Traction-related Energy of the Stockholm Commuter Train X60

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Project cooperated with MTR and SL

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ABSTRACT

This abstract summarizes the research conducted on energy-saving potentials for commuter trains X60 based on the discussions held. The study aimed to analyze and identify strategies to reduce energy consumption in the railway system. The research methodology involved an analysis of various factors influencing energy usage focusing on traction-related systems.

The findings of the study highlight the significant role of optimizing drive strategies in minimizing energy consumption. Through careful selection of acceleration and deceleration profiles, substantial energy savings can be achieved. Additionally, timetable adjustments were identified as a viable approach to reducing energy consumption without compromising travel time significantly. By considering energy-efficient timetabling strategies, rail systems can achieve notable reductions in energy usage.

Furthermore, the research explored the potential benefits of planned motor switch-off during cruising. Strategic management of motor groups during this phase can lead to enhanced energy efficiency and contribute to overall energy savings. By optimizing motor usage and minimizing unnecessary power consumption, significant reductions in energy consumption can be attained.

Combining multiple strategies, such as optimizing drive strategies, adjusting timetables, and implementing planned motor switch-off, offers a comprehensive approach to energy optimization in commuter trains. The research emphasizes the importance of considering these strategies in combination to achieve the greatest energy-saving potentials.

The outcomes of this research provide valuable insights and recommendations for the railway industry. Incorporating optimized drive strategies into train software, implementing energy-efficient timetabling practices, and developing systems for planned motor switch-off can lead to substantial reductions in energy consumption. These findings contribute to the development of sustainable and energy-efficient operations in the commuter train sector, ultimately benefiting both the environment and railway operators.

Keywords – energy use, commuter train, drive strategy optimization, passenger train operation, traction power, timetable adjustment, train modelling.

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1. INTRODUCTION

1.1. Background

Storstockholms Lokaltrafik(SL) is the organization in charge of all of Swedish Stockholm County's land-based public transportation services.[1] The Stockholm public transportation system (SL) comprises of over 450 bus routes, three shuttle boat lines, and a 100-kilometer-long metro system, in addition to trams and local trains. Every day, about 800,000 people use public transportation in the Stockholm area. Since 2017, trains and buses in Stockholm have used 100% renewable energy, and SL seeks to deliver the most sustainable public transportation in the world. In its pursuit of smarter and more efficient ways to operate public transportation in a sustainable manner, SL has demonstrated an interest in modern electric commuter trains.[2]

In 2016, SL cooperate with MTR(Mass Transit Railway Corporation) to operate the commuter trains in Stockholm.[3] MTR Corporation Limited is a Hong Kong-based 75% government-owned public transportation operator and property developer that manages the Mass Transit Railway, the city's most popular public transportation network. The MTR also invests in railways throughout the world, including setting up contracts to manage commuter rail systems in China, the United Kingdom, Sweden, and Australia.[4] MTR is continually working to minimize carbon dioxide emissions through extending the lifespan of the commuter trains, electrifying the automobile vehicles reducing consumption of energy, and making use of renewable energy.[5]

Commuter trains are an important aspect of public transportation for both residents and visitors, since they provide a low-cost, time-efficient mode of transportation that helps to reduce congestion and pollution in urban areas. Despite the fact that commuter trains are relatively energy-efficient and run on green electricity, they nonetheless consume a significant amount of energy in operation, which is mostly required by traction and comfort-related systems. With the introduction of contemporary trains, many information may be recorded for study during train operation. To achieve a 15% decrease in electricity consumption for rail traffic while minimizing operational costs for train operators. A research project on developing solutions for more sustainable transportation (funded by VinnovanfraSweden2030) is being carried out in order to establish a smart and cost-effective energy management plan.

The Stockholm commuter train X60 is based on Alstom's train platform Coradia, shown in Figure 1, the basic concept of which serves as the foundation for a variety of motorcar types on the European railway market. The X60 is part of the first series of Coradia goods known as Lirex (Light Regional Express Train). The X60 is a six-piece motor carriage with a low floor designed for low-temperature traffic in Stockholm. In multiple operations, a maximum of two devices can queue race. The X60 is tailored to the weather conditions in Stockholm. All safety-relevant components, equipment, and systems are temperature-rated from -35°C to +40°C. The Stockholm commuter train is 107 meters long and has a top speed of 160 kilometers per hour.[6]

Figure 1 The Stockholm commuter train X60

1.2. Purpose

The goal of the master thesis is to investigate the traction-related energy of the Stockholm commuter train X60. Many variables, such as driving style, timetable, train weight, and operational points of the traction system, can be adjusted to reduce total energy consumption and lessen the pressure on the infrastructure's power supply. Some of these have already been implemented and documented. Others have been proposed and are now being considered for the current master thesis, which will include a literature review on the energy utilization of the traction system and the accompanying energy saving solutions. The potential for energy savings will be analyzed and quantified using an energy simulation tool for rail vehicles based on sensor data and prior publications. Finally, some recommendations for energy-saving commuter train operations will be made.

1.3. Goals

To fulfill the purposes of this thesis, a variety of goals have been defined describing the steps required to accomplish those purposes.
These objectives can be summarized as follows:

- Provide a thorough analysis of past studies and findings in the relevant fields of study for this thesis

- Document real-time traction energy data (With a focus on the X60)
- Examine real-time statistics from the X60 commuter train in relation to traction use
- Create a simulation model for the X60 commuter train that estimates energy consumption
- Energy simulation of rail vehicles
- Quantifying the possibilities for energy savings
- Providing proposals for passenger train traction systems Traction energy saving methods

1.4. Delimitations

The electrical consumption study in the current dissertation will be restricted to the operations and transportation equipment utilized by Stockholms Lokaltrafik's (SL) Coradia Nordic modern commuter trains X60, and will also only be focused on energy consumption at the vehicle level.

This consists of the transmission of energy through the pantograph to the motors and also all other transportation systems. Losses and limits in the electric power supply network up and including the catenary, in addition to energy usage connected to infrastructure, are thus removed from the analysis. Stay-still trains are also not evaluated, limiting the analysis to the energy consumption of trains in transit.

1.5. Structure of the thesis

The structure of the thesis is organized to provide a comprehensive analysis of energy consumption for the commuter train X60 and to explore potential energy-saving strategies. The thesis begins with an introduction that establishes the background, purpose, goals, and delimitations of the research. The structure of the thesis is outlined to provide an overview of the subsequent chapters.

The literature review chapter examines the overall energy consumption in the railway system and explores energy-saving potentials specific to commuter trains. It also discusses simulation techniques for analyzing commuter train energy, traction-related energy consumption calculation theory, driving strategy optimization, estimation of running resistance, and the potential benefits of adjusting the timetable and implementing planned motor switch-off during cruising.

The methodology chapter presents a detailed overview of the academic methodology employed in the thesis. It outlines the process of data collection, including real-time train data, commuter train X60 data, and Stockholm track data. The use of a simulation tool is explained, and the modeling and validation process is described. The chapter also introduces the scenario study, including the three scenarios: drive strategy optimization, timetable adjustments, and planned motor switch-off during cruising.

The real-data analysis chapter focuses on the selection of stations, travel distance calculation, speed profile drawing, and quantification of energy consumption based on real-time data. The results of the real-data analysis are presented, providing insights into the energy consumption patterns of the commuter train X60.

The modeling chapter details the methodology used to build a train and track model specifically for the X60 commuter train. The process of estimation and parameter guess is explained, along with the validation of the ideal model. The simulation and iterative process for refining the model are also discussed, culminating in a second validation step.

The scenario study chapter explores the three scenarios in depth, describing their objectives, methodologies, and expected outcomes. The results and discussions chapter presents the findings from the analysis of the scenarios and provides a comprehensive discussion of the energy-saving potential and implications for MTR operation methods.

Finally, the thesis concludes with the conclusions and future work chapter, summarizing the key findings and highlighting potential areas for further research. The references and appendix sections are included to provide a complete list of sources and any additional information relevant to the thesis.

2. LITERATURE REVIEW

2.1. Overall energy consumption in the railway system

Energy usage in passenger trains is typically divided into traction and auxiliary systems. The traction system delivers energy for propulsion, while the auxiliary systems encompass control equipment, lighting, ventilation, heating, and other functions in the vehicles. The power and energy required for traction depend on factors such as rolling resistance, air resistance, traction and power transmission efficiency, and overcoming inertia and running resistance during acceleration. Electric power supplies, such as catenary or third rail systems, are commonly used worldwide, but diesel-powered vehicles are still prevalent in certain regions.

Within the traction system, energy consumption can be divided into unrecoverable energy and potentially recoverable energy. Unrecoverable energy includes continuous running resistance, power transmission losses, and mechanical braking energy dissipation. Losses in transmission, windings, transformers, and inverters contribute to unrecoverable energy use. Diesel-powered rail vehicles experience similar losses in their traction systems. However, regenerative braking and coasting techniques enable the recovery of kinetic and potential energy, improving efficiency, particularly in eco-driving practices.

