliary power for cooling of the traction equipment is in [8] regarded a part of drive chain losses, while in [9] and this review it is handled as part of the first area. The last and biggest share of energy goes into propelling the vehicle, where the train is slowed down in two ways. Motion resistance will constantly dissipate energy, decelerating the train if no traction is applied. In this case, the train is said to be coasting. When a train needs to stop, it can in addition slow down deliberately by dissipating kinetic energy into heat at the mechanical brakes. For some trains, it is also possible to recover kinetic energy into electric energy during regenerative braking instead. This energy can then, if it is not consumed by auxiliaries internally, rejoin the energy flow as it is fed back to the catenary where the energy is picked up by another train that can reuse it as traction energy or rejoins the grid.

Apart from the traction energy, which can be regarded as the energy required to operate the rolling stock, there is also infrastructure-related energy usage. This is called non-traction energy and includes powering signalling system, depots, stations and other equipment along the tracks [9]. As Feng et al. [10] report,
the traction energy commonly is responsible for the majority of total energy cost of the railway system. In [9] an example of the London Underground is provided, where 80% of the total energy consumption is accounted for by traction energy. Therefore, it is not surprising that the literature search showed that a lot of research is centred around increasing efficiency of the different areas of traction energy. This will also be the focus from now on, due to that non-traction energy is outside the scope of this thesis.

2.2 Energy saving potentials for freight trains

Energy savings for traction energy can be achieved through changes to different parts of the railway system, which not only includes changes to the rolling stock but also adaptations of the operations and infrastructure. In the following, the three main areas of traction energy described above will be covered separately, starting with auxiliary energy.

In the literature, most energy saving potentials were found for the part of auxiliary energy related to comfort systems. These include changes to the HVAC unit such as reducing target difference to ambient temperature and adjusting the fresh air intake based on CO\textsubscript{2} levels. To keep the temperature as constant as possible, unnecessary door opening should be avoided and thermal insulation could be improved. Other measures include installing energy efficient lights, recovery of waste heat from the power electronics and a stabling mode that minimises energy needs for the comfort systems [8, 9]. While auxiliary energy use is more substantial for passenger trains where a large interior needs to be climatised for comfort reasons, freight trains usually only have the driver that needs a HVAC and so this unit is dimensioned for the small interior inside the locomotive [11]. The above-mentioned changes will therefore likely only have small influence on the energy consumed. On the other hand, the large installed power in locomotives will generate a lot of waste heat. Increasing the efficiency of the power electronics can hence reduce the cooling required. In the end, the amount of energy used for the auxiliary systems highly depends on the climate the train is operated in, which is rather chilly for most parts of the year on Malmbanan and Ofotbanen.

The next area of traction energy is the drive chain losses. In this category there are both bigger and smaller changes possible. Bigger modifications would include replacing parts of the traction equipment with state of the art, higher efficiency counterparts. For instance, since the traction motors are responsible
for a significant share of losses in an electric locomotive [11], asynchronous traction motors could be replaced by permanent magnet synchronous motors. Easier to implement changes include smart control software for equipment, e.g. optimised motor flux control, and turning off traction groups and cooling equipment when they are not needed [8, 9, 10]. In fact, the locomotives used by LKAB for the iron ore transports are receiving a big modification as part of their ongoing modernisation where the traction inverters are replaced by new ones, which is expected to increase energy efficiency slightly.

Moving on, the area with biggest potential for energy savings is for propelling the vehicle. All kinetic and potential energy that the locomotives of a freight train build up will end up being consumed either by motion resistance or brake losses. Motion resistance in itself can be divided in two main areas, being aerodynamic resistance and rolling resistance between wheels and rails. Aerodynamic (strictly speaking fluid mechanics) resistance can be reduced by limiting the maximum speed the train operates at and by improving the design to reduce aerodynamic drag [8, 10]. Since freight trains in general and heavy haul freight trains especially operate at relatively low speeds, the rolling resistance will be much more important for these. For passenger trains, reducing weight is a major factor for reducing rolling resistance [8, 9, 10]. Since freight trains have a low number of powered axles in relation to the train weight [1], locomotives will rather have a high weight so that the wheel-rail adhesion does not limit the traction force too much. Particularly heavy haul freight trains will always try to maximise the cargo carried on each train, so lowering weight is not an option here. Still, adjusting train length to demand as suggested by [9] and [10] is beneficial for freight trains as much as for passenger trains. To reduce curve resistance, which is substantial for heavy haul trains, running gear with a softer wheelset guidance for new rolling stock can be considered [12].

Of the total traction energy, a significant share is lost due to braking and so a lot of savings can be generated by optimising braking. For doing this, two main approaches can be identified in the literature. Firstly, so called eco-driving principles can be applied, which have as goal to reduce the need of using the brakes at all. To do this, before starting to brake the driver can coast to slow down the train via the motion resistance. Making the decision when to coast is the main challenge for the driver, due to that coasting will always increase the journey time and hence can impact capacity and punctuality of the railway. There are several measures that can support the driver in that decision.
The simplest measure is driver training, more advanced solutions include signboards wayside that indicate optimal locations for initiating coasting and driver advisory systems (DAS), that based on static timetables can calculate an optimal speed profile the driver can follow [8, 9]. These measures can, apart from reducing the amount of braking required, also reduce the energy required to accelerate the train by making use of the track topography and gradient resistance. An even more advanced solution is connected DAS, which communicates with the traffic control centre to receive updates about the current traffic situation and movement authority to calculate a more realistic speed profile. Such a system has been installed on LKAB’s locomotives for some years, but has been removed for some time now. Benefits reported include avoiding unnecessary braking and stops at train crossings, limiting the number of adjustments required for traction power and braking, improved punctuality, reduced vehicle wear and up to 25% energy saving [13]. To avoid driver error through deviation from the optimised speed profile, automatic train operation could be implemented in the long term [8, 9].

Whenever braking cannot be avoided by coasting, the second approach for optimising braking can be applied. The goal is here to recover as much of the kinetic energy that is braked away as possible by braking regenerative as standard instead of mechanically. How much a train can brake in regenerative mode is limited by the infrastructure receptiveness and adhesion. Optimising timetables so that two trains in the same electrical section accelerate and brake at the same time can maximise the exchange of energy. When no other train is available to use the recuperated energy due to low traffic intensity, reversible substations that can feed back the energy into the electric grid are a good option. A last option when reversible substations are not installed would be energy storage systems either on-board the rolling stock, creating potential space and weight issues, or wayside [8, 9]. In order to reduce losses in the actual regeneration process, the deceleration profile could be adjusted to match the properties of the traction system. [9]. Because freight trains only can regenerate energy via the axles of the locomotives, the available adhesion limits the braking force that can be applied in this way. Regenerative braking thus often needs to be supplemented by mechanical braking of the wagons, otherwise the time and distance for deceleration get much longer [1].

As described above, there are a lot of measures that can help driving more energy efficient. To further support energy-saving driving styles, there can also be taken measures in the network design and track alignments that reduce
energy consumption, but due to the scale of these measures, they require a long time for implementation. This includes optimised network design to minimise conflicts, which lead to braking and stops, and track alignments with slopes helping to decelerate and accelerate around stations [8, 10]. A modern signalling system such as the European Rail Traffic Management System (ERTMS) that gives drivers more regular updates about movement authority can avoid unnecessary braking and stops [8]. Malmbanan will transfer to this signalling system in the coming years, so there is potential to save energy with this transition in the near future.

All above mentioned measures that can be taken to save energy are general and can be applied to both passenger and freight trains though the applicability of course varies depending on interactions between different measures, the rolling stock, infrastructure and operational characteristics. Some more measures specific to freight trains that have not been mentioned yet are investigated in a report by Andersson et al. [1]. These include improving the usually unfavourable aerodynamics of freight trains by covering open wagons. Since such covers would require to be removed for loading and the covers add extra weight which reduces the allowable cargo load, they are not suitable for operations of heavy haul iron ore trains. Approaching it the other way around, reducing the tare mass of heavy haul freight wagons means a higher amount of cargo can be transported without exceeding axle load limits. This does not influence the energy consumption directly, but the specific energy consumption per ton of cargo transported is reduced because the load factor increases. Another measure that can increase the capacity of freight trains and reduce specific energy consumption is adapting the infrastructure to allow for higher axle loads, longer trains and a wider loading gauge. A wider loading gauge is suitable for freight trains where the volume of cargo is limiting capacity while higher axle load is relevant for high density cargo. All these measures will increase wear and deterioration of tracks and wheels though.

In the end, what measures are relevant to reduce energy consumption depends on the circumstances. For existing rolling stock, changes to software and operations are more suitable than bigger modifications. The reviewed literature points out some measures, which are implementing DAS, optimised timetables, eco-driving, adjusting speed limits, improved control of comfort functions and traction equipment [8, 9]. From a pure energy saving point of view, freight trains can save the most energy by implementing heavy haul, improving brake energy recovery, applying eco-driving and high-efficiency drive chains [1].
2.3 Simulation of freight train energy

One of the goals of this thesis is to develop a simulation model that is able to predict energy consumption of the heavy haul freight trains operated by LKAB to a satisfactory extent. Therefore, literature was reviewed that describes simulations performed previously in the field to identify what aspects of model building are important for simulation of heavy haul freight trains.

On the most basic level, there are three types of energy simulations. The first type comprises macroscopic models that calculate energy consumption based on accumulated statistical data. The second type that exists are microscopic models that take into account the underlying physical principles on a detailed level. Lastly, mesoscopic models combine elements of the previous types [14]. For being able to do any analysis on how the rolling stock, infrastructure and operations influence the energy consumption, only microscopic models are thus relevant.

But even when only looking at microscopic models, a considerable variation in the detail of models can be seen. Being a very basic model, Lindgreen et al. [11] take into account efficiency, the most basic physical principles such as gradient resistance (although in a simplified way), rolling and aerodynamic resistance, but excluding curve resistance and the additional resistance due to wind and tunnels. Furthermore, the model only takes accelerations into account, for which an energy consumption matrix is defined based on several speed-acceleration combinations and their temporal and spatial distributions. Hence, this model is also not able to take regenerated energy into account and also cannot capture changes in average speed and the number of stops [14]. The reported deviation of this modelling approach from real trains energy consumption was consequently also high with up to 32% for goods trains, though it is fast to use for estimations.

A much more common and detailed approach in literature is to simulate the actual driving pattern of a train by integration of the instantaneous power. This is usually solved numerically using small time steps and a kinematics-based model to calculate the instantaneous power, though electric power-based methods exist too [15]. But even when looking only at simulations of higher accuracy that calculate energy consumption based on the driving pattern, the literature reviewed has a high variation of what details are included to represent the physical background to a satisfactory extent. Wang et al. [16] for example
model the regenerative braking efficiency as an exponential function of the deceleration and find that this approach gives a lower energy prediction error than assuming a constant braking energy efficiency. Bai et al. [17] instead assume an average transmission efficiency, but have calculated the gradient and curve resistance to higher detail by using a mass density function.

Why a distributed mass (mass density) model is important in that paper is because a freight train is modelled. Freight trains can be very long and heavy, so an error will always result from assuming a so-called single-particle model where all mass is collapsed into one point. The reason is that different parts of the train can be at different gradients at the same time, but also in curves and straight track at the same time. Whether a single-particle or multi-particle model should be used is hence discussed in several papers that estimate freight train energy. Lu et al. [18] give arguments for both. Single-particle models are simpler to analyse but give errors especially at changes of grade. On the other hand, multi-particle models are complicated and have a high computational expense, which can be of disadvantage when performing optimisations. The authors in the end decide to use a single-particle model, not only since they are doing optimisation, but also they argue that uncertainties in the train and track input to the model mean the higher accuracy of the multi-particle model is not required. Lukaszewicz [19] states that single-particle models often are used and viewed as accurate enough, but for long freight trains a distributed mass model should be used. Reasons given are that changes in gradients and narrow curve radii can influence acceleration calculations and run time. The author also mentions that the long brake application and release times for freight trains can influence driving simulations. Modelling of the air brake system is done by Wu et al. [20], where energy consumption for a very long freight train is simulated taking the longitudinal dynamics of such a long train into account. Apart from the brakes, draft gears connecting the wagons are also modelled. Results show that the energy dissipated by the draft gears is extremely low and therefore also minimal in the long term.

A last, important part that is often not taken into account for train energy simulations is driver behaviour, though a simpler selection of more and less aggressive driving can be selected in some simulation tools [21, 22]. Including a driver model makes it possible to study the effects on energy consumption of using different driving styles realistically, since real driver behaviour is imitated. Not including a driver model, but applying more aggressive driving (“all-in”), is reported to give 20–30% energy consumption
error when imitating real train runs [19]. This is especially important to note since a comparison with real train runs is often done as part of validating a proposed model. Other smaller parts modelled in some literature that are worth noting since they help making the simulation as closely related to physical principles as possible include [16, 19, 21, 22, 23]:

- Starting resistance
- Weather conditions (temperature, humidity, ambient wind): influence on aerodynamic resistance, adhesion, bearings
- Line voltage and adhesion: limits available traction

In the end, what details of physical principles that should be included in a simulation tool used for a study will depend on what level of accuracy is required, the level of quality of the input data and what is to be studied using the model that has been created using the tool.

On a last note, a paper should be mentioned that was found during the literature review which is interesting since it uses a different approach in studying the effect of different parameters on energy consumption. All discussion in this section has evolved around simulations because these are often used for such studies. Vierth et al. [5] use an alternative approach, using aggregate data from several train runs to investigate how recorded parameters could explain the variation of energy consumption for the train runs. For this, a regression analysis was performed, checking statistical significance of parameters in proposed regression models. This study shows that the driver has a statistical significance as explanatory variable. Other results point towards that heavier and longer train could offer advantages by scaling effects, although issues with data quality impact the validity of the results. In case high-quality data is available, a regression analysis certainly would allow for a simpler analysis than having to build a complete train and track model in a simulation tool, although achieving high data quality could be a challenge. Moreover, such a regression analysis could also be used to verify the findings of a study based on simulations.
2.4 Driving style optimisation

As mentioned in the previous section, the influence of the train driver on energy consumption is high. Several driving styles such as eco-driving and using regenerative braking as default brake have been pointed out to save energy. In this section, research on optimal driving styles will be presented.

For understanding driver behaviour, Łukaszewicz [24] suggests parameters that can describe driver behaviour. These include the look-forward distance, powering ratio (of maximum available), braking ratio (of maximum available), upper speed action limit and lower speed action limit (how much the train can deviate from target speed before action is taken). It is found that coasting and a low braking ratio is favourable for energy consumption, but this relies on that the driver has enough information about movement authority ahead and thus the look-forward distance for proper planning of the driving. The signalling system is hence very important for facilitating energy efficient driving. Especially a lower braking ratio is pointed out to give big energy savings. A low ratio means short mechanical brake recovery times for long freight trains, allowing the driver to make more efficient adjustments of the brake force. Avoiding unnecessary braking by proper planning is reported to give 5-7% energy savings without increases in travel time. Decreasing the powering ratio will reduce the acceleration and energy consumption at cost of increased running time. The same effect has been shown in another study by the same author, where a lower available adhesion, which in practice limits traction forces, leads to lower energy consumption [21]. Since lower powering ratio, braking ratio and coasting will increase travel time, a high upper speed action limit can help making up for lost time [24].

Ellis et al. [25] evaluate data gathered from real trains runs to see how the energy consumption is influenced by the acceleration and deceleration behaviour of drivers. Similar conclusion are drawn here. The aggressiveness of drivers during acceleration and deceleration is found to be related to the energy consumption. Interestingly, the authors point out that while a lower acceleration approach is better during low traffic intensity where running time is less strict, during peak hours with much traffic a more aggressive acceleration to top speed followed by coasting is more appropriate. Due to that the study has been performed on passenger trains, the applicability to freight trains is not completely clear though. That the powering ratio is important for freight trains in order to save energy is also seen in another study that indicates
that the powering ratio’s importance for energy consumption increases with a high load factor [15], which freight trains often operate at.

Yet another study that analyses freight trains shows that not only the kinematic losses due to braking should be minimised, but also the work of the resistance [17]. Therefore, the authors propose that freight trains should try to keep a uniform speed by using coasting as much as possible on long downhill slopes and before long uphill slopes, the train should accelerate to proper speed so that it doesn’t loose too much speed while going up. The unification of speed is reported to save 6.8% energy in a case study in the same paper, without increased run time. Additional measures mentioned for avoiding kinematic energy losses are to reduce the speed before train crossings on single track, so that no stop is required while waiting for a meeting train to pull in to the side track completely, and maximising coasting before a required stop. Le et al. [26] report a similar measure. Taking scheduled train crossings on single track into account could let the train pulling in to the side drive at reduced speed instead of waiting for a long time at the meeting station. According to the authors, the schedule is often not considered in simulations though.

Based on among others the suggestions for an energy efficient driving style above, it can still be quite difficult for a driver to find an optimal driving style since there are many parameters that influence what the best behaviour would be. Some literature hence tries to optimise the speed trajectory to find what general driving strategy is most suitable. Scheepmaker et al. [27] compare four different driving strategies based on a given running time budget to see which one is most suitable not only from an energy point of view, but also brake wear and workload (for the driver) point of view. The fastest and always least energy efficient driving strategy is the "minimum time train control" (MTTC) where the train accelerates to maximum line speeds and keeps it as long as possible before braking to a stop. The second strategy is called "maximum coasting" (MC), the third "reduced maximum speed" (RMS) and the last and always most energy efficient strategy is "energy efficient train control" (EETC). In this strategy, it is tried to combine the previous two strategies by finding a lower top speed and adding coasting while fulfilling run time requirements with minimum energy consumption. Results show that on shorter distances (50 km) with straight track and no gradients, EETC is the most energy-saving strategy for freight trains, followed closely by MC and farther behind RMS. When adding gradients to the track, this does not change. Only when the distance gets long (150 km), the order in the results changes
and RMS is now slightly better than MC. Looking at the workload, MTTC has the lowest workload in all scenarios mentioned here, while MC and RMS have a similar workload. For a high density traffic network, MC shows the lowest workload. EETC is reported to have a much higher workload than all other strategies. This shows that while EETC always gives the lowest energy consumption, it is not feasible for a driver to follow such a strategy unless supported by a DAS or other kind of tool that reduces workload. MC is also shown to have the overall least wear on brakes, so it could be concluded that overall a MC strategy is the most suitable to use for drivers that do not get decision support. This again highlights the importance of coasting for eco-driving strategies. The only advantage of a MTTC strategy is that the auxiliary energy consumption is reduced since it is time-dependant [22]. For a freight train, the amount saved by this would be very small though.

When braking cannot be avoided, this review has shown that regenerative braking should be used as standard. So, speed variations in transit should be managed solely by the electric brakes. In some situations, like long steep downhill gradients, a freight train will not be able to maintain its speed by just using the electric brake though. The reasons for this are the low number of powered axles on which regenerative braking forces can be generated, but also the maximum power and receptiveness of catenary for regenerated energy create limitations [28]. Lin et al. [29] investigate the problem how braking could be optimised in such a case. Their proposed solution is to apply full regenerative braking constantly and add full mechanical brake periodically so that the speed does not exceed the top speed of the railway. This leads to the most regenerated energy and a higher average speed for the downhill section compared to the alternative, which would include periodically using coasting until reaching the speed limit before slowing down using full regenerative and mechanical braking. The higher average speed is relevant here because it allows the train to run slower on other parts of the railway line without extending the run time, giving even more energy savings.

In the end, the amount of energy savings that can be achieved by the above-described driving styles and strategies depends very much on how much slack exists in the timetable useful for eco-driving. If the traffic intensity is high, margins will be smaller making it harder to for instance coast [28]. Tweaking the timetable to increase time margins could thus also help reduce energy consumption [9], though this is rather a traffic management optimisation problem and thus outside the scope of this review.
2.5 Estimation of running resistance

In the prior sections of this literature review, it has already been described that motion resistance stands for a substantial part of the energy losses for freight trains. Hence, for obtaining good energy consumption estimates by simulation, the running resistance must be modelled as accurately as possible. In this section, theory about estimation of running resistance will be reviewed.

Motion resistance can be divided into several resistances. Firstly, there is rolling resistance. This resistance originates among others from internal resistance in bearings, journal friction, flange friction due to swaying motion, deformations in the wheel-rail interface and vibrations in vehicle suspension systems [12, 30]. Curve resistance is also a rolling resistance, but is often handled separately. Then there is aerodynamic resistance due to air drag and ambient wind, grade resistance and inertia resistance when accelerating [23]. Only the rolling resistance and aerodynamic resistance dissipate energy though, while all other resistances either add kinetic or potential energy to the system and so established analytical equations exist for these. There are formal expressions for rolling and aerodynamic resistance too. But since they depend on a big number of parameters that need to be included, the calculations can get very complicated with a lot of input required, as demonstrated in an example calculation by Lindgreen et al. [31].