Dedicated cooling systems are necessary for traction motors, transformers, and inverters to manage the heat generated during energy transmission. These cooling systems require continuous control and monitoring. Supporting auxiliary systems are essential for the traction systems, including control equipment, compressed air for braking, cooling fans, and pumps. These systems ensure continuous traction function and normal train operation. On the other hand, comfort auxiliaries are connected to passenger compartments and include functions such as HVAC, lavatories, catering, and more.[7]

The division of auxiliary systems into traction auxiliaries and comfort auxiliaries may not always be straightforward, as many auxiliary systems are closely linked to traction. Analyzing the power loads of the various auxiliary systems, encompassing both traction and comfort auxiliaries, provides a comprehensive understanding of overall energy consumption in the railway system. Figure 2 (Erick, 2018) illustrates the energy flows within a passenger rail vehicle, highlighting the impact of the traction and auxiliary systems. By considering these energy flows and the functioning of traction and auxiliary systems, a holistic assessment of energy consumption in the railway system can be achieved.[8]

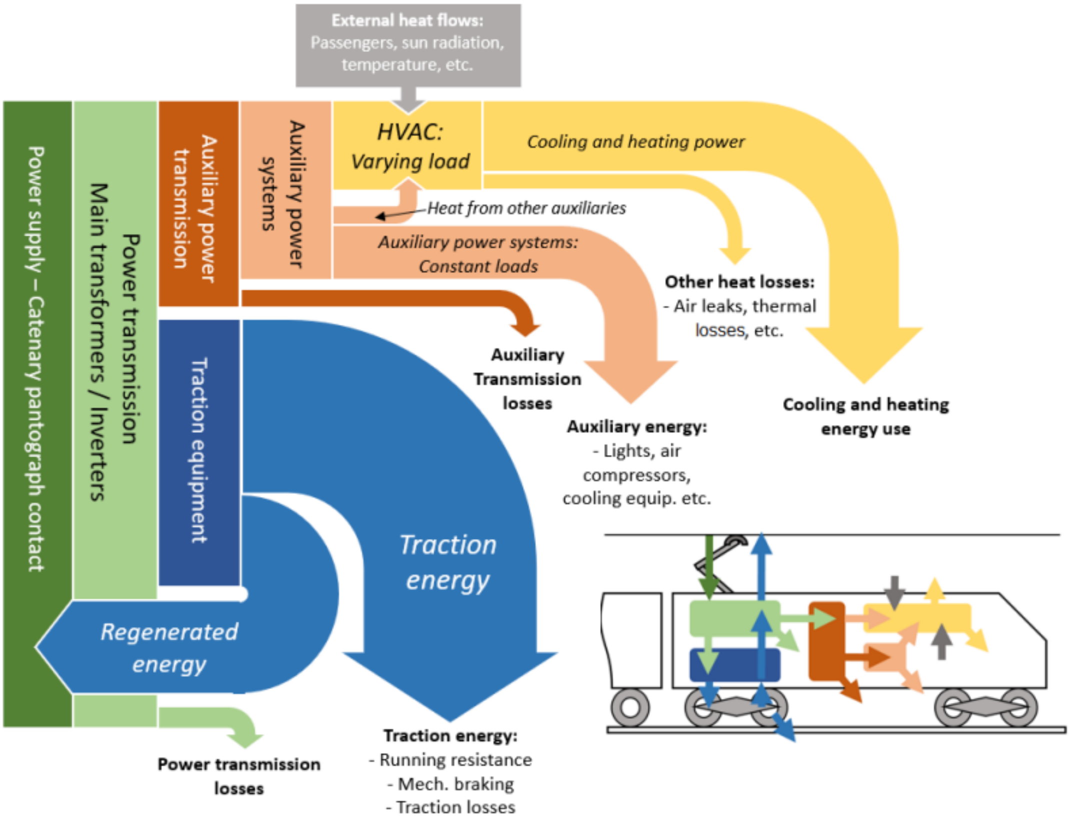

Figure 2 Energy flow diagram of a passenger rail vehicle, including heat flows affecting the HVAC energy use

2.2. Traction-related energy consumption calculation theory

To understand the concept of tractive force and its relationship with running resistance and acceleration, let's break down the components involved and delve into each one in more detail.

Traction Force (F):
The traction force is the force exerted by the powered vehicle, such as a train, to overcome various resistances and provide acceleration. It is denoted by F in the equation.

Traction Torque (T):
The traction torque is the torque generated by the powered vehicle, which is responsible for producing the traction force. It depends on the power output of the vehicle's engine or motor.

Wheel Radius (r):
The wheel radius is the radius of the wheels on the powered vehicle. It plays a crucial role in determining the mechanical advantage and the leverage for generating the traction force. The traction force is inversely proportional to the

wheel radius, as indicated by the equation F = T/r.

Equivalent Mass (m^e):
The equivalent mass, denoted by m^e):, refers to the effective mass of the train or vehicle that experiences the acceleration. It incorporates the combined effect of the actual mass of the vehicle and other factors like inertia and damping.

Acceleration (a_x):
Acceleration, represented by a_x, is the rate of change of velocity of the train or vehicle. It signifies the increase in speed over time. The tractive force is directly proportional to the acceleration, meaning a higher acceleration requires a greater tractive force.

Now, let's discuss the various components of running resistance (D) that the tractive force needs to overcome:

Rolling Resistance (D_r):
Rolling resistance accounts for the friction between the train's wheels and the track. It occurs on a straight, horizontal track and arises from factors like wheel deformation, surface roughness, and imperfections. $D_c$is a component of the total running resistance and is generally proportional to the weight of the train.

Additional Rolling Resistance in Curves (D_c):
When a train negotiates curves, an additional rolling resistance is encountered. This resistance is due to the lateral forces acting on the wheels, which result from the train's changing direction. D_c depends on the curvature of the track and the design of the train's wheels and axles.

Aerodynamic Resistance (D_a):
Aerodynamic resistance, also known as air drag, arises from the train's interaction with the surrounding air. As the train moves forward, it pushes against the air, resulting in resistance. D_a depends on factors such as the train's shape, speed, frontal area, and air density.

Gradient Resistance (D_g):
Gradient resistance arises when a train encounters an uphill or downhill slope. When going uphill, the train has to overcome the force of gravity pulling it downwards, requiring additional tractive force. Similarly, going downhill presents resistance due to the effects of gravity assisting the train's movement. D_g depends on the angle of inclination or decline and the weight of the train.

In summary, tractive force is the force exerted by a powered vehicle to overcome the resistance and provide acceleration. It depends on the traction torque, wheel radius, equivalent mass, and acceleration. Running resistance comprises rolling resistance, additional rolling resistance in curves, aerodynamic resistance, and gradient resistance. The tractive force needs to surpass this cumulative resistance

to facilitate acceleration and ensure the vehicle's movement..
Traction force $F = \frac{T}{r} = m^e a_x + D$ (of powered vehicles)
With
- Traction torque T (of powered vehicles)
- Wheel radius r (of powered vehicles)
- Equivalent mass m^e (of train)
- Acceleration a_x (of train)
-Running resistance D (of train)

where $D = D_r + D_c + D_a + D_g$
D_r= Rolling resistance (on straight, horizontal track)
D_c= Additional rolling resistance in curves
D_a= Aerodynamic resistance (air drag)
D_g= Gradient resistance

2.3. Estimation of running resistance

Estimation of running resistance is crucial for accurately predicting energy consumption in simulation models for commuter trains. Running resistance refers to the resistance encountered by the train during motion, and it accounts for a significant portion of energy losses. To ensure reliable energy consumption estimates, it is essential to model running resistance as accurately as possible.

One commonly used equation for estimating running resistance is the Davis equation.[9] The Davis equation provides a mathematical relationship between the running resistance force (FR) and the velocity of the train (v). The equation is expressed as below.

$$FR = A + B \cdot v + C \cdot v^2$$

Where A, B, and C are coefficients specific to the train and the operating conditions.

The Davis equation is derived from empirical observations and studies of train motion. By collecting data on running resistance at different velocities, researchers can determine the values of the coefficients A, B, and C that best represent the running resistance characteristics of the specific train.

In the equation, the coefficient A represents the constant component of running resistance, which includes factors such as bearing friction and other mechanical losses. The coefficient B captures the linear component of running resistance, associated with factors like air resistance and rolling resistance. The coefficient C accounts for the quadratic component of running resistance, which considers additional factors like wheel-rail interaction and train aerodynamics.

To estimate running resistance using the Davis equation, the values of coefficients A, B, and C need to be determined based on the specific train and operational conditions. These values can be obtained through experimental measurements, data analysis, or referencing existing literature for similar train types.

Accurate estimation of running resistance is crucial for achieving reliable energy consumption predictions in simulation models. By incorporating the Davis equation and determining the appropriate coefficients, engineers and researchers can better understand the energy losses associated with train motion and make informed decisions to optimize energy efficiency.

It is worth noting that while the Davis equation provides a valuable tool for estimating running resistance, there may be other factors and equations that need to be considered in comprehensive energy consumption models. Factors such as gradient, acceleration, deceleration, and auxiliary systems' energy usage should also be taken into account to achieve more accurate and realistic energy consumption estimations for commuter trains.

2.4. Energy saving potentials for commuter trains

Energy efficiency and sustainability are crucial considerations in the transportation sector, including commuter train operations. Commuter trains play a vital role in urban transportation, and optimizing their energy consumption can lead to significant environmental and economic benefits. This section explores various research works and studies that have investigated the energy-saving potentials for commuter trains. By analyzing these findings, we can gain insights into different strategies, technologies, and approaches aimed at reducing energy consumption in commuter train operations.

One of the key areas of research focuses on developing optimized driving strategies for commuter trains. Studies have explored the impact of driving patterns, speed profiles, acceleration and braking techniques, and train control systems on energy consumption. By utilizing advanced algorithms and intelligent control systems, train operators can adopt energy-efficient driving strategies that minimize unnecessary energy losses and improve overall system efficiency. Rongfang created an analytical process for calculating the ideal running sequences of a rail vehicle in order to reduce its consumption of energy.[10]

Regenerative braking systems have emerged as a promising technology for energy recovery in commuter trains. These systems allow the conversion of kinetic energy during braking into electrical energy, which can be fed back into the power supply grid or stored for later use. Research studies have investigated the effectiveness of regenerative braking systems in reducing energy consumption and improving the overall efficiency of commuter trains. Sergio, Janana, and Bruno examine experimental results from a major Brazilian railway and assess the use of regenerative brakes for recuperating energy in diesel-electric freight trains for better efficiency and reducing greenhouse gas emissions.[11]

The weight of a train significantly impacts its energy consumption. Studies have explored the use of lightweight materials, such as advanced composites and aluminum alloys, in train construction to reduce overall weight. Additionally, optimizing the design of train components, including body structures, interiors, and propulsion systems, can contribute to energy savings by reducing aerodynamic drag and rolling resistance. Heather's research classifies measures based on their intended areas of traction utilization and addresses technology such as regenerative braking and lightweight materials. It highlights a scarcity of data on measure appropriateness for various network types and their interactions. The study underlines the importance of additional research to assess measure applicability and scalability.[12]

The integration of advanced power systems can offer substantial energy-saving potentials for commuter trains. Research has focused on the development and implementation of hybrid power systems, including battery-electric and fuel cell technologies. Tajud and Zhongbei create a unique Hybrid Train Simulator that can analyze driving performance as well as energy flow between several energy sources (diesel, hydrogen, and battery). Many realistic examples based on typical UK mainstream locomotives are given. The operational efficiency of diesel and hybrids railways is studied. [13]These systems reduce dependency on fossil fuels and provide more efficient and cleaner energy sources for train operations.

Effective energy management and monitoring systems play a crucial role in identifying energy-saving opportunities and optimizing train operations. Research studies have explored the integration of real-time energy monitoring systems, predictive analytics, and intelligent algorithms to provide train operators with valuable insights into energy consumption patterns, enabling them to make informed decisions for energy optimization.[14]

Efficient infrastructure and network planning can contribute significantly to energy savings in commuter train operations.[15] Studies have investigated the impact of route planning, scheduling, and optimization techniques on energy consumption. By identifying the most energy-efficient routes, considering factors such as gradients and congestion, energy waste can be minimized, and overall system efficiency can be improved.

3. METHODOLOGY

The goal of this chapter is to present an overview of the academic methodology used in this thesis. The entire approach of this thesis was established with appropriate values and conditions for the analysis of energy consumption for the commuter train X60. In Figure 3 the methodology is visualized. The methodology of the thesis is divided into five major sections.

The initial step is to collect data about the X60 commuter train, the Stockholm track, and current running information to feed into the model. When crucial data cannot be provided directly, the model can be used with reference data from the earlier study about commuter train X55. When there are still lacking data, the parameter guess is employed according to the proper estimation, and the parameter can be set down after numerous iterative rounds.

The second section of the thesis is the real-time data analysis, which offers the current energy consumption related to train traction and serves as the standard for the entire analysis. Meanwhile, this investigation contributes to the validation of the model and scenario study.

The third phase is to create a train and track model for the X60 commuter train. The main parameters can be set in this section. More information will be provided in the modeling chapter.

The fourth step is to perform a scenario analysis to assess the potential energy savings. Drive strategy optimization, modifying the timetable, and planned motor switch-off when cruising are three situations. More information will be provided in the scenario study chapter.

The fifth section discusses the energy-saving potential of three scenarios and draws conclusions regarding MTR operation methods.

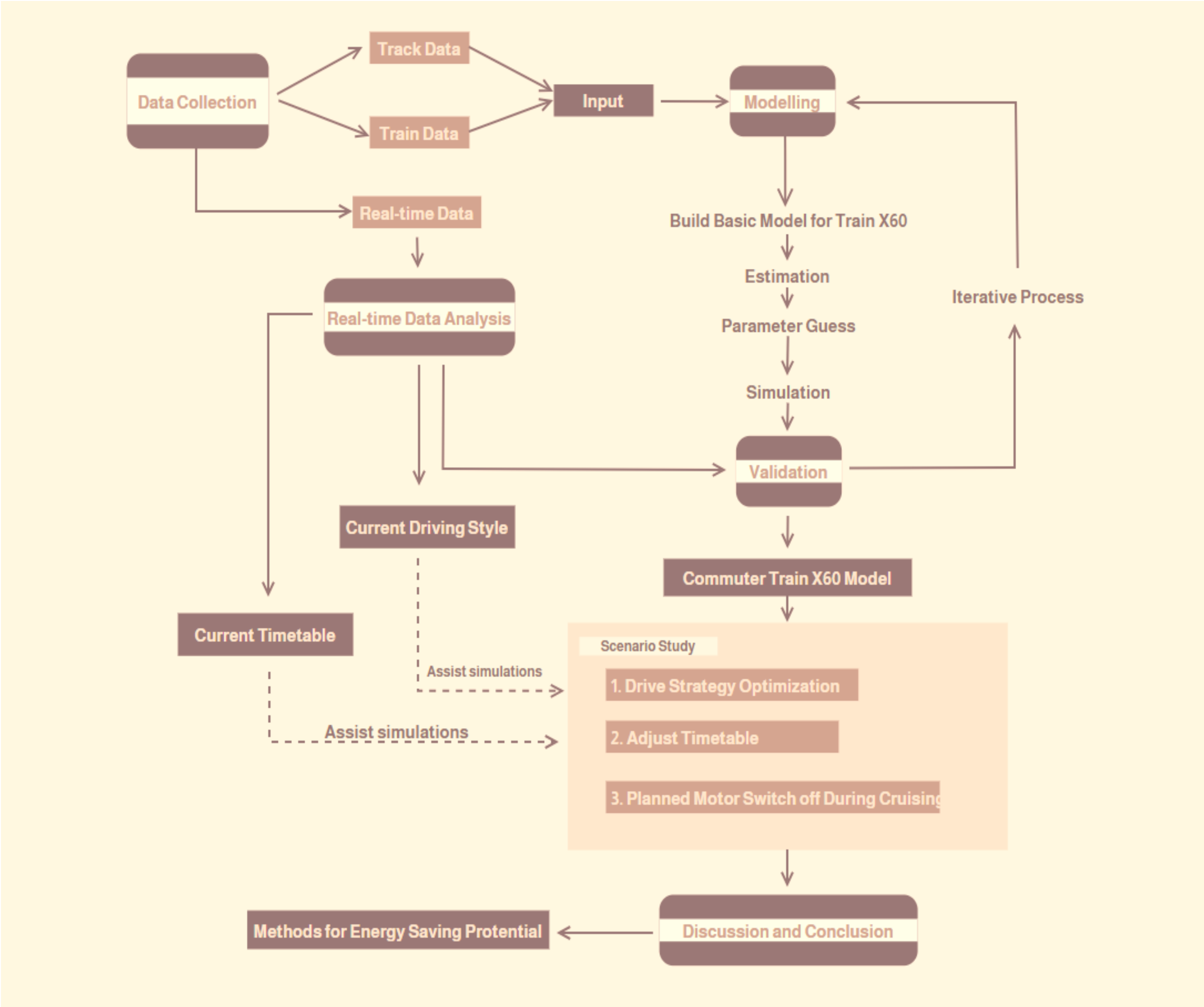

Figure 3 Overview of methodology

3.1. Data collection

Several sources were consulted to identify the technical characteristics necessary as input for developing the model of the commuter train X60 in the simulation program. The information is organized into three sections:

- The real-time train data
- The commuter train X60 data
- The Stockholm track data

3.1.1. The real-time train data

The real-time train data is sourced from the Nexala R2M system, shown in Figure 4, which is critical in monitoring the train's condition and performing automated inspections. In conjunction with a digital maintenance management system, this approach allows for more effective control of the train's manufacture and maintenance procedures.

Nexala provides a wide range of services to the land passenger transportation business, primarily rail operations. Component Condition Monitoring (Nexala C2M), Real-time Remote Diagnostic Monitoring (Nexala R2M), Engineering Maintenance Management (Nexala E2M), and in-Service Performance Planning & Management (Nexala P2M) are among the services offered. [16] The major goal of these services is to handle maintenance operations effectively, allowing for a proactive approach to condition monitoring. These services attempt to increase service quality, extend component lifespan, and improve overall operational efficiency by employing real-time data and innovative technologies.

Through the introduction of Nexala's services, rail operators can continually track the condition of different components, online diagnose issues in real-time, effectively supervise maintenance operations, and strategically prepare for optimal in-service performance. By proactively addressing maintenance needs, the ultimate goal is to provide optimized service delivery, prolonged component lifespan, and improved overall operational efficiency.

In essence, Nexala's services are intended to transform the management of maintenance in the land passenger train sector, particularly in rail operations. These services enable train operators to take a preventive approach to condition monitoring by harnessing real-time data and cutting-edge diagnostics, resulting in improved service quality, extending component lifespan, and improved operational performance.