Due to the problems with calculating rolling and aerodynamic resistance analytically, most research that was found during the literature review uses an empirical approach. There is a well-established equation for this (see Equation 2.1), often referred to as the Davis equation [32].

\[ F_R = A + B \cdot v + C \cdot v^2 \] (2.1)

Coefficient A in this equation is solely related to rolling resistance and coefficient C only to aerodynamic resistance. The B coefficient in principle relates to both rolling and aerodynamic resistance, but some research points towards that it is mainly related to aerodynamic resistance due to air impulse resistance with some likely variation with track standard [23]. Note that curve resistance is not included in the rolling resistance of the Davis equation but is calculated separately. Because a study on iron ore wagons has been performed on Malmbranan [33], where the curve resistance has been estimated already for an iron ore wagon similar to the model used by LKAB today, no attention was
given to literature estimating curve resistance. In the remaining parts of this report, rolling plus aerodynamic resistance excluding the curve resistance will be referred to as running resistance.

Lukaszewicz [23] outlines three main methods for estimation of the running resistance:

- Dynamometer or drawbar methods: estimation based on resistance when pulling the train with winch or drawbar
- Tractive effort methods: estimation based on observing the changes in speed given that the train is under traction
- Coasting methods: estimation based on observing the reduction in speed given that the train is coasting

For some methods such as dynamometers, basically only the rolling resistance part of running resistance can be estimated. In the other methods, the goal is to calculate the running resistance at different speeds based on measurements. Using least square fitting, the coefficients in the Davis equation can then be determined that show highest agreement with measuring data. Coasting methods require the least amount of data for calculating the running resistance (speed, track data, train mass) and therefore also require the least measuring equipment. Moreover, this means that there are less sources for error compared to the other methods. The only disadvantage of coasting methods is that idling resistance of the drive chain influences the estimation [23].

In [33] a full-scale test using this method is performed, which also means a limited amount of data is available for estimation of the running resistance for a specific scenario. Control of all disturbing factors is very important in this situation. To minimise the effect of ambient wind, which is not part of the model in most simulations, the train is run in both directions under the same wind conditions to obtain an averaged polynomial from both runs. But such full-scale tests can be both time-consuming, expensive and often not feasible. Modern trains have a lot of internal monitoring systems though, which allows for using commercial running data for estimation with the coasting method. This approach is used by Ogawa et al. [34]. To overcome the problem that the control over influential parameters and reliability of monitoring system data can be low, the paper uses an enormous amount of data from 5 years time to include a wide range of real-life conditions. Another challenge is that in this
case the exact position of the train must be evaluated to match the local track alignments. The fact that trains in real operation seldom coast at low speeds in addition leads to a lack of data for fitting in the low-speed range.

To some extent, the spread of running resistance data points over the speed range can be widened by using tractive effort methods in combination with monitoring system data. Aradi et al. [30] set up an energy balance and estimate the coefficients by minimising the sum of square difference between estimated and measured total energy consumption. Still, they report similar problems with the fitting being better in the high-speed range where most data is available, compared to the low and even higher speed range. In [32], instead of minimising the error of the energy consumption prediction, the deviation of a speed estimate is minimised to obtain the coefficients. An alternative approach is also presented which is based on calculating the running resistance directly and then performing the polynomial fitting, though it is found to have worse performance. Both these approaches require access to traction force data or estimation of it.

For the review, it can be concluded that all methods have in common that they try to minimise the error of some parameter. Depending on what data is available and with what accuracy and volume, different approaches of calculating the running resistance are possible. The choice of what parameter is used as reference for minimising error relies on the approach. Lastly, it should be noted that also tunnel resistance can be estimated using the presented methods and data from trains running in tunnels, see for instance [32] and [35].

### 2.6 Key performance indicators

One of the goals of this thesis is to define KPIs that can be used for monitoring energy consumption. How rolling stock energy related KPIs can be defined and what attributes they should have was therefore reviewed. Not much literature dealing with KPIs for rolling stock energy usage was found.

To track what influence implemented measures have on energy consumption, the use of data from energy meters and KPIs is highlighted in [9]. It is stated that KPIs should be developed to track the success of introduced energy-saving measures. In [36], González-Gil et al. develop this further by suggesting a structure of KPIs for a whole urban railway system, which is highlighted as necessary to capture the effect of an energy-saving measure on
the complete and complex railway system. KPIs related to the rolling stock that are mentioned include traction energy consumption, auxiliary energy consumption and braking energy recovered. Attributes mentioned, that KPIs should have, include [36]:

- Inclusive: give information at different levels (global, subsystem)
- Hierarchical: relative importance for the system
- Quantifiable: clearly defined and scientifically valid
- Descriptive: allow for evaluation and comparison of different strategies

Another paper states that KPIs should be specific, measurable, assignable, realistic and time-related [27]. As pointed out in [36], in order to have a good overview, the number of KPIs should be limited and so it is especially important that they excerpt solely the information that is most relevant. It is therefore also a good idea to have a global efficiency (main) KPI, which for instance could be specific energy consumption as suggested in [36].

### 2.7 Summary

The review of literature has shown that the main part of energy flow in the railway system is related to traction energy and a lot of research is centred around improvements to it. Three main areas for energy saving potentials that together can describe energy efficiency on the rolling stock level have been identified from the review, being driver, operations and rolling stock. From this, a structure of KPIs for a monitoring system can be set up. Further, KPIs should be chosen to be inclusive, hierarchical and quantifiable.

To estimate the effect of changed parameters on energy consumption, the most common method is simulation. For heavy haul freight trains, multi-particle models can help improving accuracy of the simulation, while longitudinal dynamics are not important for energy consumption. Lack of a driver model can result in substantial overestimation of energy consumption for freight trains. Importantly, the driving style is essential for energy efficiency and research emphasises braking should be avoided and coasting maximised. Running resistance for simulation can be estimated empirically by fitting the Davis equation coefficients to data from full-scale tests or monitoring systems, the latter requiring larger data volumes to compensate for lower data quality.
Chapter 3
Methodology

The purpose of this chapter is to provide an overview of the research method used in this thesis. The whole methodology of this thesis has been developed with the goals in mind that relevant values and conditions for analysis of energy consumption and parameters significant for describing energy consumption of heavy haul freight trains should be the result of the work. Because as soon as these results exist, fulfilling the remaining goals, i.e. defining KPIs and specifications for automatic and continuous monitoring of energy consumption, is relatively straightforward. Recommendations for improving the energy efficiency of LKAB’s operations can be generated in the process of analysing the results too.

Figure 3.1 – Overview of methodology and work process
Since the main interest of this thesis is centred around examination of parameter influence on energy consumption, it was from the first start clear that a parametric study is to be performed. So the choice of method rather evolved around by what means the parametric study is to be executed, which will be explained in the following. In Figure 3.1 the methodology is visualised and the dotted red box contains the work process which resulted from the choice of method. This work process will also be explained in this chapter, with exception for the building of theoretical reference model of the train, which is presented in detail in Chapter 4.

3.1 Method choice

The focus in the process of method choice has been on how relevant values, conditions and significant parameters can be obtained through a parametric study with an appropriate method. The first step of the process is the same regardless of which method is to be used, which is to look into which parameters could be relevant to look at. The foundation of this work has already been presented in the literature review, see Chapter 2. In Section 3.5 a list of parameters to study is developed based on findings of the literature study.

When it comes to the second step and how the relevance and significance of parameters is to be investigated, three methods could be identified for the parametric study. Firstly, field tests where trains are purposely run in specific ways to see how changes in parameters influence energy consumption is one possibility. Not only are such tests time-consuming and complicated to plan, but a limited amount of data would be collected and there is uncertainty over the level of control achieved for the studied parameters and ambient conditions. Regardless of what advantages there might be for this method, the disadvantages are so big that this method is discarded.

The second method considered is to use statistical analysis where it is examined how the studied parameters correlate with energy consumption, see for instance [5]. Such a method allows for covering a wide variety of real-life conditions in the analysis to see the average effect of parameters on energy consumption. Also, no detailed knowledge of running resistance and other harder to obtain characteristics of the rolling stock is required. On the other hand, statistical analysis requires big amounts of high-quality data to cover as many conditions as possible and to ensure the significance of results. Further, it is with statistical analysis not possible to investigate the effect of a parameter set to
a value outside of the typical range found in current operations from which the data used for analysis is originating. This last point was important for the choice of discarding this method, since it does not allow for analysing what happens when for instance the STAX is increased above the current operational limit. But the crucial argument against this method is that it would require a lot of time and work to gather a big amount of data to analyse. This has to do with that, as already stated in Section 1.4, no data tool for energy monitoring exists yet during the work of the thesis from which data could be drawn. All data collection has to be performed manually and from several sources. In addition, the data that can be collected from the energy meters used in Sweden and by LKAB is sometimes unreliable, as has been reported in [5]. See further Section 3.3 for the data collection process used in this thesis.

The last method considered and also the one which has been chosen is using simulation to study the influence of parameters on energy consumption. Advantages are that it is possible to vary the value of parameters arbitrarily and that the control over the conditions under which the simulation is performed is high. Moreover, only a limited amount of data from real trains is required to validate the simulation model. The main disadvantage is that a lot of details such as running resistance must be input into the simulation model, which must be of high quality to minimise errors. Another important aspect is that the model must be able to accurately represent the physical principles behind the influence of the parameters studied. The development of the simulation model is presented in Chapter 4.

In the end, both the second and third method had both advantages and disadvantages. The decisive argument for favouring a simulation as method over the statistical analysis is really the limited ability to collect big amounts of running data from trains in operation in this thesis. It should also be pointed out that most research found in the literature uses simulation as method to achieve similar goals, see for example [24].

After a simulation model has been created, it is validated to ensure its quality and accuracy, see Section 3.4. When that is done, the parametric study is performed, see further Section 3.5 for the setup of this study. In the end, the results of the parametric study are evaluated and analysed to ensure validity and reliability, see Section 3.6. At the end of this step, a list of relevant and significant parameters is obtained, which is used to recommend suitable KPIs and energy saving potentials to reach the goals for this thesis, see Chapter 5.
3.2 Selection of simulation tool

The choice of simulation tool is important since the level of detail in which it represents the underlying physical principles can influence the validity and reliability of results. It was therefore of importance that a proven tool would be used. For this thesis, a simulation tool developed by KTH together with MiW Rail Technology AB is used with the name STEC (Simulation of Train Energy Consumption) [37]. It simulates energy consumption and running time of a train after that train, track and operational input has been defined. Due to that STEC is Microsoft Excel-based, it has a user-friendly interface with one worksheet for train input and one worksheet where track and operational input is given. For details about the work with inputs for STEC, see Chapter 4.

Another initial reason for using STEC was that build-on customisation in the scripts is possible, even though it is not used in the end. Most importantly, the tool has been successfully used in previous studies, see for instance [1, 28]. Potential concerns with the tool were that no driver-describing parameters could be defined and brake application/release times are not accounted for. On the other hand, STEC has a coasting function and the driver behaviour can to some extent be controlled via the speed limits, traction and braking curves. Other issues related to the single-particle representation of trains in STEC, which the literature study has shown to be relevant for long heavy freight trains, have been solved, see further Section 4.2.

3.3 Data collection for modelling & validation

For building the model of the train in the simulation tool, several sources were enquired to define the technical parameters required as input. Technical documentation of both the locomotives and iron ore wagons was one source used with high quality and reliability. What could not be found there had to be estimated using data from real train runs. This includes auxiliary power consumption and the running resistance, see further Section 4.1 for details.

In total, four sources for data from real train runs were used. Firstly, data about exact train weights could be extracted from LKAB’s own database, since the trains always pass a scale before departure, ensuring no wagon is overloaded. The reliability of this data is therefore high, which is very important for all analysis in this thesis. The database of LKAB also provides information about
departure and arrival times from/to the loading/unloading railway yards in addition to information about which locomotive units and iron ore wagons were running is a specific train.

The second source of train data from real runs are the energy meters installed on-board the locomotives. As was already described in Section 1.1, these sample several parameters every 5 min together with the accumulated energy consumption and the data is saved to an internal memory before the data is uploaded to servers using mobile network. LKAB’s locomotives have energy meters from HaslerRail installed and data from these is available in an online database. Data provided includes (not all parameters listed here):

- Energy consumption (total, sample)
- Energy regeneration (total, sample)
- Current, Voltage, Power factor
- Distance
- Speed
- GPS Position
- Altitude

Of the above, only the information about total energy consumption, total energy regeneration, position and speed has been used in the work of this thesis. While the quality and reliability of data about total energy consumption and regeneration is high, the position quality was sometimes lower. Speed is based on the GPS position, so it has some error.

Given the low resolution of speed data from the energy meters, it is not useful to perform any estimations or validation. Therefore, in discussion with Trafikverket a feature was activated for the energy meters on five locomotives which allows the energy meters to constantly send sample data with a resolution of 2 s to the servers. Data received from Trafikverket this way had big quality issues though, with parts of data missing for train runs and even when a complete train run had been successfully recorded, it could sometimes be observed that the speed erroneously was zero. Likely, these problems arise due to unreliable mobile network connection, especially since the energy meters switch from Swedish to Norwegian mobile network en route to Narvik.
Another possibility considered was to simply increase the resolution of samples saved to the internal memory of the energy meter. However, given limited time for gathering the data from train runs, it was decided to only use energy meter data as source for total energy consumption respectively regeneration and for checking the position of a train when at rest for more than 5 min. It should be mentioned that not all locomotives feature the modern energy meter described here. Some still have an older model installed, which does not give access to neither the train position nor the speed. These locomotives were consequently not considered for data collection.

Given the problems receiving high-resolution data from the energy meters, instead data was manually downloaded from the train event recorder of four locomotives available that had the new energy meters installed. Depending on how much the respective locomotive has been in operation, data from several months time can be found on these, limited by the internal memory capacity. Input signals are sampled and saved to the internal memory of the recorder every time a change in speed is detected, however data that has been downloaded is from the long-term memory. This has a lower resolution of data than the short-term memory but still significantly higher than energy meter data and therefore is regarded sufficient for the purpose of validation. Another advantage is that the speed recordings are more reliable and access is provided to new parameters not available from energy meter data. These include traction force, regenerative braking force and brake main pipe pressure.

Finally, the last source of train data was old train recordings from the years 2013 and 2014. This data has the highest resolution of all sources with samples taken two times per second by having a laptop plugged into the data bus of the locomotive. A wide variety of parameters is recorded, which apart from the ones already mentioned for the energy meter and train event recorder above, includes the traction notch set by the driver, the traction notch active, traction force per bogie and wheel slippage per bogie. Unfortunately, the position of the train in the recordings cannot be distinguished since all energy meters were of the older model back then, without access to the position. This data source therefore only has limited applicability, but can still be valuable for auxiliary power and running resistance estimation thanks to the high resolution.
For the track alignment inputs required in the simulation, information from the Swedish infrastructure owner’s data base BIS was extracted for Malmbanan [38]. This ensures high accuracy of the alignments and that they are up to date as the infrastructure looks today. For the Norwegian Ofotbanen, no data was received from the infrastructure owner. Instead, 20-year-old data available from the requirement specification for procurement of the current generation of locomotives has been used. This route still exists, even though some new tunnels have been built that usually are used instead due to a more direct route. The difference in distance is not so critical since the train can be simulated to use the old route which is only a bit longer and will not affect energy consumption very much. To ensure the accuracy of the alignments is satisfactory, altitude checks have been performed, see Section 4.2 for details.

### 3.4 Validity check of train & track model

After work with track alignments and building of the theoretical reference model of the iron ore train in STEC has been concluded, it needs to be validated to ensure quality and accuracy of the input parameters to the model. Also, this serves as an opportunity to check how well STEC itself performs and to assess the error that is to be expected for the energy consumption STEC predicts.

The validation is done against data from real train runs, for which data about speed, traction and braking forces is taken from the train event recorder. The real train runs used as reference should have axle loads as close to the limit of 30 tons as possible, to minimise errors in the running resistance estimate and gradient input calculated for 30 tons axle load (see Section 4.2). Weight of the reference train is drawn from LKAB’s database and the cargo load in the simulation is changed accordingly. Energy meter data is used in order to be able and compare real versus simulated energy consumption. Because the simulated train should follow the speed profile of the real train as closely as possible, a shorter track section between two meeting stations where the real trains stops is used. This helps to simplify the effort required to follow the real speed profile, which can be very complicated for a long distance considering driver behaviour can only be controlled with speed limits, traction and braking curves in STEC. Furthermore, errors in the simulation that might cancel out over longer distance, can be expected to be more visible with a shorter distance.
A primary and secondary validation is performed, see Figure 3.1. In the primary validation, the steps taken are as follows:

1. Traction curve fitting: to replicate the aggressiveness in accelerations of the real driver in simulation
2. Braking curve fitting: to replicate the aggressiveness in deceleration of the real driver in simulation
3. Coasting applied: if the real driver coasts this is added at the same locations
4. Speed fitting: simulated speed profile should follow real speed profile
5. Parameter calibration: in case it is obvious that the parameters must be corrected to increase agreement between simulation and real train

The second validation is done exactly as the first validation except for that no parameter calibration is allowed. Also, in this validation different rolling stock units and another track section are used. The purpose of the secondary validation is to ensure the calibrated simulation inputs of the first validation are not "overfitted" and also apply to other rolling stock of the same class and other track sections. If agreement of the energy consumption predicted by STEC and the real trains for the two validations is satisfactory and a good understanding of the performance of STEC has been attained, the theoretical reference model of the iron ore train has been validated and the parametric study can start. Satisfactory agreement of simulated versus real energy consumption is defined as an error below 10%, but the lower the better. This is very important for the parametric study in order to ensure uncertainty in the results is low enough to be able and draw conclusions from them.

3.5 Parametric study procedure

In the parametric study, one specific parameter is systematically varied within a reasonable range of values at a time and the influence on the energy consumption predicted by STEC is observed. When appropriate, additional analysis is done. In order to ensure comparability between the results and that the predictions made by STEC are reasonable in the context of real train operations, a standard set of inputs for STEC is defined. These inputs form the base case and in the parametric study, single parameters of the base case are then varied, while the other parameters are kept at their default value.
With a base case defined, it is also possible to compare the simulation results to real train runs upon which the base case is defined. This helps to get an understanding of how STEC performs compared to the real trains and putting the results from STEC into perspective for the evaluation of results.

To define the base case, first the route and direction to be used had to be defined, see further Section 4.2. Afterwards, using data downloaded from the train event recorders, all through trains on the correct route in the correct direction are selected. For the selected trains, after normalising their start points to be at the position where the track input starts, their speed profiles are aggregated. An average speed profile which represents the average train is defined with help of the line speed limits in the track input. In addition, the tractive and braking curves in STEC are limited to the maximum values used by any driver over the complete speed range so that the simulated train is not driving more aggressively than any of the real drivers. The cargo load of the train is set to the maximum possible, i.e. the axle load limit is 30 tons in the base case and all other parameters in the input are adjusted accordingly. For details of the defined inputs for the base case, see Section 4.3. The adequacy of the defined base case is commented in Section 5.1.3.

In order to be able and decide which parameters are of interest to look at as part of the parametric study, the literature study in Chapter 2 is used as a basis of knowledge. Keeping in mind that one goal of the thesis is to define KPIs, a basic structure for a system of KPIs is proposed. A hierarchical structure is set up with one global KPI that describes the global system performance. Below that global KPI, three subsystems, that together can explain the variations in energy efficiency at the rolling stock level, is set up.

The first subsystem is rolling stock and is related to the performance of the powered, internal systems of locomotives in terms of energy efficiency. Next, operations form the second subsystem. This includes all operational parameters that influence the energy consumption but cannot be controlled by the driver, such as the load factor (relates to the axle load) or number of stops along the route. Lastly, and most importantly according to the literature review, the driver KPIs form the last subsystem since the driver has the absolutely biggest influence on the energy consumption depending on the applied driving style. In Figure 3.2, the proposed structure for KPIs is visualised and for each subsystem, the parameters that are found to be of interest to study, are given.
What parameters are of interest to study in the parametric study has been decided based on whether they could help defining relevant values, conditions, significant parameters for describing energy consumption and ultimately KPIs. A limitation that exists for which parameters can be studied in the parametric study is that it must be possible to achieve a variation of the specific parameter in a controlled way in STEC. Also, parameters are excluded if they are too much interlinked with other parameters that have already been included in the study. For instance, run time and average speed have an impact on energy consumption, but a longer run time and lower average speed might depend on that the train needed to make a stop en route (which increases energy consumption) or that the driver coasts a lot (reduces energy consumption). So a longer run time and lower average speed are rather a consequence of driving style or operational circumstances and thus do not have much explanatory power in themselves.