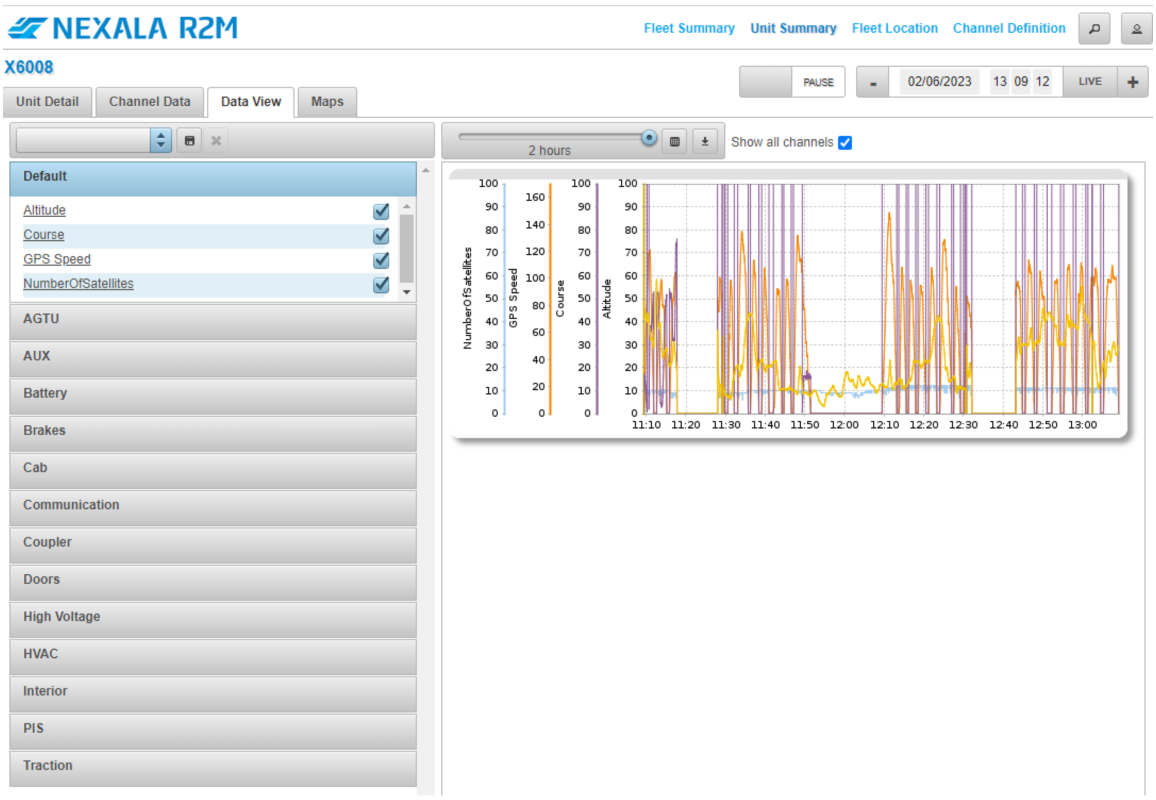

Figure 4 The platform of MEXALA R2M

3.1.2. The commuter train X60 data

The commuter train X60 data was obtained from various reliable sources, including the technical manual provided by ALSTOM. ALSTOM, being the prominent player in the Swedish railway market, has a strong track record of delivering over 1,000 trains, including the X60 commuter train.[17] The technical manual was a significant resource that met high standards and ensured dependability in the data analysis process.

However, due to the scarcity of specific train technical information, key details have to be extrapolated using data from similar X60 series publications, such as commuter trains X55 and X61. These documents gave useful information about the X60 commuter train's overall efficiency and running resistance. The modeling section should be examined for a thorough grasp of the train's characteristics before delving into more specific information.

A complete examination of the X60 commuter train was undertaken by leveraging available data and extrapolating from related sources, with the goal of understanding its performance, efficiency, and other pertinent aspects.

3.1.3. The Stockholm track data

The Stockholm track data is derived from three main resources. The first resource is the GPS signal obtained from the Nexala R2M system, which provides the GPS latitude and longitude coordinates indicating the train's position at the time of each data point. However, it is important to note that GPS signals can be delayed, resulting in a slight inaccuracy in the positioning data. Furthermore, the data generation frequency for the GPS signal is once per second, which may affect the granularity of the data.

The second resource utilized is the Swedish Transport Administration, which offers information on the altitude of stations and the altitude changes between stations. This data source provides more accurate altitude measurements, offering valuable insights into the elevation profile of the track. However, a challenge arises due to the significant distance between the collected data points, resulting in sparse data that may not be sufficient for input in the analysis systems.

To address these limitations, the last source of data comes from the Swedish Land Surveyor website, which provides additional altitude information for the train stations. This source acts as a valuable tool to verify and complement the data from the previous two resources. By utilizing this data, curve fitting techniques can be applied to estimate the altitude changes along the train's route more accurately. This allows for a more complete representation of the track's elevation profile, enhancing the quality and reliability of the analysis.

By incorporating data from these three resources and utilizing curve fitting techniques with the assistance of the Swedish Land Surveyor website, it becomes possible to mitigate the limitations of individual data sources and create a more comprehensive and accurate representation of the Stockholm track's altitude changes.

3.2. Simulation tool

For the traction energy simulations, KTH's Simulation of Train Energy Consumption software, shown in Figure 5, was utilized, which was already available. Using operational scenarios as a starting point, an auxiliary energy model was constructed that takes into consideration vehicle-specific operating modes, surrounding environment and temperature, the number of passengers on board, and so on. Energy use simulations can thus be performed for each stage of the operational cycle, including stabling, pre-service activities, deadheading, and normal train running. Based on the service profiles of the examined operation, KTH's software is then solely utilized to compute the energy and other important data for the traction during train service or deadheading.[18]

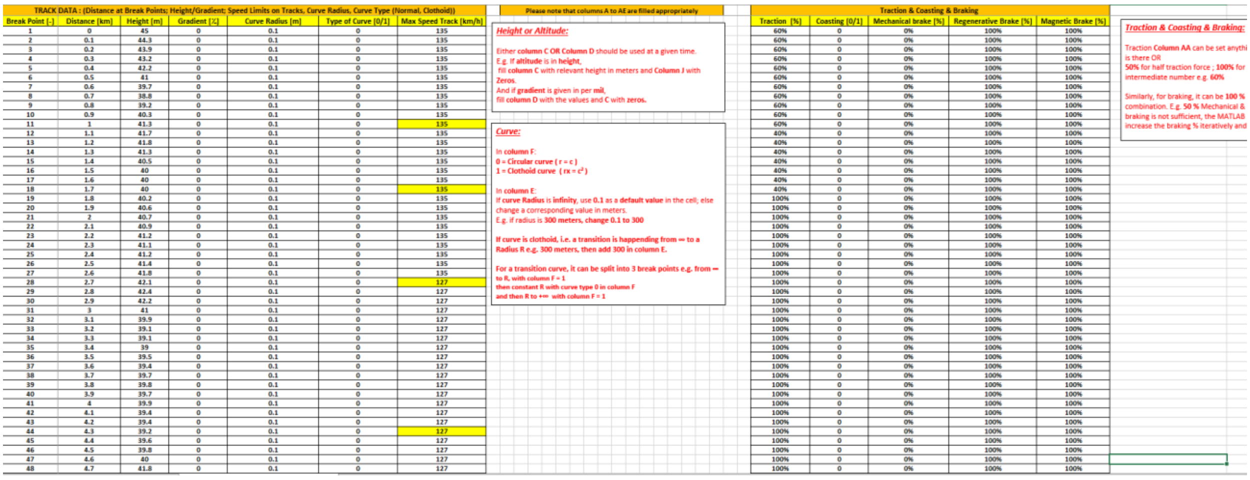

Figure 5 The platform of energy simulation software

3.3. Modelling and validation

The modeling and validation phase relies on a comprehensive dataset comprising the commuter train X60 design information, data from the Stockholm track, and real-time monitoring of the commuter train X60. These datasets serve as inputs to the simulation tool, which is utilized to construct the basic model for the commuter train X60. However, due to the existence of missing or incomplete data, certain parameters are estimated based on informed guesses derived from other reliable resources.

To ensure the accuracy and reliability of the model, an iterative simulation approach is employed. The simulated results are then compared with an ideal model derived from real-time data analysis. However, it is crucial to consider that the ideal model used for comparison in the validation process represents a single extreme example. In order to ensure the validity of the validation results, the validation process is conducted on two different running tracks. One track features a higher degree of altitude change, while the other track is relatively flatter. This multi-track validation approach ensures a comprehensive assessment of the model's performance across varying scenarios.

This chapter provides a thorough overview of the methodologies employed, the data sources utilized, and the steps taken to validate the modeling of the commuter train X60. For a more detailed understanding of the modeling and validation process, additional information can be found in the dedicated chapter on modeling.

3.4. Scenario study

Upon completing the validation process, the model for the commuter train X60 is deemed ready for simulating the train and identifying energy-saving opportunities. To explore different approaches for studying traction-related energy consumption in the commuter train X60, various scenario studies are conducted.

In consideration of the literature study and the desire to minimize physical modifications to the trains, scenarios are primarily focused on methods that can significantly reduce energy consumption without requiring extensive train replacements or material changes. Although methods involving lighter materials could potentially achieve substantial energy savings, they are only applicable when the entire train is replaced, which often entails a longer waiting period to achieve energy efficiency.

The scenarios primarily revolve around three key areas: 1) drive strategy optimization, 2) timetable adjustments, and 3) planned motor switch-off during cruising. Each scenario is carefully described in this chapter, outlining the methodology used for studying their effectiveness. Additionally, further scenario descriptions and the results obtained from the three scenarios can be found in the dedicated chapter on scenario studies.

By exploring these scenarios and their respective methodologies, it becomes possible to identify practical approaches for optimizing energy consumption in the commuter train X60. These findings contribute to the broader goal of achieving energy efficiency and sustainability in rail transportation.

3.4.1. Scenario 1 Drive strategy optimization

Commuter trains typically cover shorter distances compared to long-distance trains, and in the case of Stockholm's commuter train, the typical driving distance is around 5km. In this particular scenario, the focus is on optimizing the drive strategy for a 5km distance between two stations.

While most studies on drive strategy for short-distance commuter trains consider the entire journey as a whole, this study takes a different approach by analyzing the journey in two distinct parts. This division allows for a clearer analysis of energy consumption and energy regeneration (when the train generates electricity and feeds it back into the grid), providing valuable insights on how to save energy effectively.

In this scenario, the analysis is divided into two parts. The first part encompasses the acceleration phase, during which energy consumption is at its highest, as well as partial cruising. By examining these aspects separately, it becomes possible to gain a better understanding of the energy dynamics during these specific stages of the journey.

The second part of the analysis focuses on partial cruising, coasting, and braking. Notably, during the braking phase, the energy consumption becomes negative as the train regenerates energy. The braking segment plays a significant role in the latter part of the entire journey, and studying this aspect is crucial for comprehending energy usage patterns and identifying potential energy-saving measures.

By analyzing these two distinct parts of the journey, a more comprehensive understanding of energy consumption and regeneration in the context of drive strategy optimization for short-distance commuter trains can be achieved. This approach enables researchers to delve deeper into energy-saving opportunities and formulate targeted strategies to enhance energy efficiency in commuter train operations.

3.4.2. Scenario 2 Timetable adjustments

While adjusting timetables for commuter trains has the potential to save energy, it is important to consider the drawbacks identified in the literature review, which include operating issues, limited flexibility, impact on passenger convenience, integration with other means of transportation, and cost and implementation challenges.

In this scenario, the energy-saving potential will be discussed based on two methods. The first method involves not adjusting the timetable, which will be primarily explored in scenario 1. This approach aims to understand the existing timetable's energy consumption patterns and identify opportunities for energy optimization without making significant changes to the schedule. By analyzing the data and modeling the energy dynamics, insights can be gained on how to improve energy efficiency within the current timetable framework.

The second method builds upon scenario 1 and focuses on making minimal adjustments to the train timetable. This approach considers applying the energy-saving strategies identified in scenario 1 to specific non-peak load lines and hours. By strategically selecting less busy periods, such as off-peak hours, it may be possible to implement timetable adjustments that have a minimal impact on passenger convenience while still achieving energy savings. This method aims to strike a balance between optimizing energy consumption and maintaining service reliability during periods of lower passenger demand.

By exploring both of these methods, this scenario aims to provide a comprehensive understanding of the energy-saving potential associated with adjusting timetables for commuter trains.

3.4.3. Scenario 3 Planned motor switch off during cruising

The methodology of Planned Motor Switch Off During Cruising is extensively discussed in this chapter. As revealed by the literature study, during the cruising phase of the train's running cycle, the speed remains constant. Consequently, the force generated by the motors equals the running resistance force, without any acceleration present. The constant traction force from the motor ensures that the train maintains a steady speed.

To comprehend the efficiency of the electric motor during this phase, a representative example of an efficiency map of the motor is shown in Figure 6. At a constant rotation speed of the motor, different continuous torque values demonstrate varying motor efficiencies. The torque is calculated by multiplying the motor radius, motor force, and the angle between the force and the lever arm, shown in the formula below. Since the radius and operation angle remain constant for the train motors, the graph depicts the relationship between the traction force and the rotation speed of the electric motor. Thus, at a constant rotation speed of the motor, different continuous force levels exhibit distinct motor efficiencies.

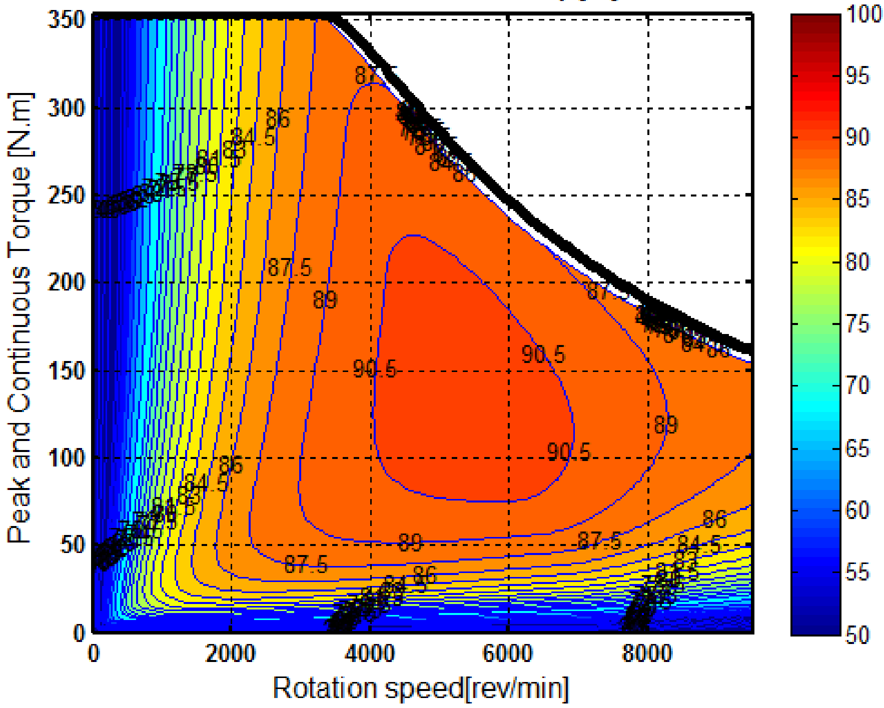

Figure 6 Example of efficiency map of the electric motor

Formula

$$T = rFsin\theta$$

$T \ = \ torque$
$r = \ radius$
$F = \ force$
$\theta = \ angle\ between\ F\ and\ the\ lever\ arm$

In the case of the commuter train, the whole traction force is provided by three groups of motors. The methodology employed in this scenario aims to maintain the same rotation speed and supply the required traction force for the entire train using only two groups of motors or even a single group. This means that two groups of motors must increase their force output to power the train, and at the same rotation speed, their efficiency increases alongside the force. Similarly, by utilizing only one group of motors, the train's force efficiency may be enhanced.

For a comprehensive understanding of the methodology and its implications, further details will be provided in the upcoming chapters of the scenario study. The focus will be on investigating the effects of planned motor switch-off during cruising, including the associated energy savings, operational considerations, and potential trade-offs.

3.5. Discussion and conclusion

The discussion and conclusion of this chapter provide an overview of the academic methodology used in the thesis and summarize the key findings and implications of the research.

The methodology presented in the chapter is divided into five major sections. The first section focuses on data collection, including real-time train data, commuter train X60 data, and Stockholm track data. The use of Nexala's services for real-time train data collection is highlighted, which allows for effective monitoring and maintenance control. The availability of technical manuals and extrapolation from related train series data is mentioned for gathering the necessary information about the commuter train X60. The utilization of multiple data sources, including GPS signals and altitude information, is explained for obtaining accurate and comprehensive Stockholm track data.

The second section discusses the simulation tool used for traction energy simulations, which is KTH's software. The software takes into account various factors such as operating modes, environmental conditions, and passenger load to compute energy consumption during different stages of train operations.

The third section focuses on the modeling and validation phase, where the dataset comprising design information, track data, and real-time monitoring is used as inputs for constructing the basic model of the commuter train X60. Due to missing or incomplete data, certain parameters are estimated based on informed guesses. The iterative simulation approach and comparison with an ideal model derived from real-time data analysis are mentioned for ensuring the accuracy and reliability of the model. The validation process is conducted on two different running tracks with varying altitude changes to assess the model's performance.

The fourth section introduces the scenario study, which explores different approaches for studying traction-related energy consumption in the commuter train X60. The scenarios primarily focus on methods that can significantly reduce energy consumption without extensive train replacements or material changes. Three key scenarios are discussed: drive strategy optimization, timetable adjustments, and planned motor switch-off during cruising. The division of the journey into distinct parts allows for a detailed analysis of energy consumption and regeneration, providing insights on energy-saving opportunities.

In conclusion, the methodology employed in this thesis involves data collection, simulation tool utilization, modeling and validation, and scenario study. The use of real-time data, technical manuals, and multiple data sources ensures the reliability and accuracy of the analysis. The scenario study explores practical approaches for optimizing energy consumption in the commuter train X60, considering factors such as drive strategy, timetable adjustments, and motor switch-off. The findings contribute to the broader goal of achieving energy efficiency and sustainability in rail transportation.

Overall, this chapter provides a comprehensive overview of the methodology used in the thesis, highlighting the importance of data collection, simulation tools, modeling, validation, and scenario study. The methodology ensures the reliability of the analysis and provides insights into energy-saving opportunities for the commuter train X60.

4. REAL-DATA ANALYSIS

The real-data analysis is done with the exported data from the Nexala system, which comprises the information generated during the time frame 2023-01-01 to 2020-06-15. This data specifically focuses on the south track line of Stockholm, where the researched stations are located. To determine the general arrival time of trains at these stations, the SL commuter train timetable is consulted, providing both the date and specific time of arrival. By narrowing down the search to only include the trains that pass through the researched stations, the system ensures a more targeted analysis of the relevant data.

The travel distance is not provided directly in the Nexala system, so the calculation of the train travel distance between two stations is described in this chapter. This calculation method allows for accurate measurements of the distance covered by the trains along the south track line. Additionally, in this chapter, the quantification of energy consumption is conducted. By analyzing the energy consumption patterns associated with train traction, the system gains insights into the efficiency and performance of the commuter trains.

Ultimately, the real-data analysis results provide valuable information for analyzing the current commuter driving style. By examining the train traction-related energy consumption, researchers can identify trends and patterns that shed light on the efficiency and effectiveness of the driving practices. This analysis helps in understanding the energy utilization of the commuter trains and can potentially lead to improvements in energy efficiency and overall performance.

4.1. Selection of stations

The choice of stations from Krigslida to Nynäsgård for the research study was based on several factors that make this section suitable for investigation, see Figure 7 and Figure 8. These stations represent a typical single track, single line segment that is not heavily congested, which aligns with the characteristics of a typical commuter train distance in the Stockholm region.

One of the key considerations in selecting this section is the resemblance to the operational conditions found in the Stockholm commuter train network. By choosing a segment that closely matches the style and characteristics of the Stockholm network, the findings and strategies developed through the research study can be more readily applied and implemented in the actual operational context. This ensures that the research outcomes have practical relevance and can potentially be adopted by the railway authorities and operators in the future.