Moreover, it should be pointed out that in the process of choosing which parameters to study, the fact that some parameters might be hard to extract from energy meter data was not taken into account. The reason for this is that even if that should be the case, it is still of interest to see what impact these parameters might have on energy consumption. In case it can be shown that their influence is high, it would be of interest in the long term to gather data from other sources than the energy meters to facilitate an evaluation of these parameters. The suitability of parameters as KPI is discussed as part of the evaluation of results from the parametric study, see Section 5.3.
3.6 Work process for evaluation of results

In the evaluation stage of this thesis, the findings of the parametric study about the significance of the studied parameters for describing energy consumption are discussed. The discussion covers both the agreement of the results with previous research in the field of study, the quantitative influence of the parameters on energy consumption and the suitability of the studied parameters for defining KPIs. The suitability is evaluated based on explanatory power of parameters and whether it is possible to calculate the parameters by only using energy meter data in a meaningful way without too much uncertainty in the calculation.

STEC does not have a proper driver model implemented and this leads to a higher uncertainty for the results related to the driver subsystem parameters. These results are thus verified in order to ensure the reliability and quality of the results. The approach for verifying the results is to select two real train runs from the set of non-stop train runs aggregated to define the speed profile of the base case in the parametric study. From this set, the trains with the highest and lowest net energy consumption are chosen that fulfil the criteria that both trains start at the same railway yard and have a very low difference in cargo load. These criteria assure that only the driver should be accountable for the big difference in net energy consumption. By checking whether the driving style of the more and less energy efficient driver can be explained with the parameters that were found to be significant for describing the driver influence on energy consumption, these parameters’ significance can be verified. Based on the discussions and verification, recommendations for KPIs, a monitoring system for energy consumption and energy saving potentials can be given.
Chapter 4

Modelling

In this chapter, the process of defining all input for the simulation model will be presented. This includes both the technical parameters for the train, the track alignments and the operational conditions that are taken into account for defining the base case.

4.1 Train

For all work in this thesis, exclusively the electric locomotives used in regular operations for the iron ore transports performed by LKAB will be considered. The IORE class locomotives are always operated in pairs of two. From now on and for the rest of this thesis, a single locomotive as shown in Figure 4.1 will be called a section, and a locomotive/IORE will thus refer to two pair-coupled sections. These locomotives are very heavy thanks to installed ballast, which maximises axle load on the 12 axles to 30 tons, and are also among the strongest locomotives in the world with a tractive force of 1200 kN [2].

For transporting the iron ore in the form of pellets from the mines to the harbours, LKAB has several different generations of iron ore wagons in operation at the same time. For the work in this thesis, the most modern and also most common type of ore wagon will be used with the series name Fanoo, see Figure 4.2. They are loaded from above and emptied through a hatch at the bottom. Two Fanoo wagons are permanently coupled together and are then called Fammoorr. Hence, the iron ore trains are always run with an even number of wagons. From now on and for the rest of this thesis, an ore wagon will refer to a Fanoo, i.e. a single ore wagon. Each Fanoo has 4 axles.
Figure 4.1 – IORE locomotive section. *Picture source: Christoph Domay*

Figure 4.2 – Fanoo iron ore wagon. *Picture source: Philipp Geiberger*
4.1.1 Basic parameters

A lot of parameters for the locomotive and ore wagons could be gathered from the technical documentation [39, 40, 41]. Table 4.1 presents some of the technical parameters that were used for defining the train input for STEC. The train in the column to the right is defined as the fully loaded standard train that LKAB operates, which maximises the train length and axle load. The infrastructure on Malmbanan and Ofotbanen allows for trains of up to 750 m and STAX 30 tons. The train in the table is hence using 68 ore wagons and all parameters are given for fully loaded wagons with an axle load of 30 tons. The operational speed of both the locomotive and ore wagons in a fully loaded train is 60 km/h, however, the automatic train control system (ATC) allows for some exceeding of the speed limit before it intervenes with brake application when top speed is exceeded by approximately 10 km/h [23]. The max speed of Fanoo without cargo load is 70 km/h and 80 km/h for IORE.

Table 4.1 – Technical parameters for iron ore train with 68 ore wagons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IORE (2 sections)</th>
<th>Fanoo</th>
<th>Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (between couplers) [m]</td>
<td>45.8</td>
<td>10.3</td>
<td>746.2</td>
</tr>
<tr>
<td>Tare mass [t]</td>
<td>360</td>
<td>21.6</td>
<td>1828.8</td>
</tr>
<tr>
<td>Cargo load (STAX 30) [t]</td>
<td>0</td>
<td>98.4</td>
<td>6691.2</td>
</tr>
<tr>
<td>Gross mass (STAX 30) [t]</td>
<td>360</td>
<td>120</td>
<td>8520</td>
</tr>
<tr>
<td>Adhesive weight [t]</td>
<td>360</td>
<td>0</td>
<td>360</td>
</tr>
<tr>
<td>Mass contribution (rotational masses) [t]</td>
<td>52</td>
<td>1.64</td>
<td>163.52</td>
</tr>
<tr>
<td>Braked weight [t]</td>
<td>280</td>
<td>48</td>
<td>3544</td>
</tr>
</tbody>
</table>

The tractive effort is limited by the available traction force at low speeds and the power of the locomotive at high speeds. As standard, IORE can generate a tractive force of 1200 kN. At start, a "boost" to 1400 kN is possible, but used seldom and not considered in this thesis. The power of the locomotives is bounded to 10800 kW and the corresponding tractive effort curve is shown in Figure 4.3. In STEC only seven points can be defined on this curve, which explains that the curve is not completely smooth. Also, the first speed and last force value must be zero in the STEC input, which is why the curve drops sharply just short of 80 km/h. In reality, the maximum tractive effort is not only limited by the power and maximum force, but line voltage and adhesion also impact it. STEC takes adhesion into account, see Section 4.1.3, but not the line voltage and this is no issue since the limitations of the power supply system are outside the scope of this thesis.
When braking, IORE can generate a maximum of 250 kN electric force if adhesion and the receptiveness of the catenary allow for it. STEC assumes no such limitation exists. If the train is fully loaded, the driver can activate a "boost" mode increasing maximum electric braking force even further to 750 kN. In the work of this thesis, the "boost" mode will be regarded as standard to allow for use of the full range of electric brake force. At high speeds, the power of the locomotive limits the boosted electric brake force, see Figure 4.4 for the definition of STEC input. Again, a total of seven points on this curve can be defined and the first speed and last force value need to be zero. As can be seen in the figure, below 10 km/h the electric brake force is reduced and blended with the mechanical brake of the locomotive to achieve the requested brake force. The maximum mechanical brake force for the locomotive is 250 kN. If the locomotive applies full mechanical brake force in the speed range from 0-5 km/h, this will be higher than the electric brake force that can be generated. The total brake force for the locomotive, which is part of the input to STEC, is in this speed range therefore 250 kN and higher above.

The maximum mechanical brake force for two pair-coupled Fanoo wagons is 125.32 kN, available over the complete speed range. The total mechanical brake force for 68 wagons is therefore 4261 kN.
In the locomotive, the driver can control the brake in several ways. Using the brake lever for the complete train, the brake main pipe pressure will drop accordingly and when dropping from 5 bar to 3.5 bar, the complete mechanical braking force is applied at the wagons. At the locomotive, the electric brake is used instead but with the same brake force as the brake pipe pressure corresponds to. The electric brake force of the locomotive can also be controlled with the traction force lever, with the higher electric brake force value from both levers being prioritised. This way it is possible to set the electric brake force to a higher value than brake pipe pressure corresponds to.

STEC always uses the electric brake to its full potential and only applies additional mechanical brake force on the wagons when required. Long brake application and release times on the wagons at the end of the train are not taken into account by STEC, i.e. full mechanical braking force is applied instantly for all wagons (brake application and release times equal to zero). This unrealistic behaviour can be handled to some extent by lowering the total mechanical brake force of the train to obtain a more reasonable mean value for the brake force. STEC also does not consider longitudinal dynamics of draft gear, but as the literature review has shown, this has minimal influence on the energy consumption.
4.1.2 Auxiliary power & efficiency

Because no data for the auxiliary power consumption was available, this had to be estimated. While coasting, only the auxiliary systems will require power. So by looking at instantaneous power data from coasting trains, the auxiliary consumption can be estimated. The same applies to when the train is dwelling, but because the power electronics require less cooling at rest a separate analysis is required for this case. The old train recordings from 2013 and 2014 described in Section 3.3 include detailed data about the instantaneous power two times per second. From these files, power data for instances when the train is coasting and dwelling at rest is filtered out and a statistical analysis for this data is done. Note that the analysed train runs both includes loaded and empty trains, because the influence of less power electronics cooling for empty trains is expected to be minor on auxiliary power and also depends on the driving style (powering ratio). Ambient temperature has an influence on auxiliary power required for cooling and variation with season is covered with data for train runs stemming from April, June, August and November.

The results are presented in Table 4.2. It was noted that when the train is coming to a stop, the instantaneous power is higher for up to a minute before it drops to a lower value and the same happens before the trains starts moving again, although only for some seconds. Likely this due to that the cooling equipment for the power electronics continues working for a while before it reduces its power and powers up again shortly before the train starts moving, plus pulsating line converter currents. Data from these instances with higher power are included in the data analysed, since they are part of the power cycle while the train is dwelling. The criteria for filtering data is that when the train speed is zero, the power data is included as part of dwelling analysis.

<table>
<thead>
<tr>
<th>Statistical measure</th>
<th>Dwell power [kW]</th>
<th>Coasting power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average [kW]</td>
<td>35.08</td>
<td>136.72</td>
</tr>
<tr>
<td>Standard deviation [kW]</td>
<td>6.01</td>
<td>8.04</td>
</tr>
<tr>
<td>Relative difference [%]</td>
<td>17.12</td>
<td>5.88</td>
</tr>
</tbody>
</table>

The standard deviation is similar for both cases, which shows that instantaneous power can be expected to fluctuate in the same way all the time. The average values in Table 4.2 apply to one locomotive section. The auxiliary power used as input to STEC is consequently 273.4 kW.
As part of the procurement of the IORE locomotives, a calculation was performed to verify the efficiency requirements for the drive chain. The verification was done at one specific operating point which can be regarded as representative for the operations the locomotives are used in. The verification only calculated the overall efficiency, including auxiliaries though. STEC however requires the efficiency for auxiliary systems and the traction equipment to be stated separately. Given that the analysis for auxiliary power above is based on instantaneous power at the pantograph, the efficiency is already taken into account. In STEC, auxiliary power efficiency is thus set to 100%. What remains is to estimate the traction system efficiency.

With help of information about the assumed auxiliary power in the verification calculation, the efficiency excluding auxiliaries can be calculated to 88.93%. However, since the efficiency varies a lot depending on the operating point [42], it was decided to do a statistical analysis for the efficiency too. The data source used is the same as in the analysis for auxiliary power above, but this time all data points when the trains are under traction are filtered out. Using the data about traction force and speed, the power at the wheels can be calculated and since the instantaneous power at the catenary is also known, a quotient of these gives the overall efficiency. To estimate the efficiency of the drive chain excluding auxiliaries, the instantaneous power at the catenary is reduced by the average auxiliary power at the catenary that has been calculated as described above and the quotient is once again calculated. The results of the analysis can be seen in Table 4.3.

<table>
<thead>
<tr>
<th>Statistical measure</th>
<th>Overall efficiency</th>
<th>Efficiency excluding auxiliaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average [%]</td>
<td>78.38</td>
<td>88.93</td>
</tr>
<tr>
<td>Standard deviation [%]</td>
<td>18.33</td>
<td>11.58</td>
</tr>
</tbody>
</table>

As the results show, the average efficiency excluding auxiliaries gets basically the same as the verification has shown. However, there is always some uncertainty in the data recordings (even though it is low) and a constant value has been used to describe the auxiliary power consumption in the calculations when it in fact fluctuates. This means that the result should not be regarded at completely accurate, which is also clear considering the standard deviation is not very low. Rather, the results indicate that the value obtained from the verification could be representative of the locomotives operating
in the full range of operating points during real train runs. In STEC, the efficiency for the traction system is therefore set to 88.93%. For efficiency of regenerated energy, the same value is used in STEC because the same drive chain components are involved both during traction and regenerative braking. It is thus assumed that the same drive chain efficiency as during traction applies. The efficiency of the feeding system is set to 100% in STEC, since losses in the power supply system are outside the scope of this thesis.

4.1.3 Adhesion

STEC takes available adhesion into account and this limits traction forces respectively braking forces if the available adhesion is exceeded. As input to STEC, a limit value for adhesion at start and the train’s maximum speed must be defined. For this purpose, the empirical equations derived by Curtius Kniffler can be used. Equation 4.1 shows the formula used in this thesis where $v$ is the speed in m/s, which applies to dry rail conditions [23].

$$\alpha = 0.161 + \frac{7.5}{44 + 3.6 \cdot v} \quad (4.1)$$

The decision to use the formula for dry rail conditions is based on that it allows for a comparison with a paper by Lundberg et al. [43] where an IORE locomotive with 68 fully loaded wagons was run along the track of Malmbanan and the friction was measured. The reported ambient conditions are bright sky with no snow and a rail temperature of -4°C. For non-lubricated, dry rail a friction coefficient of 0.3 on average is reported for a speed range of 13 km/h to 20 km/h. For 13 km/h, Equation 4.1 gives an adhesion of 0.293 and at 20 km/h 0.278 results. Considering that available adhesion is usually a bit lower than friction, the agreement of the adhesion predicted by Equation 4.1 with the results of the field measurements is considered acceptable and the adhesion used at max speed (60 km/h) in STEC is therefore 0.23.

The STEC value is a bit lower (corresponding to a maximum speed of 65 km/h) than the result the equation gives at 60 km/h (0.233) in order to compensate for the fact that adhesion values will not be adapted in STEC even when the max speed is changed. If the max speed is increased, this will increase the available adhesion at the lower speeds in STEC since the lower limit value is reached only at a higher speed. The reason the lower adhesion limit will not be changed is the limited range the max speed is varied within and uncertainty in the small changes the Curtius Kniffler equation gives for this range.
Adhesion is a very complicated subject with a lot of factors to consider and for simplicity reasons one specific condition is chosen which is then used for the entirety of this thesis. Consequently, wet rail conditions, which limit traction forces, are not taken into account at all in the work of this thesis. But considering this allows for drivers to use the full range of traction force available, the study of powering ratio influence on energy consumption gets more meaningful since the forces are not limited by adhesion at a high traction ratio. For the same reason, the upper adhesion limit at start that is used in STEC is set higher than what Equation 4.1 gives. At rest, the equation gives an available adhesion of 0.331. If the locomotive uses full tractive force, adhesion utilisation would be [12]:

\[
\alpha = \frac{F_\alpha}{m_\alpha \cdot g} = \frac{1200}{360 \cdot 9.81} = 0.34
\]  

(4.2)

In the equation, \( F_\alpha \) is the longitudinal force at the wheels, \( m_\alpha \) is the adhesive mass and \( g \) the gravitational acceleration. It shows that a higher adhesion than Curtius Kniffler’s formula gives at start is required for the train to be able and use the full potential for traction. Since the trains in real operation are able to use the maximum tractive power at start if ambient conditions are favourable, adhesion at start is set to 0.34 in STEC. The same adhesion limit values are used in STEC for braking conditions. Adhesion utilisation is in fact always lower than the lower adhesion limit in this case though. Equation 4.3 is for the case that only the locomotive is braking with full electric brake force and Equation 4.4 for when the whole train applies full mechanical brake. No brake force limitations due to adhesion utilisation are hence expected for the dry rail conditions assumed here.

\[
\alpha = \frac{F_\alpha}{m_\alpha \cdot g} = \frac{750}{360 \cdot 9.81} = 0.21
\]  

(4.3)

\[
\alpha = \frac{F_\alpha}{m_\alpha \cdot g} = \frac{4511.52}{8520 \cdot 9.81} = 0.054
\]  

(4.4)

### 4.1.4 Running resistance estimation

The last input for the train required in STEC that has not been discussed in this section yet is running resistance. STEC assumes that running resistance can be expressed in the form of the Davis equation (see Equation 2.1), so the coefficients in this equation are the input needed for STEC. To the A-
coefficient, an average addition for curve resistance is supposed to be added, but in this thesis curve resistance is handled as part of the track input to allow for the use of a multi-particle model, see further Section 4.2. Average tunnel resistance is intended to be added to the C-coefficient in STEC, which is handled later in this section.

From the literature review, it is already known that full-scale tests have been performed on Malmbanan using two older generation ore wagons, see [33]. Of these two wagons, the MV2000 wagon is most similar to the Fanoo used today. One way proposed to estimate the running resistance could therefore be to use the formulas defined for the MV2000 wagon for all 68 wagons in a fully loaded standard train and assume the error for describing the locomotive with the same formulas is small enough considering the large number of wagons. In that case the running resistance coefficients would be [33]:

\[
A \approx \sum_{i=1}^{n_{ax}} (66 + g \cdot 0.9 \cdot Q_i) = \sum_{i=1}^{12+4\cdot68} (66 + 9.81 \cdot 0.9 \cdot 30) = 93967.1 \text{ N} \quad (4.5)
\]

\[
B \approx 0.2 \cdot L_t = 0.2 \cdot 746.2 = 149.24 \text{ Ns/m} \quad (4.6)
\]

\[
C \approx 5.4 + 0.114 \cdot L_t = 5.4 + 0.114 \cdot 746.2 = 90.47 \text{ Ns}^2/\text{m}^2 \quad (4.7)
\]

\(Q_i\) denotes the axle load, \(n_{ax}\) the total number of axles for the train, \(g\) the gravitational acceleration and \(L_t\) the train length. The uncertainty with this approach is relatively high considering the formula only applies to an older generation of ore wagons and the locomotive is treated as an ore wagon. Because LKAB had a DAS installed on the IORE-locomotives earlier [13], an estimation of running resistance could be obtained from the provider of the DAS (Transrail). Table 4.4 presents the coefficients received directly from Transrail which apply to IORE together with 68 Fanoo wagons [44].

Table 4.4 – Running resistance coefficients from estimation by Transrail.

<table>
<thead>
<tr>
<th>Cargo load factor</th>
<th>A [N]</th>
<th>B [Nm/s]</th>
<th>C [Nm²/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>49700</td>
<td>149.6</td>
<td>102.64</td>
</tr>
<tr>
<td>0%</td>
<td>23017</td>
<td>149.6</td>
<td>102.64</td>
</tr>
</tbody>
</table>
Comparing the coefficients provided by Transrail for the fully loaded train with the ones calculated with formulas 4.5 through 4.7, it can be seen that the B-coefficient is very similar. The C-coefficient is slightly higher for Transrail, which could be explained by that the ore wagon upon which Equation 4.7 is based is 1.9 m shorter than Fanoo. Most surprising is though that there is such a big difference in the A-coefficients, even though Transrails formula is for a train with only 95% cargo load (axle load 28.77 tons).

According to information from Transrail, their coefficients were determined by full-scale coasting tests. So it is reasonable to assume that the coefficients from Transrail are more accurate, especially considering they were obtained with the same class of rolling stock used in this thesis. But the difference in the A-coefficients is big (96%) and running resistance estimation accuracy depends highly on the data quality and control. In addition, no detailed information about the circumstances under which the Transrail tests were performed is available. Hence, an estimation of running resistance is attempted to ensure the Transrail coefficients are more accurate than the alternative formula proposed.

To do the estimation, monitoring system data from the old data recordings stemming from 2013 and 2014 with very high resolution is used. Due to lacking data for some parameters required for the evaluation, four train runs are excluded. Given that the position of the trains cannot be verified by GPS from the energy meter, it had to be estimated. But because it is known from notes for each train run at what meeting stations the trains are stopping, the position estimation can have accuracy up to some meters.

All train recordings are between Kiruna and Narvik, so for simplicity reasons the location with the longest straight section with constant gradient for this route was searched for in the track alignment information from Trafikverket. The longest section identified is at Abisko meeting station and is 876 m long with 0‰ gradient. Because the complete train must be on this straight line before data can be used for estimation, the effective useful length is only 130 m which results in a very limited amount of data applicable for estimation due to that all the trains run relatively fast past this section of track. When the train enters the section can be identified by knowing when and where the train stops the last time before the section and calculating the distance the train needs to cover to enter the section from that point. Due to the uncertainty of exact train position, distance margins are applied both at the start and end of the measuring section. This reduces the useful length from which measurements
Modelling can be taken further to 90 m respectively 70 m depending on the uncertainty of the train position.

Due to that not all trains are applying coasting on the measuring section, a tractive effort method is used. The direct approach proposed by Hansen et al. [32] is implemented, which is the easiest approach found in the literature that does not require any fitting algorithm. Since traction force data is available, estimation of it is not necessary and the formula used to calculate running resistance for each sample from the data within the measuring section is the following

\[ F_R = F_{\text{traction}} - F_{\text{tot}} = F_{\text{traction}} - m_e \cdot a \]  

(4.8)

where \( a \) is acceleration, \( F_{\text{traction}} \) the total traction force and \( m_e \) is the equivalent mass of the train, including tare mass, cargo load and additional contribution from rotational masses. The acceleration in the above formula can be calculated by determining the speed difference between two measurement samples 0.5 s apart. The applied method is sensitive to errors in acceleration which quickly can lead to unrealistic running resistances. Because the speed differences between samples is small and fluctuates, similar to a method employed by Ogawa et al. [34], the acceleration at each sample is calculated by using the previous and following sample speed. An average acceleration at the sample is then calculated by using the acceleration from the two previous and following samples too, see Equation 4.9. This gives a more stable acceleration estimate and ultimately more reasonable running resistance estimates. The sampling rate \( \Delta t \) is 0.5 s for the data used.

\[ a_i = \frac{\sum_{j=i-2}^{i+2} \frac{v_{j+1} - v_{j-1}}{2\Delta t}}{5} \]  

(4.9)

The results of the estimations are shown in Figures 4.5 and 4.6. The second figure is needed for an empty train included in the analysis. Two trains also only had 66 wagons, but this has little influence on the overall resistance.
Figure 4.5 – Results for running resistance estimation of loaded trains.

Figure 4.6 – Results for running resistance estimation of empty train.
As can be seen in the figures, the speed for all trains was quite high when passing the measuring section. Due to the short length of the section, the number of sample points is thus very low. Because running resistance estimation from monitoring system data depends on a large volume of samples to get a reasonable curve fitting, the estimation performed here is not suitable for that. Considering there is uncertainty in the position of the trains and ambient wind conditions too, the quality of this estimation is low. Still, because the difference in the A-coefficient of the two formulas compared is so big, even a low-quality estimate can point towards which formula is more accurate. While there is a large spread in the sample values for some trains, which is not uncommon as the estimated running resistances create a "cloud" of values which the curve is fitted against, there is a clear tendency that the majority of values are closer or even below the curve corresponding to the Transrail formula. The Transrail formula and coefficients are therefore accepted as the ones used in the simulations of this thesis.

To be able and vary the load factor and train length as part of the parametric study, the coefficients of Transrail are parameterised in the same format as Equations 4.5 through 4.7. Because the difference of the coefficient obtained with Equation 4.6 from the Transrail coefficient is so small (0.24%), Equation 4.6 is used when the B-coefficient needs to be adjusted due to changed train length. The C-coefficient from Transrail is 13.45% higher than calculated by Equation 4.7, so in case the train length is changed, the C-coefficient will be calculated by using Equation 4.7 together with a scaling factor, see Equation 4.10 below where $L_t$ is the train length.

$$
C \approx 1.135 \cdot (5.4 + 0.114 \cdot L_t)
$$

(4.10)

The A-coefficient from the Transrail-formula is parameterised in the same format as Equation 4.5, i.e. with a constant term and a changing term which is dependent on the axle load. The coefficients of this equation can be found because both an A-coefficient for an empty train and 95% loaded train exists and the linear line can be fitted to these points. The axle load in the formula is calculated as the weighted average of the locomotive axle load (always 30 tons) and the wagon axle load (varies). In order to take the number of axles into account, which can change with adjusted train length, a scaling factor is used. The resulting formula is

$$
A \approx \frac{12 + n_{wagons} \cdot 4}{12 + 68 \cdot 4} \cdot (15354.1 + 1191.7 \cdot Q_{tot})
$$

(4.11)
where

\[
Q_{\text{tot}} = \frac{12 \cdot 30 + n_{\text{wagons}} \cdot 4 \cdot Q_{\text{wagons}}}{12 + n_{\text{wagons}} \cdot 4}
\]  \hspace{1cm} (4.12)

and \(n_{\text{wagons}}\) respectively \(Q_{\text{wagons}}\) are the number of Fanoo wagons and axle load of the wagons. The above formula will likely give a higher error the farther away from the standard axle load 28.77 tons used in the Transrail formula one gets. Depending on how accurate the A-coefficient reported by Transrail is, the parameterised formula above might be more or less accurate since it is based on the data from Transrail. Still the formula is regarded to be a reasonable approach to expressing the A-coefficient and the coefficient used at 30 tons axle load in STEC is thus 51106 N for the standard train.

### 4.1.5 Tunnel resistance

In STEC it is intended that an average tunnel resistance is added to the C-coefficient input. No data about the tunnel resistance of IORE and the wagons is available. One approach for estimating the additional aerodynamic resistance in tunnels is to use monitoring data in a similar way as described for estimating the running resistance. The majority of tunnels on Malmbanan and Ofotbanen are concentrated to the area between Kiruna and Narvik and all except one are shorter than a standard train of 746 m, which makes the analysis very limited. There are also a lot of snow protection galleries along this route, see Figure 4.7. Some of these snow protection galleries connect directly to a tunnel, giving an overall length longer than the standard train length. However, the snow protection galleries are not as air-tight on the sides as a tunnel and often have a different cross-section. Thus, they result in a different additional resistance than the tunnels and only a blended estimation of both tunnel and snow protection gallery is possible. A high uncertainty is expected for such an estimation and thus it is avoided by instead checking on how high share of the total route has additional aerodynamic resistance from tunnels and snow protection galleries.

In this thesis, trains will be simulated to run from Kiruna to Narvik, see further Section 4.2. Because no data was received from the infrastructure owners, the total length of tunnels and galleries was estimated using the online tool of the Swedish cartography agency which has high accuracy maps and a functionality for measuring distances on the map [45]. Tunnels are precisely marked out on the maps and can therefore be measured up to some metres accuracy. Snow
Figure 4.7 – LKAB’s iron ore train exiting a snow protection gallery.
*Picture source: Christoph Domay*

Protection galleries are however not marked out and so satellite images in the same tool were used for estimation on Malmbanan. For Ofotbanen, no satellite images are available in the tool and the total distance of galleries in Norway are thus estimated roughly to be a bit more than the total length on the Swedish part of the route. Table 4.5 presents the estimation results, which includes additional margins.

Table 4.5 – Estimation of total tunnel and snow protection gallery length on the route from Kiruna to Narvik.

<table>
<thead>
<tr>
<th>Type</th>
<th>Total length [km]</th>
<th>Share of route length [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnels</td>
<td>8.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Snow protection galleries</td>
<td>9.5</td>
<td>5.8</td>
</tr>
<tr>
<td>Tunnels + Galleries</td>
<td>18</td>
<td>10.9</td>
</tr>
</tbody>
</table>

The results show that the share of total route length (164.73 km) for which the train runs in tunnels respectively galleries is low at around 11%. From theory, it is known that the tunnel resistance is influenced by among others the train speed, tunnel length, ventilation inside the tunnels and blockage ratio \([12, 32, 35]\). The speed of IORE is quite low at 60 km/h nominal for the
standard train and the average length of tunnels (not galleries) is short with roughly 360 m. In addition to that, the snow protection galleries often have a larger cross-section than tunnels and are not always air-tight on the sides so air can escape there, reducing resistance and pressure gradients. Based on this, the influence of tunnel resistance on the standard train used in this thesis is expected to be low.

The tunnel resistance can also be estimated with the additional resistance for a reference, typical freight mainline train from the energy baseline in the FINE1 project that is part of the Shift2Rail research programme [46]. For a 326 metre long train with a maximum speed of 120 km/h, the aerodynamic resistance is stated to increase by 10% within tunnels. The speed of a standard iron ore train is considerably lower than for the freight mainline train but at the same time the train is more than double the length. However, it must not be forgotten that in relation to the rolling resistances, the aerodynamic resistance of the standard train of this thesis is very much lower. At 60 km/h, an increase of the C-coefficient by 10% will increase the resistance the standard train needs to overcome by only 171 N, which is extremely little compared to for instance the A-coefficient of 51106 N. It is thus concluded that the tunnel resistance can be disregarded in the STEC input without much effect on the simulated run time and energy consumption.

4.2 Track

This section presents all work done related to defining the track input for STEC. For the parametric study, one route is chosen on which all simulations are then performed and for which the track input is defined in STEC. The decision has been made that the route between Kiruna to Narvik is simulated, which has several reasons. Firstly, this is the most frequently used route for the iron ore transports LKAB operates [2]. Secondly, this route has the most challenging topography of all routes LKAB operates on, which should help making the influence of different parameters, especially the driving style, on energy consumption, clearly distinguishable. Lastly, but most importantly from a practical point of view, the fact that the majority of iron ore trains operate on this route also means most data from the train event recorders is available for this route, giving the highest amount of train runs to choose from for validation. The direction is chosen to be towards Narvik, because fully loaded trains are more relevant for studying parameter impact on energy consumption than the empty/lightly loaded trains running towards Kiruna.
4.2.1 Gradients

To define the vertical alignment, data from Trafikverket’s track data base BIS [38] is used for the Swedish part of the route. The iron ore trains from Kiruna always start their journey on LKAB’s own railway yards, which are not included in the data from Trafikverket. The location where the track input starts is thus Peuravaara, which is the closest point to the railway yard defined in the data (roughly 700 metre distance from start location). The data from Trafikverket has accuracy down to the metre and vertical transition curves are also defined. STEC cannot take curves as input but only constant gradients. Hence, for the length of the transitions, the average of incoming and outgoing constant gradient is used. This creates an error as the curve is approximated by a straight line, but the smallest curve radius for any transition in the data is 55000 m so the error will be minimal. Trafikverket’s data ends at the Björnfjell meeting station.

For the Norwegian Ofotbanen between Björnfjell and Narvik, no data from the infrastructure owner was received as described in Section 3.3. The old data used instead has a resolution down to the metre, but does not include transitions. Considering the transitions in the Swedish track data are approximated as constant gradients, this does not result in a problem. However, the old track data does end 600 m short of the location of Narvik station, which was checked against data about the track-km for each station which is available on the homepage of the infrastructure owner [47]. For the final distance to track-km 3.7 where Narvik meeting station is located, the gradient of the last data point is assumed. In reality the iron ore trains usually continue even further and enter the railway yard of LKAB directly. But that is disregarded here since the additional distance for this is only around 1 km and will not lead to much additional energy consumption because the trains are decelerating anyway. To ensure the final altitude at the end of the track input is reasonable, it was checked against accurate data from an online map tool of the Norwegian cartography agency [48]. The altitude of the track input is 41.5 m at the end point and for the same location, the data tool reports an altitude of roughly 45 m (uncertainty where exactly track input ends). For a total track length of 164.73 km, an altitude discrepancy of 3.5 m is considered satisfactory. Figure 4.8 shows the altitude profile for the route.
As has been pointed out in the literature review, a multi-particle model for long freight trains is required if the highest level of accuracy is to be achieved. Because the iron ore trains operated by LKAB are both heavy and very long, a distinct error is expected in the results of simulations performed with STEC since it assumes the train to be a single particle. To increase accuracy and reliability of the results, a multi-particle model is implemented. Two approaches for implementing this were considered. Firstly, there is the possibility for build-on customisation in the underlying scripts for STEC where a multi-particle model could be implemented. The second approach is to write a separate script which recalculates the gradients for the track input in STEC. Advantage of the first approach is that once it is implemented, it would require very little work if the track input is changed. On the downside, changing the scripts for STEC would be complex and time-consuming due to that the performance of the simulation tool after the script changes would have to be verified. The second approach allows for a simple implementation without changes in the underlying scripts of STEC. The disadvantage is that every time a change to the track input is made, the script has to be run again and the new track input manually added in STEC. Comparing the two approaches and considering the limited time budget of the thesis, the downsides of approach number one outweigh its advantages and the latter approach is thus used.

Implementation of the script is done in Matlab [49]. The way it works is that it is assumed that the distance \( x_j \) STEC is currently at in the process of the simulation represents the front of the train. Knowing the location of the front, the gradients for the last 750 m are summed up and the average is calculated,
see Equation 4.13 below. This value is then the new track input at that distance step \( x_i \) of the track input.

\[
G_{\text{multi},i} = \frac{1}{L_{\text{tot}}} \cdot \sum_{i=L_{\text{tot}}/\Delta x}^{i} G_{\text{single},i} \cdot \Delta x
\]  

(4.13)

In the equation, \( G_{\text{single},i} \) is the actual gradient from track data, \( L_{\text{tot}} \) is the total train length rounded upwards to the closest multiple of \( \Delta x \), which is the step length. In STEC, a step length of 10 m is used and the data of the gradients is also input at that resolution. This explains why, even though the standard train is 746 m long, \( L_{\text{tot}} \) is 750 m. This gives some small error compared to if the average gradient would have been calculated for 746 m only. More importantly though, the equation does not take the varying mass density along the length of the train into account. The locomotive has a mass density of 7.9 tons per metre and the wagons 11.67 tons per metre at 30 tons axle load. Though, the locomotive only stands for 6.1% of the total train length and the rest of the train can be assumed to have an equivalent mass density. So the error resulting from assuming homogeneous mass density along the length of the train will be limited and the multi-particle gradient estimation is still much more accurate than with the single-particle model.

The choice of using 10 m as the step length in STEC is based on that it is the smallest step length recommended to be used in STEC. A smaller step length will give more precise simulations, but at the cost of computational time, which is not an issue here since the additional time required is only some minutes when choosing the smallest recommended step length. The step length was therefore set to an as low value as possible, i.e. 10 m. A higher gradient resolution than the step length for the track input of STEC does not give any benefits and so it is limited to the same resolution as the step length.

### 4.2.2 Horizontal alignment

From full-scale tests with ore wagons on Malmbanan, it has been reported that the curve resistance stands for a significant part of the total rolling resistance [33]. Also taking into account that curve radii between Kiruna and Narvik get as low as 300 m, it is very clear that the curve resistance is important in the simulations of this thesis. In STEC it is only possible to input the average curve resistance as part of the A-coefficient in the Davis equation and the complete train is assumed to be at the same curve radius, i.e. a single-particle
representation. For the very long and heavy iron ore trains, the curve resistance for different parts of the train can vary significantly depending on the local alignment. To solve this issue, a multi-particle representation of the train is used like for the gradient input to STEC. However, since curves cannot be input as part of the track input, the curve resistance is recalculated into an equivalent positive gradient resistance that is added to the local multi-particle gradient (note potential energy gain for this, in reality energy loss due to curves).

The data for the horizontal track alignments is obtained from the same sources and with the same level of detail as for the gradients described earlier in this section. So for the Swedish part of the route, curves, straight lines and transitions are available. The old data for Ofotbanen lacks data about the transitions but includes everything else. Missing transitions of course mean the horizontal orientation of the train at the endpoint of the track input in STEC will not be correct. That does not have any effect on energy consumption in itself though, in contrast to the final altitude which is related to potential energy, so no check is performed for this.

For the transitions in the Swedish data, the average curve radius for the transitions must be determined to be able and calculate the curve resistance in a reasonable way. Average curve radius is determined from the average of incoming and outgoing curvature of the linear clothoid used by Trafikverket in transitions [50]. Equation 4.14 applies for the case when the transition connects a straight line with curvature zero with a curve with outgoing radius $R_2$. If the transition instead starts from an incoming curve radius $R_1$ and ends at the outgoing curve radius $R_2$, the radius of the average curvature can be described by Equation 4.15.

$$ R_{average} = 2 \cdot R_2 $$  \hspace{1cm} (4.14)

$$ R_{average} = \frac{2 \cdot R_1}{2 + R_1 \cdot \left( \frac{1}{R_2} - \frac{1}{R_1} \right)} $$  \hspace{1cm} (4.15)

When it comes to the actual calculation of curve resistance, the formula reported for the MV2000 ore wagon in [33] is used, see Equation 4.16. It is based on full-scale tests where both equations for the old Uad class ore wagon and MV2000 class ore wagon were established. Fanoo has an upgraded variant of the three-piece bogie used on the Uad wagons, while the MV2000 wagon has radial steering capability thanks to a linkage system. Thus, the running
resistance for Fanoo is somewhere in between Uad and MV2000. However, it can be considered to be closer to the MV2000 [51].

\[ F_c = \sum_{i=1}^{n_{ax}} Q_i \cdot \frac{500 \cdot g}{R - 55} \]  

(4.16)

In the formula, \( n_{ax} \) is the number of axles for the train, \( Q_i \) is the axle load, \( g \) is the gravitational acceleration and \( R \) is the curve radius. To implement the multi-particle representation of the curve resistance, the calculations are integrated into the same script which is used for calculating the multi-particle gradient described earlier. So, each distance step \( x_i \) is assumed to be the front of the train and for the 750 m before that (for the standard train), the curve resistance for the single-particle model is calculated every 10 m, which is the step length \( \Delta x \). The average of these resistances is then calculated and the resulting curve resistance is recalculated into an equivalent gradient which is added to the multi-particle gradient calculated in Equation 4.13, see Equation 4.17. \( m_{tot} \) is the total mass of the train and \( L_{tot} \) the train length.

\[ G_{new,i} = G_{multi,i} + \frac{1000}{m_{tot} \cdot g \cdot L_{tot}} \cdot \sum_{i=i-L_{tot}/\Delta x}^{i} F_{c,i} \cdot \Delta x \]  

(4.17)

\( L_{tot} \) must again be rounded upwards towards the closest multiple of the step length \( \Delta x \). This again creates a small error (compare with gradient calculations), but the curve resistance in Equation 4.16 is calculated with the individual axle load of each axle, so no error due to assumption of homogeneous mass density exists. However, Equation 4.16 is in the source stated to only be valid for curve radii above 350 m. Considering the smallest curve radius on the route from Kiruna to Narvik is 300 m, some error must be expected from this. Because the smallest curve radius is only present on Ofotbanen where the train runs downhill almost all the time, the error for predicted energy consumption is acceptable since the train is constantly braking anyway. The run time should not be affected at all.

Lastly, it should be mentioned that because the track input gradient is increased everywhere due to that the equivalent curve resistance is added everywhere, the final altitude in the simulation will not be reasonable anymore, see Figure 4.9 for the standard train. But because STEC in each step calculates the energy consumption based on the local gradient, this will not result in an error of the predicted energy consumption. The higher altitude at the end position...
can be interpreted as that the potential energy of the train has been reduced by the amount of energy required for the train to overcome the total curve resistance along the simulated route (2075.6 kWh for altitude difference 89.4 m; approximate since actual altitude does not include original multi-particle gradient). The final output of the script is a vector that includes gradients for the multi-particle representation of the gradients and curves along the simulated route with step length resolution.

![Figure 4.9 – Comparison of actual altitude profile and profile generated with multi-particle representation of gradients and curves (30 tons axle load).](image)

### 4.3 Operations: Base case

The purpose of this section is to present the work done to define the base case used for the parametric study. For more information about the purpose of the base case, see Section 3.5. Making the simulated energy consumption in the parametric study reasonable from an operational point of view is important because an unreasonably fast train for instance has a too high energy consumption compared to what a fast train in reality would consume. In that case the results of the simulation cannot be properly compared with how the trains are actually operated. There are several inputs to STEC that can be changed to create a reasonable operational profile for the simulations. As part of the track input, the line speed limits must be defined. However, the speed limits can also be set lower to force the simulated train to slow down at a specific section of track where that is expected, such as steep uphill gradients. Instead, the maximum speed of the train could of course be lowered to an
average speed. But that would mean that the train only runs at a reduced max speed without any major speed variations which is unrealistic. Also, in order to be able and properly see the effect of changes to some of the parameters in the parametric study, such as traction ratio, braking ratio and coasting, accelerations and decelerations along the route must exist. It is also possible to define the location of stops for the simulated train and for how long the train should dwell before starting to move again. To simplify study of the effect of adding stops on energy consumption, per default no stops should be included.

For the base case, it can be concluded from the above that it should be defined for a train that has no stops along the route and that has speed variations along the route. In order to create a realistic speed profile for such a train, data for all through trains available on the route from Kiruna to Narvik is extracted from the train event recorders (see Section 3.3 for a description of this data source). A total of ten train runs could be found in the data. Because the starting position of the trains on the railway yard in Kiruna varies, using the GPS position of the energy meters, the speed profiles are normalised so that only data from when the trains are passing the point where the track input for STEC starts (Peuravaara) is included. Due to that the speed recordings have small changes all the time and the sampling rate is not constant, the average speed of all samples within 250 m distance is calculated for every train. This averaged speed is then in turn averaged for all ten trains within the same distance interval of 250 m. In Figure 4.10, the averaged speed profiles for all ten train runs is shown together with the average of all speed profiles.