Furthermore, the selection of this section was driven by the availability of sufficient data to collect. Conducting a comprehensive research study requires access to reliable and extensive data on train operations, energy consumption, and other relevant parameters. The stations from Krigslida to Nynäsgård were deemed to have an adequate amount of data available, enabling a thorough analysis of energy consumption patterns and the evaluation of different energy-saving strategies.

By focusing on this particular section, researchers can gain valuable insights into the energy dynamics and operational characteristics of commuter trains in a representative setting. This understanding serves as a foundation for developing and testing energy-saving strategies that are specifically tailored to the Stockholm commuter train network.

Additionally, the choice of this section opens up possibilities for the implementation of the identified energy-saving strategies in the future. By studying a section that is not heavily congested and represents a typical commuter train distance, the findings and strategies developed can potentially be extended to other similar sections within the Stockholm network. This scalability and applicability of the research outcomes contribute to the long-term goal of improving energy efficiency and sustainability in the overall commuter train operations.

In summary, the selection of stations from Krigslida to Nynäsgård for the research study was driven by their alignment with the characteristics of a typical commuter train distance in Stockholm, the availability of sufficient data, and the potential for implementing the identified strategies in the future. By conducting the study in this section, researchers can gain insights that are relevant to the Stockholm network and contribute to the broader objective of enhancing energy efficiency in rail transportation.

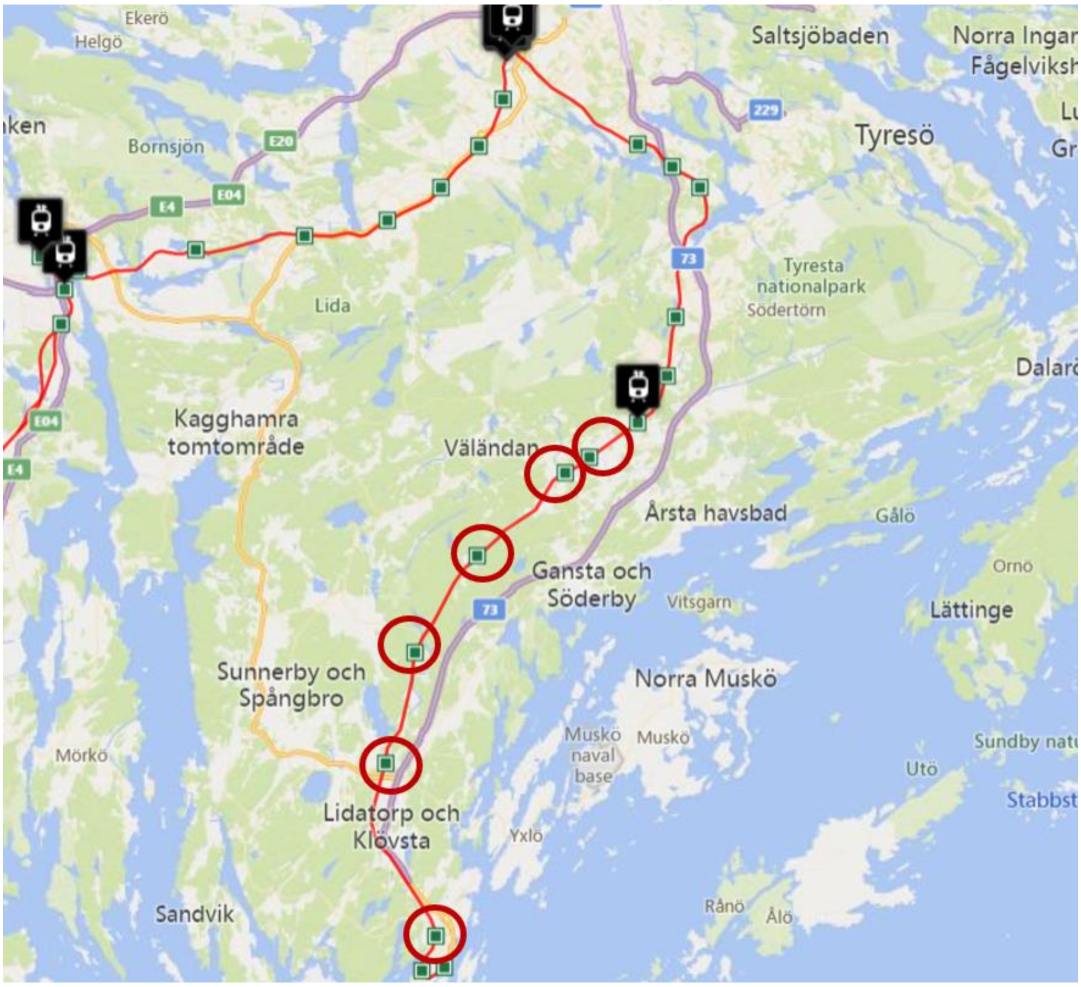

Figure 7 Stations from Krigslida to Nynäsgård (Nexala R2M)

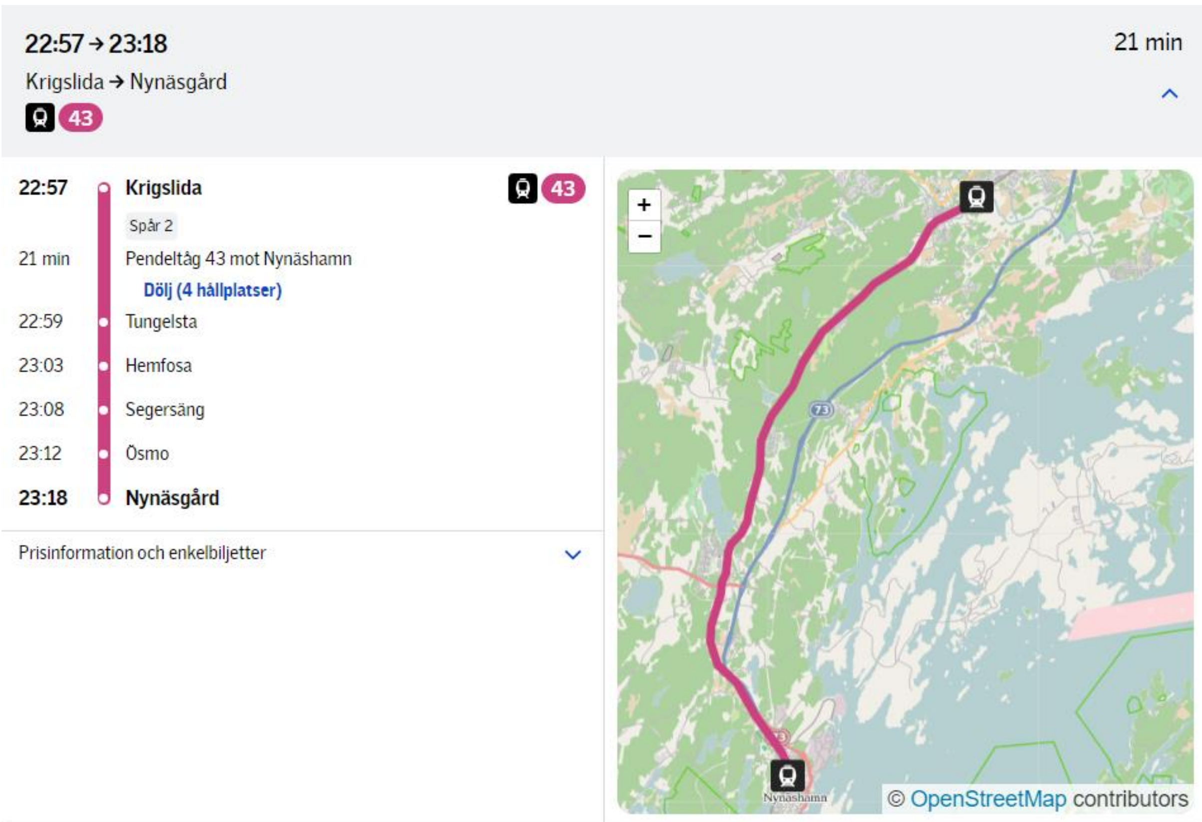

Figure 8 Timetable from Krigslida to Nynäsgård (SL)

4.2. Travel distance calculation

To calculate the travel distance for commuter trains when GPS latitude and longitude data is not available, an alternative method can be employed. Since the GPS signals obtained from the Nexala R2M system may have slight inaccuracies and not all trains provide GPS coordinates, an approach based on train speed and time can be used.

The first step is to analyze the exported data from the Nexala R2M system and identify the points where the train's speed is equal to zero. These points serve as reference markers for the beginning and end of the travel distance. Let's assume that the point where the speed is zero represents the start of the travel distance (station A), and the next occurrence of zero speed represents the end of the travel distance (station B).

By knowing the instantaneous speed of the train at each second, and having access to the corresponding time information, it becomes possible to calculate the travel distance between station A and station B. The principle behind this calculation is to integrate the product of the instantaneous speed and time over the relevant time period.

For instance, if the train's speed at each second is recorded, and the corresponding time intervals are known, the travel distance can be estimated by summing up the products of the instantaneous speed and time for each interval within the duration of the journey from station A to station B. This integration process yields an approximation of the total distance traveled.

It's important to note that this method assumes a constant speed between the recorded data points, which might not perfectly reflect the actual train behavior. However, given a sufficient number of data points and a reasonable assumption of speed continuity, this approach can provide a reasonable estimation of the travel distance.

Overall, when GPS latitude and longitude data are unavailable, the method described above offers a practical way to calculate the travel distance for commuter trains. By utilizing the recorded instantaneous speed and time intervals, an estimate of the distance traveled between two reference points (station A and station B) can be obtained, allowing for further analysis and evaluation of train operations and energy consumption.