![Figure 4.10 – Averaged speed profiles of recorded non-stop train runs from Peuravaara to Narvik and average of these profiles in bold purple.](image-url)
Based on the average speed profile of the ten recorded train runs, the line speed limits for the track input in STEC can be defined. However, as can be seen in Figure 4.10, the speed profiles of the trains are not completely in sync at the end where some trains seem to arrive earlier in Narvik. This could be due to that some trains have a longer route when they cannot use the tunnels on Ofotbanen as shortcut. The speed profile defined for STEC is thus oriented at the changes in the multi-particle track gradient (including curves) rather than the exact location where the average speed profile has a significant change in speed. As standard, reductions in the speed limit start when the gradient has increased to 3 ‰ to facilitate coasting before that and increases in speed limit are placed where the gradient gets negative. But speed limit changes are only introduced when there is a significant change in the gradient and the average speed profile. The defined speed limits in STEC and the average speed profile can be seen in Figure 4.11.

![Figure 4.11 – Comparison of line speed limit, base case speed profile and averaged speed profile of recorded non-stop train runs.](image)

As Figure 4.11 shows, the defined speed profile is always below the line speed limits, which are also showcased. On Malmaban the line speed limits are often even higher than the 70 km/h indicated, but practically a loaded iron ore train is only allowed to operate at 60 km/h and cannot overspeed more than 10 km/h without ATC intervention. It can further be noted that the defined speed profile often has a higher top speed of 64 km/h compared to the average speed profile. In the context of the parametric study, this allows for some variation of the train max speed without being limited by the defined speed profile, which acts as line speed limit in the simulation.
With the background that STEC always applies as much tractive force and braking force as possible during accelerations and decelerations, traction and braking curves are also limited so that the maximum forces are approximately never higher than what any of the drivers from the ten recorded train runs used. In Figures 4.12 and 4.13 the defined traction curve and electric braking curve for the base case are shown together with a scatter plot of applied forces by the real drivers. The mechanical brake curve is defined with the help of forces in STEC, but for comparability reasons it is shown as brake pipe pressure in Figure 4.14 where 3.5 bar is equal to full mechanical braking force and 5 bar means zero mechanical braking force.

![Figure 4.12 – Defined traction curve for base case.](image)

![Figure 4.13 – Defined electric brake curve for base case.](image)
The remaining base case train input parameters for STEC, that have not been mentioned in this section, are summarised in Table 4.6. The base case uses the standard train (746 m, 30 ton axle load). For the multi-particle gradient input for this standard train, refer to the resulting altitude profile in Figure 4.9. The total simulated distance is 164.73 km with a step length $\Delta x$ of 10 m. In the parametric study results presented in Section 5.2, whenever an input parameter is not mentioned, refer to the inputs defined in this section.

Table 4.6 – Train input defined for base case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max speed</td>
<td>60</td>
<td>km/h</td>
</tr>
<tr>
<td>Tare mass</td>
<td>1828.8</td>
<td>t</td>
</tr>
<tr>
<td>Adhesive weight</td>
<td>360</td>
<td>t</td>
</tr>
<tr>
<td>Rotating mass contribution</td>
<td>8.94</td>
<td>%</td>
</tr>
<tr>
<td>Cargo load</td>
<td>6691.2</td>
<td>t</td>
</tr>
<tr>
<td>A-coefficient</td>
<td>51106</td>
<td>N</td>
</tr>
<tr>
<td>B-coefficient</td>
<td>149.6</td>
<td>Ns/m</td>
</tr>
<tr>
<td>C-coefficient</td>
<td>102.64</td>
<td>Ns²/m²</td>
</tr>
<tr>
<td>Efficiency (traction/braking)</td>
<td>88.9</td>
<td>%</td>
</tr>
<tr>
<td>Efficiency feeding system</td>
<td>100</td>
<td>%</td>
</tr>
<tr>
<td>Adhesion limit at rest</td>
<td>0.34</td>
<td>-</td>
</tr>
<tr>
<td>Adhesion limit max speed</td>
<td>0.23</td>
<td>-</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>273.4</td>
<td>kW</td>
</tr>
<tr>
<td>Efficiency auxiliaries</td>
<td>100</td>
<td>%</td>
</tr>
</tbody>
</table>
Chapter 5

Results & Discussion

5.1 Validation

In this section, the results of the two validations done for the train and track model defined as input to STEC are showcased. The validation also serves as an assessment of the performance of the simulation tool STEC. Based on an understanding of the performance, comments about the adequacy of the defined base case for performing the parametric study are given too. For more information about the process of the validation, refer to Section 3.4 of the methodology chapter.

For being able to validate the model, recordings of real reference train runs are needed. The criteria for the selection of suitable reference train runs are:

- Correct route (from Kiruna to Narvik)
- Two stops on Malmbanan with short distance between them
- Simple speed profile
- Very high axle load
- Different rolling stock units and track sections for first and second validation

Two stops are required to be able and simulate the train from start to stop and these should be on Malmbanan because the track input has higher quality here. A short distance and simple speed profile help to simplify the speed fitting versus the reference train. The very high axle load ensures the reference
train operates at full length (68 wagons) and close to the base case, which is relevant since the defined input to STEC is expected to have lower accuracy the farther away from the 30 tons axle load it gets. Lastly, the different rolling stock units and track sections should prove the input parameters to STEC to be valid for all rolling stock of the same class and the multi-particle model too.

From the four data files from train event recorders of four different locomotive units, only three train runs from two locomotives could be identified that fit the criteria. The shortest one of these only covers a distance of 10.55 km and is thus used for the first validation. Both of the remaining cover a distance of roughly 23 km and the one with the simpler to handle speed profile is used for the secondary validation.

### 5.1.1 First validation

The real train run used as reference for the first validation runs from Stordalen meeting station to Abisko meeting station. Locomotive sections 114 and 120 are pulling the train that has a cargo load of 6533 tons, equal to 29.42 tons axle load for the wagons. Using Equation 4.11, the A-coefficient is set to 50442 N. Track input is calculated as described in Section 4.2. After defining this, the process described in Section 3.4 is followed, i.e. speed limits, traction and braking curve are adjusted to fit the speed profile of the reference train. Coasting is applied too. Max speed for the train is 64.25 km/h. For the remaining input parameters that have not been mentioned here, refer to the definition of the base case in Section 4.3 which uses the same values for these.
Figure 5.1 shows the resulting speed profile for the validation. As can be seen, the agreement between simulation and the real reference train is very good. However, when looking at the corresponding power profile in Figure 5.2, only some parts show good agreement with the reference train. The reasons for this lack of agreement did not lead to any calibration of parameters, since no obvious cause of the disagreement stemming from inaccurate input parameters could be identified. Rather, reasons for the disagreement mainly originates from limited options that STEC offers for replicating driver behaviour of the real train, i.e. lack of a driver model.

![Figure 5.2 – Comparison of power profiles for simulated and real train.](image)

The first reason for the disagreement can be seen when studying the scatter plot of applied forces at the locomotive wheels in Figure 5.3. While the real train uses varying traction forces at the same speed on different parts of the trip, STEC will always try to use the full available traction force. This explains why the red data points from the simulation nearly all follow the defined traction curve, which can be distinguished in the scatter plot. To limit the aggressiveness of accelerations and electric braking made in the simulation, the traction curve is limited at a lower force than some of the real train data points might suggest. Using limitations in the traction force will lead to another problem too, since for instance shortly after 200 s, the speed drops for the real train. Because only one traction force limit can be defined at every speed in STEC, the drop in speed will lead to that STEC applies full traction force again, while the real train applies a lower traction force than just shortly before when the train still was accelerating at the same speed. The traction curve in STEC was trimmed to minimise this problem, but it cannot
be completely mitigated. All power profiles differences in Figure 5.2 up until 530 s can be explained by this issue with erroneous traction forces.

![Figure 5.3 – Scatter plot of applied forces (excluding mechanical brakes).](image)

Shortly after 530 s, the real train starts coasting for a short time while the speed increases. STEC does not have that functionality but can only apply coasting when the speed is supposed to decrease, which leads to a first negative power spike and thereafter to positive power spike. Upon reaching the speed limits enforced as part of the track input to follow the speed profile of the real train, STEC keeps the speed exactly, which is not realistic since the driver does not know the exact resistance the train is facing at the moment and the speed thus fluctuates. This is not visible in the speed profile of the real train since the data used is from the long-term memory of the train event recorder which has a lower resolution. Still, because STEC follows exactly the target speed (speed limit) upon reaching it, it leads to a lot of shifts in power and power spikes, which is especially visible in the range from 650 to 710 s. These instant power spikes are not realistic in reality either, due to that a real driver would require some time to make the adjustments to the power as STEC applies them.

Since STEC does not take mechanical brake application time into account, the brake force from these is often also applied instantaneously, see figure 5.4 where the brake pipe pressures change instantly for the simulation. It looks like the same is the case for the real train, but the brake main pipe pressure shown for the real train is measured at the locomotive, so it takes some time before the pressure drop has reached the last wagon. To mitigate this problem to some extent, the mechanical brake force limit defined in STEC is scaled down
by 70% compared to what the actual brake pipe pressure would correspond to, so that the average force value for a short mechanical brake application in the simulation is more reasonable. The brake pipe pressure for the simulation shown in Figure 5.4 corresponds to these lower mechanical brake forces. A last flaw in the simulation is that STEC always prioritises the electric brake over the mechanical brake. This is of course the best approach to save energy by recovering as much braking energy as possible. However, the real train uses more mechanical brake than electric brake sometimes too. This is visible around 615 s, where STEC uses a much higher electric braking power than the real train, but also has a much lower brake pipe pressure reduction.

![Figure 5.4 – Comparison of brake pipe pressure for simulated and real train.](image)

In the end, even though a lot of optimisation for the traction and braking curves has been done, the complex behaviour of the driver of the reference train cannot fully be imitated. The lack of a dedicated driver model makes it really hard to achieve a reasonable behaviour in STEC and the fact that only one traction and braking curve can be defined for the complete simulation makes it even more complicated. Unsurprisingly, given the described problems, the energy consumption results for the simulation presented in Table 5.1 are not so good. The very high relative error for regenerated energy mainly stems from the higher use of electric brakes than mechanical brakes for the simulation, especially in the range from 620 to 650 s. The very good agreement of run time is expected given the close matching of the speed profiles in Figure 5.1. The error for gross energy could be reduced a lot by optimisation, but given the flaws of STEC described earlier a closer matching of the real train power profile is not believed to be possible because these flaws can explain most
of the deviation. Therefore, no parameter calibration was performed and the parameters are believed to be accurate enough.

Table 5.1 – Results for first validation (separate logging of consumption for the two locomotive sections of real train, altitude increase start to finish 3 m).

<table>
<thead>
<tr>
<th></th>
<th>Gross Energy [kWh]</th>
<th>Regenerated energy [kWh]</th>
<th>Run time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>951.75</td>
<td>237.56</td>
<td>959.1</td>
</tr>
<tr>
<td>Real train</td>
<td>842</td>
<td>186</td>
<td>953</td>
</tr>
<tr>
<td>Absolute error</td>
<td>109.75</td>
<td>51.56</td>
<td>6.1</td>
</tr>
<tr>
<td>Relative error</td>
<td>13.04%</td>
<td>27.72%</td>
<td>0.64%</td>
</tr>
</tbody>
</table>

It should be emphasised that no speed limits were enforced for the first 6.4 km of the simulation, see Figure 5.5. Given the close matching of the speed profile and good matching of the power profile for the most part of this distance, the resistance that STEC simulates must be quite accurate.

Figure 5.5 – Speed limits used in simulation and resulting speed profile.

5.1.2 Second validation

With an increased understanding of what flaws STEC has when it comes to imitating real train runs, some criteria were set up for choosing the reference train of the second validation. No coasting while the speed increases should be present. Also, the range within which the speed varies after acceleration at start should be as small as possible to be able to determine a reasonable traction curve for each speed valid for the whole simulated trip. Considering
the problems with distribution between mechanical and electric braking and brake application time, as little braking as possible should be applied in the real train run. However, since only two train runs could be chosen from, the above criteria could not be fulfilled. Still, the criteria helped when choosing between the train runs and one of them was discarded due to very early braking.

The total distance between stops of the chosen train run is 23.6 km, but to avoid coasting when the speed increases, only the first 12.12 km are simulated. This is the last point where an energy meter recording is available before coasting at speed increase is applied, so the simulation ends while the train is still in motion. No braking and coasting are applied at all during the simulation, removing the error sources connected to these completely. The reference train run starts between Björkliden meeting station and Kopparåsen meeting station. While the leading locomotive section is the same as in the first validation, the second section is different (106) and the wagons too. With a cargo load of 6590 tons (axle load 29.63 tons) the A-coefficient is 50682 N according to Equation 4.11. Max speed is 53.5 km/h. For the remaining inputs, refer as for the first validation to Sections 4.2 and 4.3.

![Figure 5.6 – Comparison of speed profiles for simulated and real train.](image)

The speed profile for this validation is not as closely matched as for the first validation, see Figure 5.6. The reason for this is, similar to the first validation, the problem that the speed drops and STEC applies full traction according to the defined traction curve, while the real train applies a lower traction. A compromise is always required for defining the traction curve, since if the traction force limit is set too low at a certain speed, this may cause problems later on in the simulation when the train requires a higher traction force to
overcome a gradient at the same speed. This explains the power peaks at these locations in the power profile when the traction force limit jumps, see Figures 5.7 and 5.8. The remaining power peaks of STEC in comparison to the reference train result from that speed limits are enforced to limit the speed in the simulation as much as possible without risking application of brakes (see Figure 5.9). Because STEC follows the enforced speed limit closely where that is a limitation, applied traction force varies unrealistically quick. A better speed fitting would of have been possible, but by avoiding braking in this validation, a substantial source of error for the first validation is eliminated.

![Figure 5.7](image1.png)
**Figure 5.7** – Comparison of power profiles for simulated and real train.

![Figure 5.8](image2.png)
**Figure 5.8** – Scatter plot of applied forces (excluding mechanical brakes).
All in all, while the real train driver cannot be imitated completely, several sources of error in the first validation do not exist in the second validation. It is therefore expected that the simulated energy consumption has a lower deviation from the reference train. In fact, the gross energy consumption error has been reduced by around 70 kWh compared to the first validation. Because the accumulated gross energy is so much bigger than in the first validation, the relative error gets very low, see Table 5.2. Note that since the simulation ends while the train is in motion, any difference in speed at the end of the simulation will result in a difference in kinetic energy. This is compensated for in the results, where the end speed of the simulation is 3.97 km/h lower, equal to 1.42 kWh. Given that the speed of the simulated train is higher for some parts of the trip, the deviation in run time increases compared to the first validation. Though the error is still very acceptable considering that braking could be avoided all together as a consequence of this.

Table 5.2 – Results for second validation (separate logging of consumption for the two locomotive sections of real train, altitude increase start to finish 68 m).

<table>
<thead>
<tr>
<th></th>
<th>Gross Energy [kWh]</th>
<th>Regenerated energy [kWh]</th>
<th>Run time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>2277.41</td>
<td>0</td>
<td>1162.2</td>
</tr>
<tr>
<td>Real train</td>
<td>2238</td>
<td>0</td>
<td>1179</td>
</tr>
<tr>
<td>Absolute error</td>
<td>39.41</td>
<td>0</td>
<td>-16.8</td>
</tr>
<tr>
<td>Relative error</td>
<td>1.76%</td>
<td>0%</td>
<td>-1.42%</td>
</tr>
</tbody>
</table>
5.1.3 Discussion of validation

The second validation does not really serve as a way to ensure any parameter calibration from the first validation is accurate, as originally intended. Because no obvious source of error related to the parameter input was found, no calibration is performed that could be checked in the second validation. Instead, based on the understanding gained about limitations of STEC in the process of the validation, the second validation serves as a way of validating the explanations for error sources found in the first validation. The lacking control over STEC described above has made it really hard to validate the actual model used in the simulation. The lack of a dedicated driver model gets apparent here. It is interesting to see that all the flaws of STEC described are almost exclusively applicable to freight trains. Originally, STEC was developed for passenger trains. Passenger trains usually accelerate quickly to max speed and roughly try to keep it without taking the topography too much into account. So flaws such as not being able to coast while the speed increases is not really a problem there since the train tries to accelerate as fast as possible anyway.

In the end, considering the good results for the second validation it is believed that the errors in energy consumption can in fact to a large extent be explained by the lacking control over the behaviour of STEC when imitating a reference train. A driver model is certainly missing. Good understanding of STEC’s performance has been achieved too. The input parameters and multi-particle model used for STEC are believed to be accurate enough to generate satisfactory predictions of gross energy consumption for all rolling stock of the same class. This is based on the good prediction in the second validation and that the prediction error of the first validation is very likely to be below 10% in case the described flaws of STEC would not exist. The first validation also showed that simulated resistance is quite accurate. However, given that regenerated energy is not considered at all in the second validation and the error was high in the first validation, the parametric study results will focus on gross energy, since regenerated energy results must be interpreted very carefully. It is worth mentioning that the reference train runs operated in winter conditions and the validation is only applicable for these ambient conditions.

If more time would have been available, additional data from the train event recorders from more locomotive units could possibly have been gathered. With a higher volume of data, better suited reference trains could maybe have
been found that are easier to validate given the flaws of STEC. The impression during the data evaluation was that the fully loaded trains on the route from Kiruna to Narvik very seldom stop at two consecutive meeting stations though, so a huge amount of data would have to be evaluated to find several train runs to choose from. Given all data analysis for the validation is performed manually in this thesis, this would require a larger time budget than available or a data tool that can perform the data analysis.

In the parametric study, the limitations of today’s STEC are less of a problem since no reference train needs to be imitated. The base case simply defines a "driver" that behaves like STEC simulates it. However, the problems that only one traction and brake curve can be defined for the whole simulation in combination with that STEC always uses the limit value when the speed is changing remains. Consequently, STEC simulates a very aggressive driving style that does not even consider coasting in order to increase the speed. On the other hand, the simulated "driver" always prioritises the electric brake, which is part of eco-driving. The only part that is actually unrealistic in the simulation of the base case is the fact that traction and brake forces are applied instantaneously, which results in very fast speed changes. This can be seen in Figure 5.10, where the simulated speed profile for the base case follows the defined speed limits very closely.

![Figure 5.10 – Comparison of simulated speed profile for base case with defined speed limits and averaged speed profile of recorded non-stop train runs.](image)

To some extent the unrealistically fast force application times can be mitigated by reducing the force limits in the traction and braking curve to the most common values of real train operations (compare e.g. Figure 4.12) so that an
average acceleration is replicated. The problems arising from this are though, that it is not so clear for all of the speed range what is the most common value and that the common value might not always suffice for propelling the train properly for the whole trip. A higher traction force might be required at specific locations to overcome gradients, given that the speed profile defined through the speed limits is individual for the base case.

Unsurprisingly, given the aggressiveness and instantaneous force application simulated by STEC, the base case has a poor energy performance. Table 5.3 shows the results from the simulated base case (total route Kiruna to Narvik) and compares them with the highest gross energy, highest amount of regenerated energy and shortest run time of any of the ten train runs used to define the speed profile, traction and braking curve for the base case. Compared to the "worst" driver, STEC overestimates the gross energy by nearly 30%. This is in line with what has been reported in [19], where it is stated that not including a driver model in the simulation can lead to overestimates of up to 30%. In the context it should be noted that even the "worst" driver from the real train runs drives much more energy efficient than what STEC simulates. The run time of STEC is also very fast, however it is only slightly more than a minute faster than the fastest real train run. Finally, the very high error for regenerated energy confirms that the resulting regenerated energy from simulations must be interpreted very carefully, though it can be explained to some extent by that the regenerated energy at the higher electric brake forces generated by the locomotive in "boost" mode cannot be accepted by the power supply system everywhere. When descending on the long steep downhill towards Narvik, STEC constantly uses the full available electric brake force. For the following parametric study results, these always have to be understood and interpreted in relation to the limitations of STEC when it comes to driver behaviour and force application times described in this section.

<table>
<thead>
<tr>
<th></th>
<th>Gross Energy [kWh]</th>
<th>Regenerated energy [kWh]</th>
<th>Run time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>12938.77</td>
<td>10286.58</td>
<td>11703.6</td>
</tr>
<tr>
<td>Real trains</td>
<td>9994 (highest)</td>
<td>5112 (highest)</td>
<td>11770 (shortest)</td>
</tr>
<tr>
<td>Absolute error</td>
<td>2944.77</td>
<td>5174.58</td>
<td>-66.4</td>
</tr>
<tr>
<td>Relative error</td>
<td>29.47%</td>
<td>101.22%</td>
<td>-0.56%</td>
</tr>
</tbody>
</table>

Table 5.3 – Comparison of base case with recorded non-stop train runs.
5.2 Parametric study results

The results of the parametric study will be presented in this section. For each investigated parameter, a short definition in the context of the parametric study is given. Only input parameters that have been changed in comparison to the base case are mentioned. Refer to Section 4.3 for the remaining parameters. Results for regenerated energy are seldom shown due to high uncertainty.

5.2.1 Powering ratio

The powering ratio is defined as the amount of power used when applying traction in relation to the maximum possible. A powering ratio of one is thus equal to 10800 kW, which is the upper limit for IORE, and no further limitations to the traction power are considered in STEC.

For the analysis of powering ratio, the only change to the base case is that the traction curve is changed. As seen in Figure 5.11, the traction curves are in this case only limited by the power and not by the maximum traction force of any driver as for the base case traction curve (compare Figure 4.12). Consequently, the gross energy consumption for the base case of this analysis changes. For a power ratio of one (100%), gross energy amounts to 12945 kWh, run time is 11686.7 s and the analysis results are presented in relation to these numbers.

![Figure 5.11 – Defined traction curves for powering ratios.](image)

The powering ratio is a driver-describing parameter and related to how aggressive the driving style is. This can be explained by that, while running at a relatively constant speed or constant speed like STEC simulates it, the
power required to keep the speed is usually given and relatively constant. It is rather when the train is increasing its speed significantly, i.e. during the accelerations, that the powering ratio matters, because the driver can actively choose how much power to apply. A higher ratio gives a faster acceleration. Note that the lowest powering ratio analysed is 0.6 due to that an even lower ratio would have limited the ability of the train to overcome gradients.

Figure 5.12 – Results for powering ratio analysis.

In Figure 5.12, the results are presented. They are in line with what has been described above, so a lower powering ratio and more gentle acceleration will result in lower gross energy consumption, but increase the run time. The absolute savings presented in the figure only apply to the specific speed limits defined for the base case. Since these determine how frequent and how much the train accelerates, the speed limits specify how much influence the powering ratio has on energy consumption. Given that the speed limits are defined according to a typical average speed profile, the numbers should represent a realistic estimate. Though, the instantaneous full power application of STEC will cause some error and a real train will probably have even more shorter accelerations with a smaller influence. Also, STEC always applies the maximum available traction force, which is good for comparability, but not realistic for a real driver.

The relative difference results must be interpreted carefully given that they are calculated in relation to the simulation results for a powering ratio of one. The gross energy is unrealistically high as for the base case, so for a more realistic driver with a lower gross energy, the relative difference of gross energy, given
the powering ratio, will likely increase. The opposite is expected for the run time. Real drivers have a longer run time and so the relative difference in run time is expected to decrease. All in all, this means it is expected that the relative difference of a reduced powering ratio is equal to or higher for gross energy than for run time.

An explanation for the fact that the absolute and relative difference changes more in the lower powering ratio range could be that heavy freight train drivers usually accelerate when the topography is advantageous with little or no uphill gradient and downhill gradient in the best case. The speed limits for the base case have been designed according to this assumption, so speed limits increase when the gradient is favourable. Consequence of this behaviour is that the lower powering ratio leads to a longer time for acceleration varying quadratically. In turn, this means gradient resistance helps accelerating the train for a longer time, i.e. as a second-order polynomial. Such a shape can be distinguished in the result figure. The powering ratio can be concluded to be significant for energy consumption.

5.2.2 Braking ratio

Braking ratio is defined as the amount of braking force used of the maximum available from the combination of electric and mechanical brakes. Similar to the powering ratio, this is a driver-describing parameter. It expresses how aggressively the driver chooses to decelerate when a significant speed reduction is required.

For this analysis, only the brake curve is changed compared to the base case. The total available braking force is set to the maximum possible, regardless of any limitations that STEC does not take into account. The total braking force curve is then scaled down uniformly over the whole speed range, see Figure 5.13. Gross energy consumption for the base case of this analysis, with a braking ratio of one (100%), is 12967 kWh and run time amounts to 11675.6 s. It was possible to scale down the brake forces all the way to a ratio of 0.3. Below that, the braking force would get too low to handle the steep downhill gradients on Ofotbanen. Here, the fact that only one braking curve can be defined for the whole simulation is the limitation, since even lower ratios would have been of interest because they are commonly applied by drivers.
Similar influence on energy consumption is expected for the braking ratio compared to the powering ratio, as a slower deceleration will take more advantage of the gradients for speed reductions. In addition, there is the effect that a longer distance for braking means less distance at full speed. The speed limits of the base case are set so that a reduced speed limit starts at an uphill gradient. A longer time for braking following a second-order polynomial is expected to result from a reduced braking ratio and likewise curve for gross energy. When looking at the results in Figure 5.14, such curves can be distinguished.

Figure 5.13 – Defined braking curves for braking ratios.

Figure 5.14 – Results for braking ratio analysis.
The absolute and relative reductions are much lower than for the powering ratio though. For several reasons, this discovery must be interpreted carefully. Firstly, the lack of brake application times will have a bigger influence on how realistic the simulation is compared to the traction application time which is very short. Secondly, the high braking ratios are very seldom applied in real operation (compare Figure 4.14) and the low ratios (<0.3) that are common could not be analysed. Thirdly, the defined speed limits for the base case in STEC are favourable for the powering ratio due to that a higher speed limit is starting when the gradient shifts to the negative sign. Through (mostly) the whole simulated accelerations, the gradient is thus in favour. However, since reduced speed limits in general are starting when the uphill gradient reaches 3‰, the distance with an uphill gradient, that is in favour of speed reductions, is often relatively short. When the braking ratio is reduced, this means the braking will often have to start already when the gradient still is negative. This counteracts the effect of reduced energy consumption when the gradient can help reduce the speed more. In other words, the design of the speed limits for the base case restricts the comparability. So, while the results show that the braking ratio indeed has an effect on energy consumption and run time in the way that is expected, the amount of energy savings that are achieved through a reduced braking ratio and the increase in run time remain unclear.

5.2.3 Ratio of mechanical and electric braking

The ratio of mechanical and electric braking refers to how much of the total braking during the trip is done using the electric brakes, i.e. a measure of how much of the energy wasted during braking is recovered. To save as much energy as possible, the literature review has shown that braking should be avoided as much as possible. When braking is necessary, the electric brake should be used as frequently as possible and the mechanical brakes as little as possible. It is the driver that decides what brake to use how often and how much, so this ratio is a driver-describing parameter.

Because STEC always prioritises the electric brake and uncertainty is high for regenerated energy results, an analysis of this parameter with the help of STEC is not possible. Instead, data from the ten recorded through train runs, used to define the speed profile, traction and braking curve of the base case, is analysed. The train run with the highest amount of regenerated energy and the train run with the least regenerated energy that starts from the same location of the railway yard in Kiruna have been selected. The difference in cargo load
is also only 6 ton and the same leading locomotive section is used, giving very similar conditions for the two train runs. The difference in the regenerated energy is huge with 5112 kWh compared to 2936 kWh. In Figure 5.15, the electric braking force and mechanical braking force expressed as change in brake pipe pressure are shown.

![Graph showing electric brake force and difference in brake pipe pressure for train runs with low and high regeneration](image)

Figure 5.15 – Comparison of electric brake force and brake pipe pressure difference versus nominal (5 bar) for train runs with low and high regeneration.

Given the huge differences in regenerated energy, electric braking should be prioritised more by the driver that recovers the higher amount of energy. This can very clearly be seen when looking at the different strategies for applying the electric brake. While the "bad" (less regenerating) driver uses a higher electric braking force at a higher frequency, the electric braking force is often only applied for a short amount of time. The "good" driver uses a high electric braking force too, but uses it constantly for long periods of time. Thus, in total the electric brake energy recovered gets much larger since the power in combination with the applied time matters for regenerated energy.

Now, in order to put this into perspective with the ratio of mechanical and electric braking, it can also be seen in Figure 5.15 that the "good" driver in general applies less mechanical braking. The instances where mechanical brakes are used match to high degree for both drivers. So in total, even though there probably will be a difference in how much energy is braked away in total for each train, the share of the braking performed with electric brakes is clearly much higher for the train run with more regenerated energy. In can be concluded from this that the ratio of mechanical and electric braking is significant for describing how much energy is regenerated in total.
Finally, it was seen that the "good" driver uses 322.8 kN of electric brake force on average (distance-weighted). STEC always maximises the use of electric brakes, which in practise means the limit value is applied constantly. Given the high error in regenerated energy predictions of STEC for the base case, it was attempted to lower the electric braking force limit in the traction curve of the base case to 250 kN, without changes to the mechanical brake force limits. This results in a much more reasonable estimate of 4448 kWh regenerated energy (compared to 5112 kWh for "good" driver). What can be learnt from this is that the reason for the large overestimation of energy consumption for the base case probably is related to that the applied electric braking force is unrealistically high. With this new knowledge it was also attempted to redo the simulation with the electric brake force limits set to 500 kN and 750 kN. The results in Table 5.4 can be interpreted as an estimate how much energy could be regenerated roughly, if higher electric braking forces could be applied constantly. In reality, limitations such as adhesion, the line voltage and receptiveness of the power supply system for receiving regenerated energy on the Norwegian Ofotbanen, where the highest potential for regeneration exists, make this rather an approximate demonstration of what future potential exists.

Table 5.4 – Predicted regenerated energy for different electric brake force limits.

<table>
<thead>
<tr>
<th>Constant electric brake force limit [kN]</th>
<th>Regenerated energy [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>4448</td>
</tr>
<tr>
<td>500</td>
<td>8072</td>
</tr>
<tr>
<td>750</td>
<td>10828</td>
</tr>
</tbody>
</table>

### 5.2.4 Amount of coasting

Coasting is highlighted in almost all literature as a measure to drive trains more energy efficient. A parameter that describes coasting is therefore analysed. The amount of coasting is defined as the fraction of the total distance covered by the train during the trip, that is spent coasting. The driver decides when to coast, so this is a driver-describing parameter.

The initial change made to the base case for this analysis is that coasting is activated in the options, using a coasting distance of 1.5 km. Shorter and longer distances were tried, but lead to simulation problems due to unrealistic
speed drops during coasting. During the simulation with this setup, it was however noticed that STEC tried using coasting at most of the locations where speed limits drops were defined, but failed at many because the speed drop resulting from coasting would be too small and braking was applied instead. So in a second step, the reduced speed limits which had, in general, been defined to start when the gradient reaches 3‰, were optimised. This was done by delaying the location where the reduced speed limit starts until the train has reached that lower speed, effectively avoiding as much braking for speed reductions as possible. At some locations, the uphill gradient was not long enough for the train too reach the lower speed through coasting though. Doing this optimisation for all defined speed limits of the base case, the distance that is coasted for during the simulation could be extended from 4.7 km before the optimisation to more than triple of that with a distance of 15.19 km. The effect of applying optimised coasting on simulated energy consumption and run time is presented in Table 5.5 below.

Table 5.5 – Results for base case before and after applied optimised coasting.

<table>
<thead>
<tr>
<th>Amount of coasting [%]</th>
<th>Gross energy [kWh]</th>
<th>Regenerated energy [kWh]</th>
<th>Run time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12938.77</td>
<td>10286.58</td>
<td>11703.6</td>
</tr>
<tr>
<td>9.22</td>
<td>11356.08</td>
<td>10067.62</td>
<td>11632.5</td>
</tr>
<tr>
<td>Absolute difference</td>
<td>-1582.69</td>
<td>-218.96</td>
<td>-71.1</td>
</tr>
<tr>
<td>Relative difference</td>
<td>-12.23%</td>
<td>-2.13%</td>
<td>-0.61%</td>
</tr>
</tbody>
</table>

As would be expected, the influence of coasting on energy consumption is big. Given that the train needs to brake less when reducing speed through coasting, the amount of regenerated energy gets lower too. The reduction is here not of the same size as for gross energy though. The major disadvantage of coasting is increased travel time, however the run time decreases after coasting is applied in the results. This can be explained by that the higher speed limits are applied for longer distances when the start of the lower speed limits was pushed back in order to facilitate as much coasting as possible. The train of course does not keep to the higher speed limit but coasts. Still, this leads to a higher average speed compared to if the lower speed limit would have started earlier.

The results shown in Table 5.5 do only apply for the specific setup defined for the base case. Considering the unrealistically high gross energy of the base case in the first place, most drivers will in reality probably already have implemented some of the coasting applied in the simulation, depending on knowledge of the topography. The speed limits defined in STEC are optimised
to allow for as much coasting during speed reductions on uphill gradients as possible. Real drivers often know the local gradient at the locomotive, but given the trains are long and heavy, the overall resistance the train needs to overcome is not available to the driver. So exact optimisation as done here is thus not realistic for a driver without support tools such as a DAS. STEC does not allow for coasting during speed increase on downhill gradients, so real drivers can save even more energy from that type of coasting.

In the end, the amount of energy that can be saved through coasting highly depends on how the speed limits are defined in the simulation, i.e. where speed limits change and by how much the speed changes, and how much of the coasting potential is already used by the real drivers. The "driver" STEC simulates is poor in terms of energy efficiency and can draw very much benefit from the coasting. The actual numbers presented in the results here should hence not be interpreted as representative of real saving potentials, but can indicate the amount of energy that can be saved only by letting trains coast for speed decrease. It can be concluded that using coasting, especially in connection to gradients, is very important and significant for energy consumption.

### 5.2.5 Maximum speed

The higher the speed a train travels at, the more aerodynamic resistance must be overcome and the more kinetic energy must be added to the system in the first place. A lower maximum speed that the train operates at could thus reduce the energy consumption and is investigated here.

To perform this analysis, only the maximum speed defined as part of the train input is varied. In reality, it is however the driver that decides what maximum speed to use. Consequently, also the maximum speed is a driver-describing parameter. Thanks to that the upper speed limit for the base case has been defined to 64 km/h, the speed limits are already prepared to allow for this analysis. The train maximum speed is varied between 59 km/h and 64 km/h. Below 59 km/h, the distances between some of the defined changes in speed limits were too small, which resulted in unrealistic speed drops for STEC. The results are showcased in Figure 5.16.

The changes in gross energy are big, as the results show. Given that STEC applies very aggressive accelerations, in reality the increase in gross energy
consumption will be lower when the maximum speed rises. A linear behaviour can be seen both for the change in run time and gross energy consumption. For the run time this is expected as a higher max speed will increase the average speed linearly too. Given that the aerodynamic resistance will increase with the second power of the speed, a second-order polynomial was expected for the gross energy though. A possible explanation for this is that the increase in the aerodynamic resistance is very limited compared to the additional energy that is required to accelerate the train to its changed maximum speed several times along the route.

To check this explanation, a second analysis was performed where again the max speed is changed, but in addition the defined speed limits are set to 64 km/h everywhere, so that no conflict with train max speed arises. This allows the train to run constantly at the defined max speed for the whole trip and the influence of additional energy required for accelerations is eliminated everywhere except for at the start. A lower range of values within which the max speed is varied is used for the sake of representing more realistic run times. The average speed of the ten recorded through train runs is 47.3 km/h.

The results in Figure 5.17 support the explanation given above. The shape of the curve for gross energy follows a second-order polynomial and the change in gross energy with the changed speed is quite small. Note however, that the changed max speed has a big influence on the run time, which is given in minutes in the figure.
What can be concluded from this analysis are several things. Firstly, the fact that the big changes in gross energy seen in Figure 5.16 mainly originate from increased energy required for accelerations once again shows how important it is to limit the amount of accelerations. By this, accelerations that require addition of power from the catenary and not taking advantage of downhill gradients are meant. This also leads into the second conclusion. Because the influence of the aerodynamic resistance on energy consumption is quite small, a high maximum speed can be of advantage if it means that more of the potential energy from gradients can be converted directly into kinetic energy. From this, the last conclusion follows. Given that a high maximum speed is not always bad and that the change in gross energy consumption that follows from a changed maximum speed depends on several sources (aerodynamic resistance and energy required for accelerations), this parameter is not significant for describing energy consumption.

5.2.6 Dwell time

Whenever a train needs to stop at a meeting station or on the line due to conflict with other trains, signalling problems or other reasons, the auxiliary systems will continue consuming energy. The auxiliary energy consumption is time dependant, so to reduce energy consumption the dwell time should be kept as short as possible when the train is forced to stop completely. The parameter dwell time describes the time spent at rest during the trip and thus describes operational circumstances.
Doing the analysis of this parameter in STEC was considered unnecessary, because a very accurate analysis is possible without the need for simulation. In Section 4.1, a statistical analysis of auxiliary power consumption for dwelling locomotive sections was performed. The average dwell power for one locomotive section was determined to be 35.08 kW, taking into account efficiency. For a complete locomotive with two sections, the dwell power can therefore be estimated to be 70.16 kW on average. In Table 5.6 the gross energy consumed at rest for different durations of time is shown.

Table 5.6 – Results for dwell time analysis.

<table>
<thead>
<tr>
<th>Dwell time [min]</th>
<th>Gross energy [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.17</td>
</tr>
<tr>
<td>5</td>
<td>5.85</td>
</tr>
<tr>
<td>10</td>
<td>11.69</td>
</tr>
<tr>
<td>15</td>
<td>17.54</td>
</tr>
<tr>
<td>60</td>
<td>70.16</td>
</tr>
</tbody>
</table>

Meeting stations exist roughly every 10 km along the route from Kiruna to Narvik. Assume the worst case in ordinary operation, i.e. a train that must stop at a meeting station while the conflicting train in the other direction has just reached the meeting station after that. With a 40 km/h average speed for the conflicting train, the train would have to wait for 15 min. The gross energy consumed by the auxiliaries in that case is a small amount compared to the total gross energy consumed during the trip from Kiruna to Narvik. The average total gross energy for the ten recorded through train runs is 8924.6 kWh and the added energy consumption from 15 min dwelling would be 0.2%. When the duration of the stop is very long, the added energy consumption from the dwelling gets more significant (0.79% for 60 min). However, in that case the operations are probably disrupted due to a major problem. Under such circumstances an analysis of energy efficiency is pointless because drivers will focus on catching up time, rather than focusing on eco-driving. It can be concluded that, even though variations depending on the ambient conditions exist, dwell time is not significant for describing energy consumption under normal operational circumstances.
5.2.7 Number of stops

All results presented so far in this section have been dealing with non-stop trains except for dwell time. Since the route from Kiruna to Narvik has a high traffic intensity, it is not uncommon that trains have to stop for train crossings. Stops will lead to additional energy consumption since kinetic energy is wasted in the process of braking, even though some amount can be regenerated. It is thus of interest to study the effect of the number of stops on energy consumption. This parameter depends on the traffic situation on the railway and is related to operational circumstances.

Note that stops outside of the area of meeting stations are not considered here since they could be located anywhere and thus are not realistic to analyse. In the track input of STEC, the location of only one stop at a meeting station is added for each simulation so that the effect of each meeting station on energy consumption can be studied. Because the "driver" STEC simulates behaves the same way all the time, a comparison of meeting stations under the same premises is possible. The location of the stop is defined according to where the train would stop at the meeting station in reality, i.e. not taking a gradient profile into account. The stop/dwell time is set to 1 second to eliminate any influence of dwell power on energy consumption. No other changes to the base case were implemented initially.

It was quickly realised that the speed from which the train must brake to stop has an influence on the difference in gross energy that a stop at different meeting stations generates. This is because braking from a higher speed means more kinetic energy will be lost. The speed limits for the base case were thus set to be uniformly 48 km/h (based on average speed of recorded non-stop trains). Given that STEC applies very aggressive braking, the braking distance is too short to be realistic. This is especially a problem since the influence of the gradients during braking operation is not visible when braking distance is too short. In a second step, the simulations for each case are run again with the mechanical brake force curve of the base case scaled down by 70% for speeds of 10 km/h and more. The following results are based on the latter simulations with longer brake distance.

After the simulations are performed, the meeting stations are ranked according to the increase in gross energy consumption they cause. Since the additional time the stop causes is also relevant from an operational point of view, the
combined effect of each meeting station on gross energy and run time is also studied, see Appendix A for details. This did however not lead to much of a change in the ranking, indicating that the increase in energy consumption due a stop at a meeting station correlates with increases in run time.

The top of the ranking with lowest additional energy consumption for stopping is dominated by the meeting stations on Ofotbanen. What the meeting stations, that require the least additional energy to stop at, all have in common, is that they all have a downhill gradient directly after the meeting station. This can clearly be seen in Figure 5.18 where the best (most energy efficient to stop at) meeting stations are marked with solid lines. The explanation for this is that potential energy is converted to kinetic energy to a higher degree, requiring less power from the catenary to build up the kinetic energy of the train again.

![Figure 5.18](image-url) – Comparison of local multi-particle gradients including curve resistance around meeting stations (solid line for best meeting stations).