4.3. Speed profile drawing

To draw the speed profile of a commuter train running, several steps are involved, starting with the calculation of the travel distance, followed by data processing and analysis. In this case, the focus is on analyzing 5 stations and 10 drivers along the route from Krigslida to Nynäsgård. However, it's important to note that due to potential inaccuracies in the data, further processing is required to ensure reliable results.

First, the travel distance between each pair of stations needs to be calculated, as described in the previous response. This provides the necessary distance values to plot against the speed and travel time.

Next, data processing is performed to address any inconsistencies or missing data points. If a commuter train has missing data during its journey, those incomplete records are removed from the dataset. Additionally, trains that do not reach the final destination station are also excluded from the analysis. These steps help ensure that the data used for generating the speed profiles are as complete and accurate as possible.

It's worth noting that the start and stop stations may have some distances within the station boundaries. As a result, the travel distance recorded for a journey from station A to station B includes the partial distances traveled within the start and stop stations. Consequently, for the same journey between two stations, there might be slight differences in the recorded travel distances. However, these differences typically fall within an acceptable margin of error.

With the processed data and travel distances, the speed profiles can be plotted. The profiles show the relationship between speed and distance or speed and travel time. By plotting the speeds recorded at different distances or times during the journeys of the 10 drivers across the 5 stations, a visual representation of the speed variations can be obtained. This allows for further analysis and evaluation of the train operations and characteristics along the selected route.

In conclusion, by performing data processing and analysis, the speed profiles of commuter trains running between the 5 stations can be derived, shown in Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13. Although some data inconsistencies may exist and minor variations in travel distance are present due to station distances, these factors can be addressed to obtain meaningful insights into the speed variations along the route.