When it comes to the gradient before the stop, the tendency is less obvious but still visible, i.e. an uphill gradient seems to be advantageous before the stop. This goes against the expectation that an uphill gradient gives a higher benefit because the gradient is in favour of slowing the train down. The explanation for this is that the gradient when accelerating again after the stop is more important than the gradient before the stop. This is because the major part of increased energy consumption for a stop is related to the acceleration. An uphill gradient before the stop can only save a bit more than a downhill gradient because kinetic energy is directly transformed into potential energy while braking on the downhill will lead to losses in the form of heat. When excluding run time from the ranking, Straumsnes and Djupvik meeting station are the best (see
Appendix A) and these have the steepest downhill gradient after the stop, while having the steepest downhill gradient also before the stop. On third and fourth place comes Katterat and Abisko meeting stations. These instead both have uphill gradients before the stop. Only in fifth place comes Rombak, which has a steeper outgoing gradient from the stop than Abisko, but also a quite steep downhill gradient before the stop. This proves the incoming uphill gradient of Abisko is superior to the downhill gradient of Rombak.

Another interesting finding could be seen when comparing the change in gross energy for stopping at a specific meeting station before and after the lower mechanical brake forces are introduced. In Table 5.7 this change is presented for a selection of meeting stations with the highest variations. It can be seen that for meeting stations where the incoming gradient is positive, a lower brake force leads to a reduction of the gross energy that is caused by the stop. The opposite is true for negative incoming gradients. This indicates that when the incoming gradient before a stop is positive, slower braking is better, i.e. as much kinetic energy as possible should be converted into potential energy instead of being braked away with efficiency losses. When the incoming gradient is negative, the brake force should be high to shorten the brake distance, but still prioritising electric braking. Thereby, the negative gradient can be utilised for longer to overcome motion resistance at full speed.

Table 5.7 – Comparison of increase in gross energy due to addition of stop.

<table>
<thead>
<tr>
<th>Meeting station</th>
<th>For high brake force [kWh]</th>
<th>For low brake force [kWh]</th>
<th>Difference [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rautas</td>
<td>211.72</td>
<td>188.46</td>
<td>-23.26</td>
</tr>
<tr>
<td>Katterat</td>
<td>144.83</td>
<td>131.34</td>
<td>-13.49</td>
</tr>
<tr>
<td>Abisko</td>
<td>160.92</td>
<td>150.78</td>
<td>-10.14</td>
</tr>
<tr>
<td>Rensjön</td>
<td>237.1</td>
<td>239.52</td>
<td>2.42</td>
</tr>
<tr>
<td>Torneträsk</td>
<td>216.07</td>
<td>218.5</td>
<td>2.43</td>
</tr>
<tr>
<td>Straumsnes</td>
<td>124.84</td>
<td>128.51</td>
<td>3.67</td>
</tr>
</tbody>
</table>

Finally, in Table 5.8 the results from the simulations for all meeting stations with the reduced mechanical braking force are presented. The extremely high maximum run time addition is an outlier and is from the simulation with a stop in Stenbacken. For the same meeting station, the gross energy addition is highest too. The steepest outgoing uphill gradient of any meeting station with large margin explains this and Stenbacken should thus be avoided for stops all together. The lowest run time and gross energy addition are for Katterat and Straumsnes, both with a steep outgoing downhill gradient. If time is
no limitation, for Straumsnes and Djupvik a stop could possibly be handled without any additional energy being required by coasting all the time during acceleration. Acceleration through coasting would probably be too low to give acceptable run time additions though. Considering STEC applies very aggressive accelerations and decelerations even after the mechanical brake force has been reduced, the results for real drivers will probably be lower. It can be concluded that, even for real drivers, the number of stops will be significant for describing energy consumption.

Table 5.8 – Statistical results for adding a stop in simulation.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard deviation</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional gross energy [kWh]</td>
<td>192.74</td>
<td>42.08</td>
<td>255.56</td>
<td>128.51</td>
</tr>
<tr>
<td>Additional run time [s]</td>
<td>162.6</td>
<td>190.58</td>
<td>899.1</td>
<td>92.7</td>
</tr>
</tbody>
</table>

5.2.8 Load factor

Due to capacity reasons mainly, the wagons of each train should be filled with as much cargo as possible to minimise the number of trains that need to be operated to transport a defined amount of cargo to its final destination. As reported in the literature review, a higher cargo load and consequently axle load can also be of advantage for the specific energy consumption. For investigating this, the parameter load factor is defined, which is defined as how much of the STAX is utilised. Given that the load factor is influenced by the amount of cargo available to be transported and STAX of the infrastructure and wagons, this parameter describes operational conditions.

To study the influence of axle load, two parameters are changed in the train input to STEC. Firstly, the cargo load is adjusted to represent the axle load the wagons should have in the simulation. Secondly, using Equation 4.11 the A-coefficient is calculated. The B- and C-coefficients are dependent on the train length and are therefore not changed. Curve resistance is also influenced by the amount of cargo load, but since it has been recalculated into a gradient, the increased train mass defined in the train input will take that into account since a higher total mass increases the gradient resistance. Axle loads in the range from 27.5 tons to 32.5 tons are simulated. The lower half of this range represents the typical cargo loads LKAB’s iron ore trains operate at today. As described in Section 1.1, there is ongoing work to increase the STAX
of Malmbanan and Ofotbanen to 32.5 tons and the upper half of the range represents this case.

![Figure 5.19 – Results for load factor analysis.](image)

In Figure 5.19 the difference in specific energy consumption resulting from the changed axle load is shown. Specific energy is here expressed as kWh per net-ton-km because that is what a transport company cares about in the context of energy consumption, i.e. to consume as little energy as possible to move each ton of cargo for a defined distance. There is a clear tendency that a higher axle load due to increased cargo load decreases the specific energy consumption. The locomotive and empty wagons represent the "dead weight" of the train, which does not contribute to carrying any cargo but consumes a defined amount of energy itself for overcoming the motion resistance. This amount of energy is distributed over the amount of hauled cargo in the specific energy consumption. When the amount of cargo transported by the train increases, the above results indicate that the increase in energy consumption due to higher motion resistance for the wagons is lower than the reduction of specific energy for the "dead weight" which is distributed over a larger amount of cargo. Since the amount of energy consumed for the "dead weight" does not change in the simulations, the higher the amount of hauled cargo already is, the lower the reduction in specific energy for the "dead weight" gets due to a further increase in hauled cargo. In other words, increasing the axle load from 27.5 tons to 30 tons gives more reduction in specific energy consumption than increasing the axle load from 30 tons to 32.5 tons. This tendency can be seen in the results too.
The concrete savings in specific energy consumption presented in Figure 5.19 do only apply to the bad "driver" that STEC simulates. The fact that STEC does not have a driver model that changes behaviour based on the train weight is actually an advantage here, because it means the results are obtained under the exactly same premises. In real train operations, the effect of higher axle load on specific energy consumption can be hard to distinguish due to varying driver behaviour and operational circumstances. Given that the validations showed that the resistance STEC simulates is quite accurate, the results presented here are expected to also have relatively high accuracy.

However, the high gross energy for the bad "driver" STEC simulates raises the question how much savings can be achieved for a more realistic driver with lower total gross energy. This was investigated for the most interesting case, which is how much is actually saved for an increase of the wagon axle load from 30 tons to 32.5 tons. The approach was to manipulate the base case by changing the max speed in the train input to 55 km/h, 58 km/h and 64 km/h. One setup with a max speed of 47 km/h and uniform speed limits was also used. These all result in different total gross energies. For each setup, the simulation is done with 30 tons axle load and 32.5 tons axle load and the difference in specific energy for the two simulations was calculated.

Figure 5.20 – Energy saving by increasing axle load from 30 tons to 32.5 tons for different total gross energies (at 30 tons axle load).

Figure 5.20 shows the energy savings for the increased axle load, calculated as the change in specific energy multiplied with the simulated distance (164.73 km) and the cargo load for 32.5 tons axle load (7371.2 ton). Each of these energy savings is plotted against the gross energy consumption for the
simulation at 30 tons axle load. From the five blue data points received from the simulations, a curve could be fitted that exactly matches the data points. A second-order polynomial was used with a $R^2$-value of 0.9999. With the help of the equation resulting from this, the red data points could be calculated. These represent a very "good" respectively "bad" driver for real operations (based on the ten recorded non-stop train runs), see Table 5.9. In reality the savings will be a bit lower because a safety margin for the wagon axle load is used.

Table 5.9 – Estimated energy saving for increase of axle load

<table>
<thead>
<tr>
<th>Gross energy at 30 tons [kWh]</th>
<th>Energy saving for 32.5 tons [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8000</td>
<td>335.63</td>
</tr>
<tr>
<td>10000</td>
<td>357.27</td>
</tr>
</tbody>
</table>

What is interesting to note in Table 5.9 is that it indicates a worse driver with a higher gross energy consumption can save more specific energy with a higher axle load than a more energy efficient driver. The likely explanation for this can be described with Equation 5.1 below, valid for the simulation model.

$$E_{\text{gross}} = E_{\text{aux}} + (E_{\text{kin}} + E_{\text{pot}} + E_{\text{roll}} + E_{\text{aero}}) \cdot \frac{1}{\text{Efficiency}}$$ (5.1)

It describes the components that make up the gross energy. Energy consumed for overcoming all rolling resistances ($E_{\text{roll}}$) and potential energy ($E_{\text{pot}}$) are both influenced by the axle load, but not the driver. The parts of energy consumption that can be influenced by the driver are kinetic energy ($E_{\text{kin}}$) and aerodynamic resistance ($E_{\text{aero}}$). The energy for auxiliaries ($E_{\text{aux}}$) will also change because energy efficient driving often results in longer run time, but the change is minor and will be disregarded. As has been seen earlier in this section, aerodynamic resistance does not change very much for different average speeds, so it is the kinetic energy that must be added to the system that really matters. For a very energy efficient driver, the energy consumed for kinetic energy will be lower for the cargo, but also the "dead weight", than for a "worse" driver. What this means is that the amount of energy for the "dead weight" that can be distributed over more cargo for the higher axle load gets less. The consequence of a lower amount of energy that can be distributed over the cargo is that the achieved reduction in specific energy consumption due to an increased distribution gets lower. From that follows also that the gains of a higher axle load gets lower. Based on Table 5.9, it can be concluded that the load factor is significant for describing (specific) energy consumption.
5.2.9 Number of wagons

Apart from the load factor, also the train length, i.e. the number of wagons in the train, can help increasing the capacity for hauling as much cargo as possible. A similar effect on the specific energy consumption can be expected for longer trains as for higher axle load train due to a better distribution of energy consumption for "dead weight" over a larger amount of cargo. In real operations, the number of wagons hauled can vary depending on availability of rolling stock and limitations of the infrastructure. This parameter hence describes operational circumstances.

To investigate the influence of a varying number of wagons and, in direct consequence, train length, several parameters of the base case are changed. Due to an increased number of axles, the A-coefficient is recalculated using Equation 4.11. The B- and C-coefficients are recalculated too, owing to the changed train length, see Equations 4.6 and 4.10. The changed train length also means the multi-particle gradient input, including the curve resistance, must be recalculated. Finally, the cargo load, tare mass of rolling stock and mass contribution from rotational masses must be adapted. The range used for the analysis goes from 62 wagons to 74 wagons, which is based on that these numbers result in a hauled cargo load closest to the boundary values of the load factor analysis. The number of wagons is also only changed by two at a time, because Fanoo-wagons are always pair-coupled, i.e. 7 simulations are executed in total.

Figure 5.21 – Comparison of savings in specific energy consumption for higher load factor and number of wagons.
In Figure 5.21, the difference in specific energy consumption resulting from a change in the number of wagons is showcased and compared to corresponding results for the load factor. For comparability reasons, the difference is plotted against the cargo load. Given that the principle for why the specific energy consumption can be reduced is very similar for adding extra wagons and increasing the axle load of existing wagons (better distribution of energy consumption for "dead weight" over cargo load), the results are expected. The same tendency as for the load factor analysis can also be seen, where the reduction in specific energy consumption gets smaller for every additional two wagons that are added. Most importantly though, it can be clearly seen that increased axle load results in higher savings than an increased number of wagons. The explanation for this is the fact that increase in motion resistance resulting from adding extra wagons is higher than the additional resistance when loading existing wagons with more cargo. This is reflected in the higher number of changes to the base case that are required compared to the load factor analysis. Not only does the rolling resistance increase, but also total rotational mass, total tare mass and aerodynamic resistance (even though the load factor also can have a small influence on the amount of turbulent air on the inside of wagons). The "dead weight" also changes consequently.

Due to that STEC does not have a driver model that adapts to the train weight, the simulations could all be performed under the exactly same circumstances without any influence from driver behaviour or operational limitations. The results are thus very comparable with the results from the load factor analysis. But because the B- and C-coefficients have not been estimated as part of the modelling chapter and the validations are all performed with the coefficients at their default value provided by Transrail, the reliability of theses values is lower when they are changed, as in this analysis. All parameters have some error, so the more parameters need to be changed, the higher the uncertainty of the results. Therefore, the difference in specific energy resulting from a changed number of wagons could be both higher and lower than indicated. However, the specific energy savings estimated in this section for an increased axle load, which are expected to have higher accuracy, are so much higher than for an increased number of wagons, that it is concluded that the latter measure is inferior from an energy efficiency point of view. Nonetheless, the number of wagons is significant for describing (specific) energy consumption.
5.2.10 Drive chain efficiency

The last parameter that is studied as part of the parametric study is the drive chain efficiency. Faulty components or control software of the drive chain and upgrades to the power electronics will directly influence the energy efficiency of the locomotives. This parameter thus describes the performance of the rolling stock from an energy point of view.

In order to study the drive chain efficiency, only the traction and regenerative braking efficiency, which are set to the same value in STEC, are changed versus the base case. Changes in the auxiliary power efficiency are excluded from the analysis since it is unknown what the default efficiency is. In STEC, the efficiency is taken into account in the average auxiliary power measured at the catenary and the efficiency is thus set to 100%. Further, auxiliary power has a low share of the total consumed energy and changes in drive chain efficiency are therefore anyway more interesting to study.

As the spread of the data points in the results in Figure 5.22 indicates, simulations were done with 0.1% step changes of efficiency within 1% from the default efficiency (88.9%). This is a reasonable range for what changes faulty components, software problems or upgrades to the drive chain can generate for the drive chain efficiency. Bigger changes in efficiency are simulated too in order to gain a better understanding of the tendency the curves show. In reality high efficiency drops down to 70% would mean a major problem though and the locomotive would probably not be used in regular operation in that case.
While the curve for regenerated energy is linear, a slight bend for the gross energy curve can be distinguished. The net energy curve is a combination of the two former shapes. The explanation for the bend of the gross energy can be found when looking at Equation 5.1. All energy within the parentheses represents the gross energy that is drawn from the catenary and used to overcome the motion resistances. To obtain the actual total incoming energy, this energy must be multiplied by one over the efficiency. So the curve of gross energy varies as one over the efficiency. In the efficiency range studied here, this curve has a relatively linear shape. The recuperated energy however is just multiplied directly by the efficiency and thereby redistributes some energy from regenerated energy to losses, i.e. shows a linear behaviour.

Lastly, looking at the actual numbers, the influence of a changed efficiency is largest for the net energy, since a reduced efficiency means both a higher gross energy intake and lower amount of regenerated energy. For a change of efficiency by ±1% compared to the default efficiency, the total net energy changes by around 250 kWh and for a change of 0.5% around 125 kWh. Keeping in mind that gross energy is lower and regenerated energy much lower for a real train run compared to the simulated base case, the change in net energy due to altered drive chain efficiency is expected to be much lower. It can be concluded that drive chain efficiency can be significant for describing net energy consumption, but that depends on how high variations of the efficiency from the nominal value can be reasonably expected.

5.3 Evaluation of results

Based on the conclusions of the parametric study in the previous section, each of the analysed parameters will be discussed further in this section. The purpose is to evaluate whether the findings about the significance of parameters are in line with what the literature review has shown and ranking the parameters quantitatively to see how suitable they are as KPI. In addition, comments about whether the parameters can be tracked with the available energy meter data (refer to Section 3.3) in a reasonable way is also given.

5.3.1 Driver parameters

Starting with the driver-describing parameters, using both powering ratio and braking ratio as parameters was inspired by the five driver-describing
parameters defined in [24]. A comparison with the results for the same parameters in that paper is therefore of interest. For the powering ratio, the results presented here are in line with what the paper reports, i.e. the same trends can be seen for both the gross energy and run time. Because STEC has no driver model implemented, the discrepancy in the relative differences reported versus the paper is expected. On the other hand, there are big differences in the reported influence of the braking ratio. In [24] it is reported that the braking ratio has a big impact on energy usage. The result from this thesis rather points towards a small effect. However, as has been explained earlier, the design of the base case means it is very possible that the braking ratio is much more important. The results of this thesis are rather unclear for that parameter. All in all, the tendencies for the impact of powering ratio and braking ratio on energy consumption are in line with existing literature.

The ratio of mechanical and electric braking is often mentioned in the literature in the sense that regenerative braking should be maximised. Even though no simulations were performed for the ratio in this thesis, the comparison of two drivers at the opposite ends of the spectrum of this parameter has shown that maximising regenerative braking indeed is very important for energy consumption. It is interesting to note that the "good" driver in that comparison applied a braking technique on long steep downhill sections in accordance with optimal techniques found in one paper [29]. Coasting is one of the main components of eco-driving and is emphasised very often in the literature. The results from this thesis indicate the same, i.e. coasting has an enormous potential to save energy if applied properly according to the track topography.

The parameter maximum speed is mentioned in the literature as a measure to reduce energy consumption, but never investigated closer in the literature reviewed. As the results for this parameter in the previous section indicate, a lower maximum speed does indeed reduce the energy consumption due to both less acceleration energy and aerodynamic resistance. However, it has also been concluded that a high maximum speed not necessarily is bad if it means converting more potential energy into useful kinetic energy. So the actual max speed a driver reaches does not really tell much about how energy efficient the driver controls the train. In other words, relating max speed to energy consumption is complicated and thus not realistic to be used as a KPI.
Because the parametric study in this thesis has been conducted using a simulation tool that has no driver model, it is of interest to verify the findings about significant driver-describing parameters. For this purpose, the two recorded train runs of the analysis of the ratio of mechanical and electric braking are reused. The difference in cargo load is only 6 tons and both trains have no stops, so the driver behaviour must explain the huge difference in net energy for the two trains, which amounts to 4026 kWh. Gross energy difference is 1850 kWh, so the majority of the difference is related to regenerated energy. The difference in run time is 369 s.

![Figure 5.23 – Comparison of speed profile for good and bad driver.](image)

As can be seen in Figure 5.23, the speed for the "good" driver (lower net energy) is often actually higher than for the "bad" driver. This proves that the maximum speed has a low explanatory power for energy consumption. Further, it can be seen that the "good" driver at two instances is close to coming to a stop, probably while waiting for extended movement authority. If these speed reductions would not have happened, the difference in net energy would have been even higher.

Moving on to Figure 5.24, here the force at the wheels of the locomotive and the multi-particle gradient profile are shown. It is clearly visible that the "good" driver coasts significantly more, so the amount of coasting has explanatory power. The powering ratio is, when the good driver applies traction, often similar to the "bad" driver ratio. But because the good driver coasts a lot more, on average the powering ratio gets lower for the "good" driver. This confirms the explanatory power of powering ratio. The braking ratio for the electric brake is also often lower for the "good" driver because the
"bad" driver applies higher braking forces for short periods of time. Though, when the "good" driver applies constant electric brake forces, it is often higher than for the "bad" driver. The difference in average braking ratio is less obvious than for the amount of coasting and power ratio, but still has explanatory power when taking the mechanical brakes into account (see Figure 5.15). For the significance of the ratio of mechanical and electric braking, refer to the corresponding analysis in Section 5.2 which is done for the same train runs. Finally, note that the difference in local powering ratio and braking ratio along the route often is related to that the "good" driver coasts more. In other words, the powering and braking ratio can be explained by the amount of coasting to some extent.

![Figure 5.24 – Comparison of force at wheels for good and bad driver.](image)

Amount of coasting is the parameter that has the highest quantitative and clearest influence on gross energy consumption and is thus also very useful as KPI. It can be tracked with energy meter data because it is known how much power the auxiliary systems require on average, so whenever the instantaneous power is below a defined threshold the train is coasting. In case the driver applies the mechanical brakes, that would be visible in the power because the locomotive starts electric braking equal to the change in brake pipe pressure. The data from the energy meters is given in time domain though, so the distance covered would have to be estimated from the GPS position. Defining the amount of coasting in the time domain is unpractical because the run time can vary a lot. However, coasting for a long distance is also not necessarily good for gross energy if coasting is applied at unfavourable locations that result in a lot of energy-consuming acceleration at the end of the coasting.
For amount of coasting to work as KPI, it relies on that drivers are educated to not use coasting extensively where it is not appropriate.

Even though it could not be clearly shown in the parametric study, braking ratio has been reported to have a high impact in literature and should thus be of interest to use as a KPI. However, with the data available from the energy meters, it is not possible to track the amount of mechanical braking used reliably. Because even if the locomotive always applies electric braking equal to the brake pipe pressure change, it cannot be distinguished whether the electric brake force is only applied on the locomotive or results from a drop in brake pipe pressure. Also, a high electric brake force is not necessarily bad as it can mean that less mechanical brake force needs to be applied. It is therefore not possible to track the braking ratio from energy meter data, even though it would be an interesting KPI. To some extent, it can be tracked indirectly, because a driver that coasts often for speed reductions also requires less braking in general due to a lower speed when the train starts braking.

Closely related to the discussion about braking ratio is the parameter ratio of mechanical and electric braking. It probably has a lower quantitative influence than the actual braking ratio and is related to regenerated energy rather than gross energy. It is still important because it shows how much the electric brake is prioritised by the driver. As explained above, the mechanical brake force cannot be tracked in a reliable way. So this parameter is not possible to use as a KPI. An alternative way to track how much the electric brake is prioritised is by simply looking at the total amount of regenerated energy. There is one problem to this though, which is that using the brakes more often comes at the cost of less coasting, i.e. the braking ratio should be low. To take this into account too, the ratio of total regenerated energy and gross energy can be used as KPI. This way, a higher amount of regenerated energy is only better if it means that the gross energy is not increased by the same amount. What such a KPI however cannot take into account is that the electric brake might be prioritised by a driver, but due to limitations in adhesion or infrastructure, e.g. line voltage, a more extensive use of the mechanical brakes is required. Factoring in ambient conditions with weather data would thus be a further improvement but cannot be tracked via the energy meter data. Limitations in the power supply system might be possible to take into account, but this is rather complicated, seldom a real issue and outside the scope of this thesis.
Limited adhesion or line voltage can also influence the powering ratio, but rather in a positive way because it is reduced. The powering ratio has a lower quantitative influence on gross energy than amount of coasting. It provides a good way of assessing the aggressiveness of the driver when it comes to accelerations and is significant for describing gross energy consumption, i.e. suitable as KPI. It can also be tracked very easily by identifying when the power of the locomotive is positive and not below the threshold defined for coasting. Since even an energy efficient driver may require a very high power sometimes due to fast accelerations (e.g. caused by traffic condition on the railway) and steep uphill gradients, the average traction power should be calculated and used as KPI traction power.

### 5.3.2 Operational parameters

The first operational parameter analysed in the parametric study was the dwell time. Such a parameter is not mentioned in the reviewed literature, but it is pointed out in some papers that a shorter run time is in favour of reduced auxiliary energy consumption, which is time-dependant. The simple analysis in the parametric study agrees with this and showed that the time spent dwelling has an influence on energy consumption, but the quantitative impact is very small. So, while it would be possible to track dwell time with energy meter data via the train speed, it is not considered worth it to use the dwell time as a KPI, at least for freight trains.

Number of stops is not directly mentioned as parameter in the reviewed literature either. But it could be classified to fall into the category of avoiding unnecessary braking to save energy, which the results of the parametric study agree with. They indicate that this parameter has explanatory power for the energy consumption, but the exact amount of energy that an additional stop adds to the gross energy consumption not only depends on the driver, but the exact location of the stop. This can be tracked using the GPS position and recorded speed from the energy meters. However, given that a stop could potentially be anywhere along the line, a KPI tracking this should be simplified to only consider the number of stops as an indication of the long-term traffic situation along the railway. For stops caused by train crossings, which is the most common reason of stops, performance indicators could be introduced that track how frequently each meeting station is used for stops.
Saving specific energy with higher axle load is mentioned in the literature reviewed in connection to heavy haul freight trains, where not the volume but the density of the cargo limits the carrying capacity. In combination with higher axle load, the train length or number of wagons is mentioned too. Both of these parameters have shown a clear quantitative influence on specific energy consumption in accordance with expectations from the literature. It is not discussed in detail in the reviewed literature how these two measures relate to each other in terms of saved specific energy consumption. The results of this thesis indicate that the quantitative influence of increased axle load is higher. Depending on what the STAX and maximum allowed number of wagons in a train is, the increase in specific energy consumption resulting from not using the full capacity can be higher than adding an additional stop on the trip. For a long-term strategy of reducing the specific energy consumption for heavy haul freight trains, these two parameters are important to track. Especially the load factor, which relates to the axle load of each train, is a useful KPI due to its higher impact. However, with energy meter data, neither load factor nor the number of wagons for each train can be tracked. In order to use these as KPIs, information from a database that includes cargo load and the number of wagons is required. Though, for heavy haul freight train operators, such databases usually exist, which is also the case with LKAB.

5.3.3 Rolling stock parameters

The final parameter that was studied in the parametric study is the drive chain efficiency, which is supposed to represent the influence of the rolling stock on energy consumption. A lot of measures that can increase the drive chain efficiency have been suggested in some literature, but the effect of a changed efficiency is not studied. Efficiency will always impact energy consumption, which the results of the parametric study also show. The result analysis indicates that small changes in the drive chain efficiency only have a significant effect on net energy consumption if the total energy consumption is large. Gathering data for a long period of time, this can be achieved. Still, efficiency only has a clearly distinguishable effect on net energy if large enough variations of efficiency from the nominal value can be expected. So the usefulness of drive chain efficiency as KPI depends. To be able and evaluate drive chain efficiency, the force at the wheels must be known in order to calculate the quotient of incoming power at the catenary and power at the wheels. Due to that traction force is not available from energy meter data, efficiency cannot be calculated this way. An alternative way of detecting if
a certain locomotive unit stands out in terms of energy efficiency, would be to run a regression analysis where each individual locomotive is assigned a dummy variable, see [5]. This requires large amounts of data though, so this is only an option if an energy monitoring system is already established.

5.4 Recommendations

Based on the evaluation of the parametric study results in the previous section, recommendations for a structure of KPIs and how these can be implemented in a monitoring system will be given in this section. Also, potentials for energy savings of heavy haul freight trains are presented. These recommendations are all geared towards the operations and rolling stock of LKAB, but should for the most part also be applicable to other heavy haul freight train operators.

5.4.1 Suitable KPIs for energy monitoring

In Figure 5.25, the recommended structure for a system of energy monitoring is presented, which uses KPIs to track the energy efficiency performance.

![Figure 5.25 – Structure for energy monitoring system with KPIs](image)
At the top of the structure, a global KPI is defined that describes the overall performance. Below that, there are three subsystems defined which together can explain the energy efficiency. The purple arrows in Figure 5.25 point towards the subsystems and the blue arrows indicate the KPIs defined for each subsystem. The evaluation of the parametric study has shown that mainly, only driver-describing parameters can be tracked using energy meter data. Apart from the number of stops and average stabling power, all other KPIs require knowledge of additional parameters in excess of the energy meter data, such as the cargo load. This is indicated by the blue framing of these KPIs. Yellow framing on the other hand means that it is possible to track a KPI solely with energy meter data, but requires a higher resolution of samples than every 5 min (Swedish standard as of today). Green framing means the KPIs can be tracked directly using the available energy meter data.

The possible energy efficiency of heavy haul freight trains can vary a lot depending on the route and direction of travel. Especially, this is true for the driver KPIs. For instance, a trip that mainly just goes uphill, offers little possibilities to coast and use regenerative braking compared to a trip in the opposite direction. Therefore, the KPIs of the structure defined in Figure 5.25 above should be calculated for each route and direction separately. But a global evaluation is of course also possible, particularly for the KPIs that do not vary much depending on route and direction of the operations. In the following, the input and calculation of each KPI in the energy monitoring system is described.

**Specific energy consumption**

This KPI is used to describe the energy efficiency at a global level. It is very useful because it expresses the overall performance of the heavy haul operations, i.e. how much energy is required to haul all cargo to its final destination by rail. Specific energy consumption is calculated by using data about the net energy consumption for each train trip, the covered distance from the GPS position of the energy meters together with the cargo hauled by each train. The fact that cargo load must be known results in that the energy meter data is not enough to calculate this. A database for cargo loads is required and must somehow be integrated into the energy monitoring system. Most heavy haul freight train operators, including LKAB, have such a database available. The cargo load can be obtained from scales or wagon-mounted load sensors.
Ratio regenerated of gross energy

This KPI is calculated by dividing the total regenerated energy by the total gross energy for a concluded trip. It can simply be calculated from energy meter data by identifying when the train has reached its destination and has come to a stop. What this KPI expresses is not only how much the driver uses the electric brake compared to the mechanical brake, but it relates the amount of regenerated energy also to how little energy the driver requires for the trip in the first place. Thereby, excessive use of the electric brake at the cost of increased gross energy is penalised (e.g. at higher maximum speed).

Amount of total distance coasted

As the name points out, this KPI tracks and is computed by checking how much of the total distance of a trip that a train driver coasts. This is an important KPI due to that coasting has big influence on energy consumption and that it also gives an indication of the braking ratio used (which is not possible to track by itself in a reasonable way). So this KPI is a major indication of the driving style. Defining a certain range within which the power must fall, it can be known when the driver coasts. The distance can then be estimated via the GPS position. To be able and calculate it, a high sampling rate of the power and high accuracy of GPS data from the energy meter is required. Thus, this KPI cannot be tracked without modifications to the energy meters.

Average traction power

Average traction power is calculated by identifying whenever the power exceeds a defined threshold and averaging the power from all these instances of the trip. It provides a measure of the overall aggressiveness of the driving style applied in acceleration. For realistic results, a higher resolution of power data from the energy meters is required, i.e. modifications to the energy meters are required. A further development of this KPI is the average powering ratio, where the average traction power is divided by the maximum power. However, the maximum available power can vary depending on adhesion and limitations in the power supply system, making the powering ratio less viable as KPI. In order to incorporate adhesion limitations in the average traction power, weather data could be used. Depending on the variation of load factor, heavier/lighter trains can result in a higher/lower required traction power. This could be factored in too in order to improve explanatory power.
Number of stops

This KPI tracks how often the trains are forced to stop on their trips, pointing towards the traffic situation on the railways. It can be calculated from energy meter data by checking the GPS position of the train together with the speed. If it is known which meeting stations require the least additional energy for a stop, a further development to this KPI could be to track how frequently each meeting station is used for stops and optimise where the trains stop the most. Because a train certainly can stop for less than 5 min, a higher resolution of GPS position in the time domain is required for the energy meters in order to track this KPI to high enough accuracy.

Load factor

Calculation of the load factor is done by dividing the cargo load of each train by the maximum possible capacity for the used class of wagons and STAX of the railway. This KPI describes how well the capacity of each train is utilised, which has a direct effect on specific energy consumption, as could be shown in this thesis. Cargo load must be known, so this parameter can only be tracked if the monitoring system is receiving cargo load data from a corresponding database. It is noteworthy that higher axle loads can increase rate of wheel and rail damage, which could require KPIs for risk management (outside scope).

Number of wagons

No calculation is required for this KPI, because the input required defines the KPI. Train length is not available from the energy meters, so this data must be drawn from another database. For freight train operators, including LKAB, the train length is usually available in a database. If data for each train can be imported into the energy monitoring system, this KPI can be tracked. As the results of this thesis show, for heavy haul freight trains the load factor is more important than the number of wagons as KPI due to higher effect on specific energy consumption. In cases where the trains operate at the maximum length that the infrastructure allows on a regular basis (applies to LKAB), this KPI can still be interesting in order to see how often broken wagons reduce the train length and consequently increase the specific energy consumption. This KPI is also only valid when the axle loads are so high on average that fewer wagons do not result in an advantage due to rising load factor and axle load.
Average stabling power

This KPI has not been mentioned anywhere in the work of this thesis up until this point. As will be seen in the suggestions for potential energy savings in operation, even though stabling is outside the scope of this thesis, there is room for improving energy consumption during stabling. Thus, stabling power has been added as KPI to be able and track this energy saving potential. This is also the only KPI that can be defined for the rolling stock in a reasonable way. It can easily be computed using the energy consumption data from the energy meters with the lower time domain resolution of 5 min in combination with knowledge of the time between recordings.

Drive chain efficiency

The evaluation of the parametric study results has shown that the drive chain efficiency is only relevant as KPI if large enough variations of efficiency from the nominal value can be expected. This could be the case for components that are suspected to be faulty or if the power electronics are upgraded (which is the case for LKAB). If there is an interest to track this KPI, there is no reasonable way of estimating the drive chain efficiency from energy meter data or any other available data source. That is also the reason for the dashed arrow and framing of this KPI. However, what is possible would be to do a statistical analysis where each locomotive gets assigned a dummy variable. When performing a regression analysis, it is then possible to see if any specific locomotive unit stands out and has significant explanatory power for energy consumption. In that case, this could indicate that the drive chain efficiency differs from that of other locomotive units. Such an approach would require a huge amount of already collected data from an energy monitoring system and does not differentiate between drive chain and auxiliary power efficiency.

All in all, the above described KPIs and defined structure for an energy monitoring system are able to provide a good overview of the energy efficiency of the operations, but less for rolling stock for which it is hard to define KPI based on energy meter data. For the driver-describing KPIs, braking ratio would have been interesting too. Lack of mechanical brake data makes this impossible though and the aggressiveness during braking can only be tracked indirectly to some extent via the amount of coasting. It should be noted that the energy meters installed on LKAB’s locomotives do not track power directly, but via the energy consumption it can be derived.
Comparing the recommended structure of KPIs with the findings of the literature, it can be seen that the KPIs of the structure in Figure 5.25 are both inclusive, hierarchical, quantifiable and allow for studying the effect of implemented measures such as improved eco-driving. The defined KPIs could also be broken down even further and allow for evaluation of individual drivers, meeting station frequency of use and rolling stock units (with statistical analysis). In the long term, once an energy monitoring system is up and running, the large amount of data gathered will allow for performing statistic analysis. To ensure the quality of data used to calculate the defined KPIs and for any further analysis, factors such as impact of major traffic disruptions, reliability and required resolution of energy meter data must be considered.

Lastly, when it comes to the implementation of the energy monitoring system, the suggestion is to start with tracking of the parameters that do not require a higher energy meter data resolution than what is available today, i.e. the KPIs framed in green in Figure 5.25. Thereafter, once energy meter data resolution has been increased to satisfactory extent, the yellow-framed KPIs can be introduced into the monitoring system. In the final step, cargo load and number of wagon data is integrated into the monitoring system too, allowing for blue-framed KPIs to be tracked. Eventually, statistical analysis could facilitate further analysis, such as drive chain efficiency. Additional KPIs could also be added in the future if new data gets available or a specific energy-saving measures should be tracked in higher detail than the defined KPIs allow.

### 5.4.2 Potential energy savings in operation

In the process of working with this thesis, several potential energy savings for the operations of LKAB could be identified that can be introduced in the next few years. Even more energy saving potentials exist of course, but measures that require new rolling stock or are expected to have too low effect are excluded. Refer to Chapter 2 for more energy saving potentials.

Firstly, the parametric study results showed that STAX should be increased further for both the infrastructure and wagons to allow for higher axle loads. This reduces specific energy consumption more than operating longer trains and higher STAX should hence be prioritised. When the iron ore wagons are filled with more cargo due to a higher STAX, less turbulence will be created on the wagon inside lowering air drag, but wheel and rail damage increase too.
The parametric study has also shown that there are significant differences in regenerated energy depending on the amount of electric braking being applied. Removing infrastructure limitations so that higher "boost" mode electric brake forces can be used constantly on long steep downhill sections can reduce total net energy substantially. The mechanical brake can then only be used for making small adjustments of speed, which is the most energy efficient strategy.

Eco-driving is highly important for saving energy and also reduces wheel and brake wear. However, it comes at the cost of increased travel time. Timetables can be adjusted to allow for this as standard. Further, train crossings should be planned to happen at the stations with most favourable topography, which also results in the least run time addition and higher line capacity.

The results have shown that there are huge differences in driving styles applied. Systematic driver training on eco-driving is therefore very important. The ability to coast and avoid unnecessary braking depends largely on the knowledge of stops and the track topography beforehand. The introduction of ERTMS on Malmbanen will give some improvement. However, due to that the iron ore trains are very long and face substantial curve resistance, the local gradient resistance is seldom close to the actual resistance the trains need to overcome. For giving drivers a better understanding of where coasting and braking is appropriate, support tools are thus needed. In the most basic form this could be wayside signboards or a document with instructions. With the help of readily available mobile applications, drivers can also be aware of oncoming traffic and plan accordingly. (Re-)Introducing DAS is a more advanced solution, which eases the additional workload that eco-driving leads to and can be evaluated with an energy monitoring system in place.

In general, before any energy-saving measures are implemented, the optimal approach is to first establish the energy monitoring system with appropriate KPIs. Thereafter, the measures can be implemented and their effect on the KPIs evaluated and compared with expectations. Another advantage with a monitoring system is that it facilitates visualisation of the effect of different driving styles, which can help motivate drivers to apply eco-driving strategies.

Finally, it was noted that the locomotives are heated unnecessarily much during stabling. Optimise the stabling mode of the locomotives can save some energy, which is why a KPI has been defined for this too.
Chapter 6

Conclusions & Future work

6.1 Conclusions

The entire work of this thesis has evolved around enquiring what parameters are relevant for describing energy consumption of heavy haul freight trains and how KPIs can be developed from these. To reach the goals set up, a standard iron ore train with two locomotive sections and 68 ore wagons has been modelled in the simulation tool STEC. Because curve resistance and gradient resistance can vary much along the length of heavy haul freight trains, a lot of attention has been paid to modelling the gradients and curve resistance with a reasonably detailed multi-particle representation of the train. Using this train model in simulations, all remaining goals for this thesis could be met.

In a parametric study, parameters related to driver, operations and rolling stock were investigated. The lack of a driver model has actually been of advantage in this work, giving exactly the same "driving style" and premises to work with for all analysis. Under these conditions, it was possible to estimate how much specific energy a typical iron ore train can save by raising the axle load from 30 tons to 32.5 tons, which is believed to be rather unique. Interestingly, the results also point towards that applying eco-driving saves less energy by the rise in axle load than a less efficient driving style. Further, the results indicate that adding extra wagons saves less specific energy than increasing axle load.

The driving style in general and coasting in particular could be shown to have a huge influence on energy consumption. Aggressiveness of accelerations and braking as well as prioritising the electric brake on long steep downhill sections can also be pointed out to be very important for energy efficiency.
Keeping in mind that some uncertainties have existed in the simulations, the exact savings predicted from simulation will likely not correspond to reality. Still, the trends in the results of the parametric study agree with previous research in the relevant fields and a list of KPIs based on the studied parameters could be aggregated. With a sufficiently high sampling rate of energy meter data, it is adequate for calculating driver KPIs and some additional KPIs. Other KPIs require access to cargo load and the number of wagons for each train, which is expected to be available for most heavy haul train operators.

To sum up, it can be concluded that it is very useful and important for heavy haul freight trains operators to have a good understanding of the current energy efficiency performance of both the drivers and operations in general. The use of an energy monitoring system is essential for being able to work with, implement and interpret the effect of saving measures in a structured way. In the work of this thesis, KPIs that are significant for describing energy consumption and can be tracked using energy meter data have been defined. A recommended structure for an energy monitoring system has been specified with the help of these KPIs. Thereby, this thesis has laid a foundation for the development of such an energy monitoring system that can be used to track and improve energy efficiency of heavy haul freight trains over time.

### 6.2 Future work

Because of the limited time budget of this thesis, only a limited amount of data from recorded train runs could be processed manually. With an energy monitoring system in place or a huge amount of accurate, aggregated data, it would be possible to perform statistical analysis. Because LKAB has relatively uniform operations and collects a lot of accurate data from several sources, e.g. cargo load from scales, a regression analysis would be very interesting to perform. With that approach, the findings of this thesis could be reinforced and the explanatory power of potential new parameters/KPIs be trialled.

The simulation tool STEC has been very hard to handle when trying to imitate real drivers. New functionality geared towards freight trains could thus be developed. Suggestions include possibility to coast at speed increase and manually decide where the train should coast, ability to limit acceleration and deceleration rate or define several traction and braking curves for different sections of the track and an option for mechanical brake application delays.
References


Appendix A

Ranking of meeting stations

Table A.1 – Ranking of meeting stations between Kiruna and Narvik according to the additional gross energy consumption required for a stop at each of them and the product of additional gross energy consumption and run time addition. At the top of each ranking are the most favourable, i.e. lowest energy/time addition, meeting stations and the worst are at the bottom.

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<tr>
<th>Ranking for gross energy</th>
<th>Ranking for gross energy + run time</th>
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<td>Katterat</td>
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Appendix A: Ranking of meeting stations