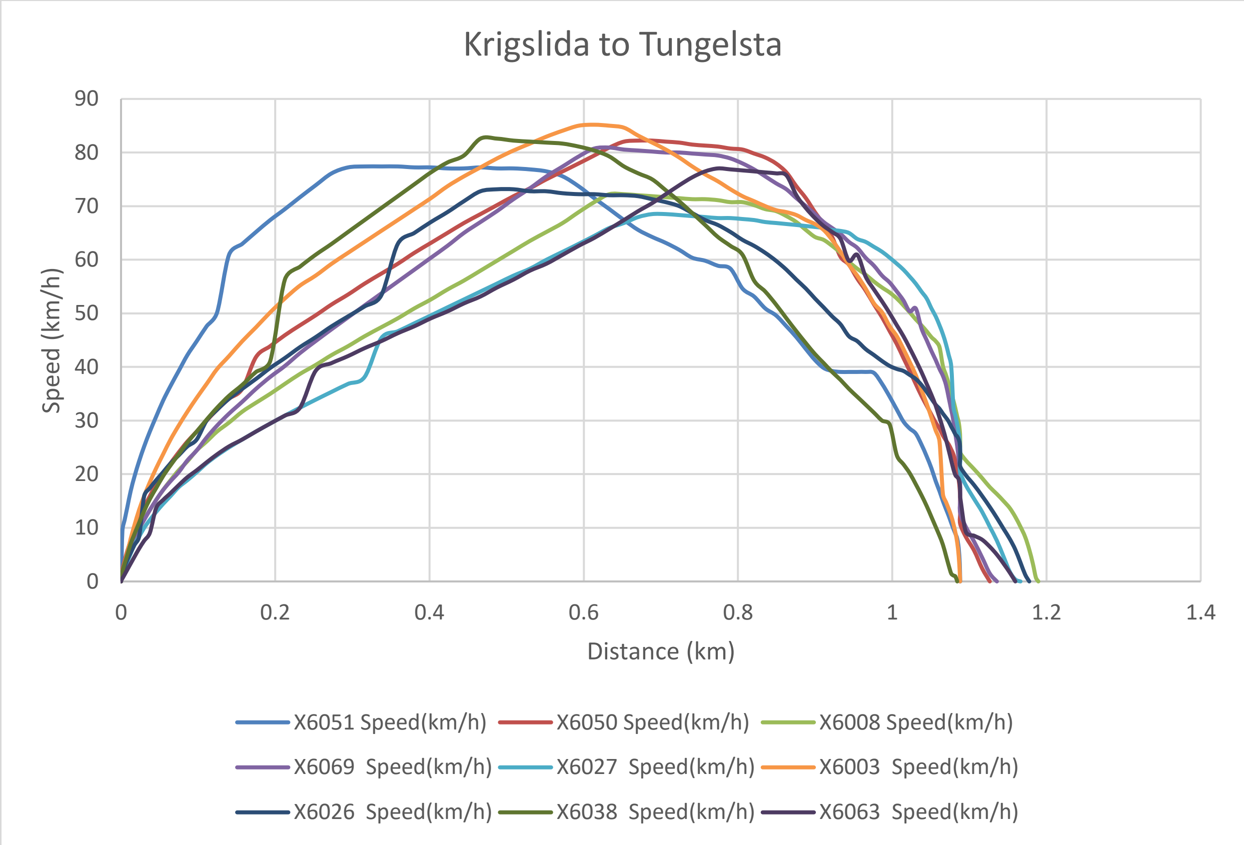

Figure 9 Krigslida to Tungelsta

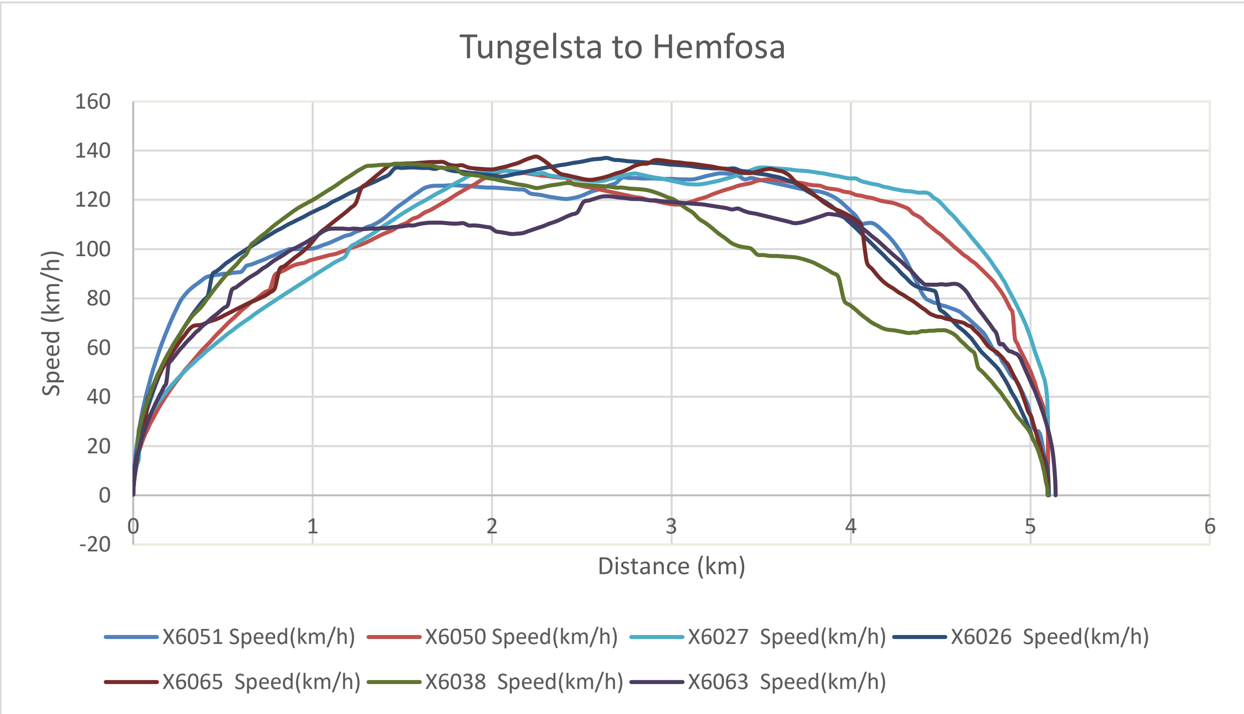

Figure 10 Tungelsta to Hemfosa

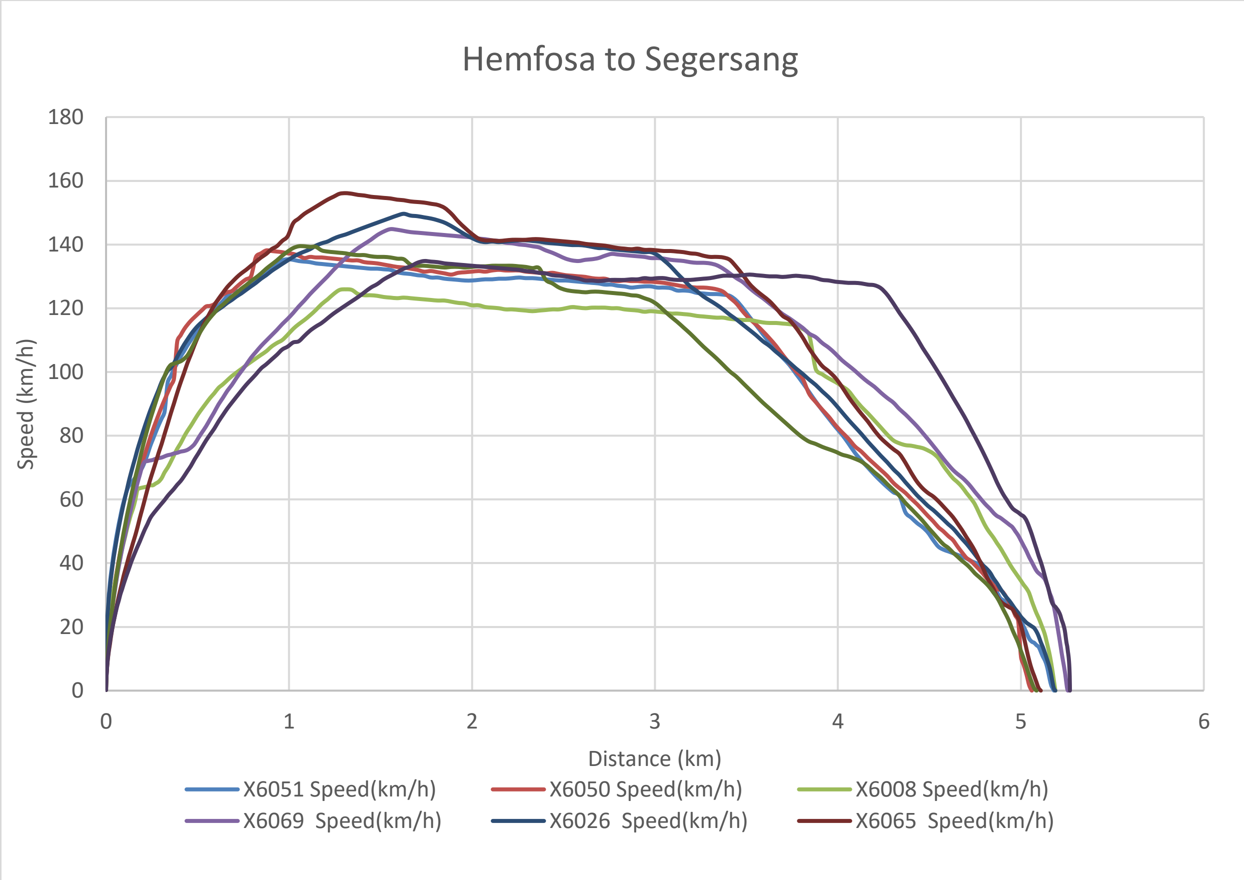

Figure 11 Hemfosa to Segersang

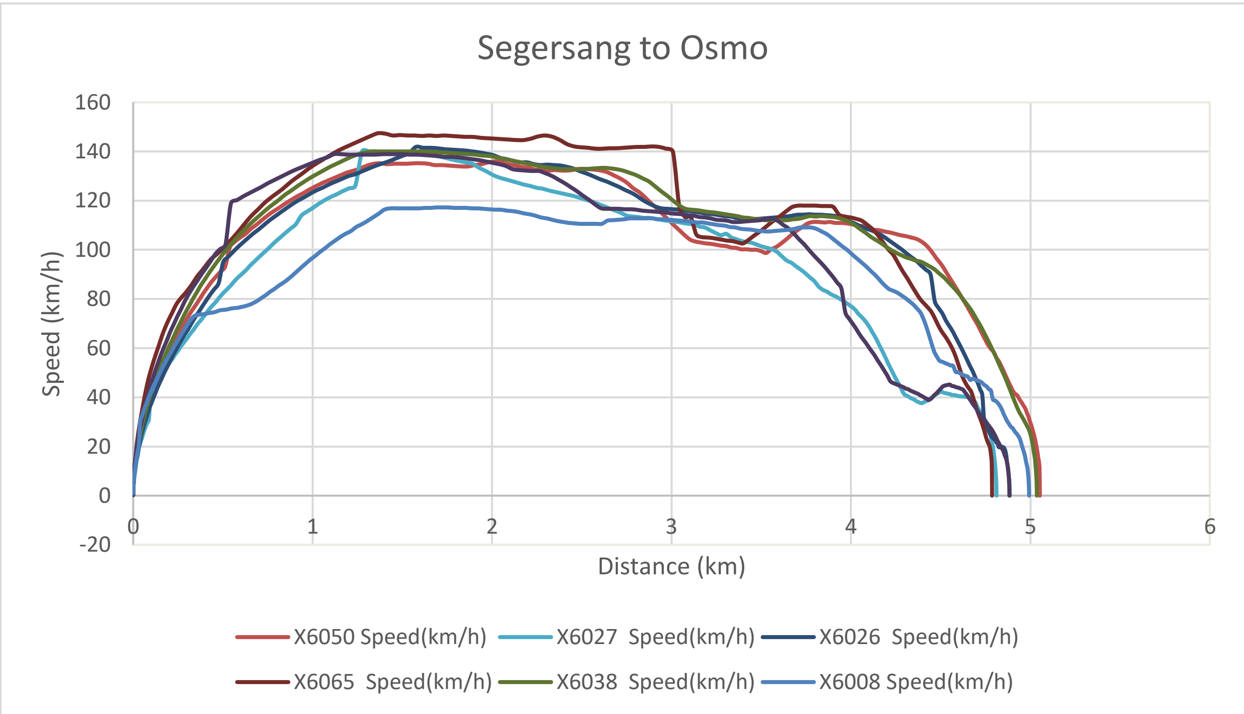

Figure 12 Segersang to Osmo

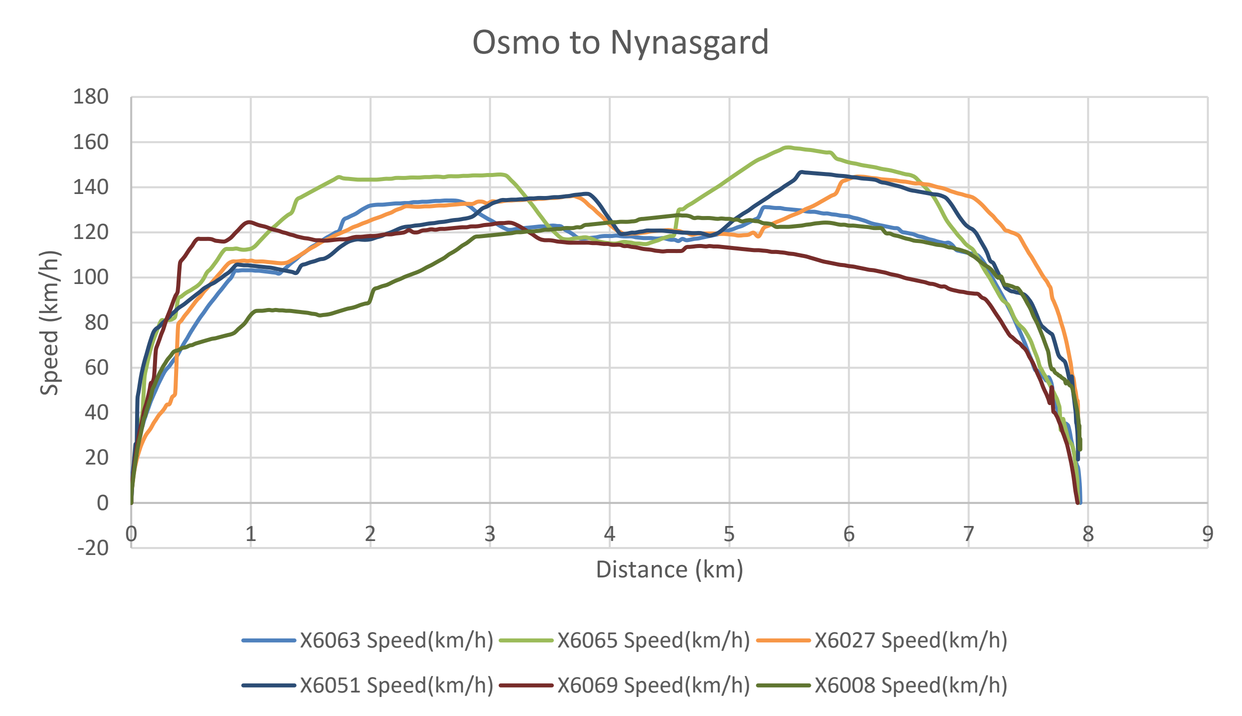

Figure 13 Osmo to Nynsagard

4.4. Quantification of energy consumption

To quantify the energy consumption of a commuter train, it is necessary to go beyond the speed profile and analyze the traction-related energy consumption. The energy consumption in the railway system can be broadly divided into two main parts: auxiliary power systems and traction equipment.

The Nexala R2M system used in this study does not directly provide separate energy consumption values for these two parts, which poses a challenge. However, the system does offer an overall power consumption value, which represents the sum of the auxiliary power systems and traction equipment. By utilizing this information, it is possible to estimate the traction-related energy consumption.

The auxiliary power systems primarily consist of HVAC (Heating, Ventilation, and Air Conditioning) systems and other auxiliary devices such as lights, air compressors, and cooling equipment. The energy consumption of these auxiliary power systems tends to remain relatively constant during the operation of the commuter train.

In order to isolate the traction-related energy consumption, a method can be employed as illustrated in the example Figure 14. When the commuter train is stationary and the speed is zero, the energy consumed during this period is solely attributed to the auxiliary power systems. By establishing this as the baseline, the constant electric power consumed by the auxiliary power systems can be subtracted from the total electric power consumption, resulting in the electric power specifically attributed to the traction sector.

It is important to note that the instantaneous power consumption can be multiplied by the instantaneous time to calculate the energy consumption related to traction. This enables further study and analysis of the energy consumption patterns and characteristics of the commuter train.

In conclusion, quantifying the energy consumption of the commuter train involves addressing the challenge of separating the energy consumed by the auxiliary power systems and the traction equipment. By subtracting the constant electric power from the auxiliary power systems during periods of zero speed, the electric power consumption specifically attributed to the traction sector can be estimated. Multiplying the instantaneous power by the instantaneous time allows for a more comprehensive understanding of the energy consumption dynamics and facilitates further investigation into energy consumption patterns.

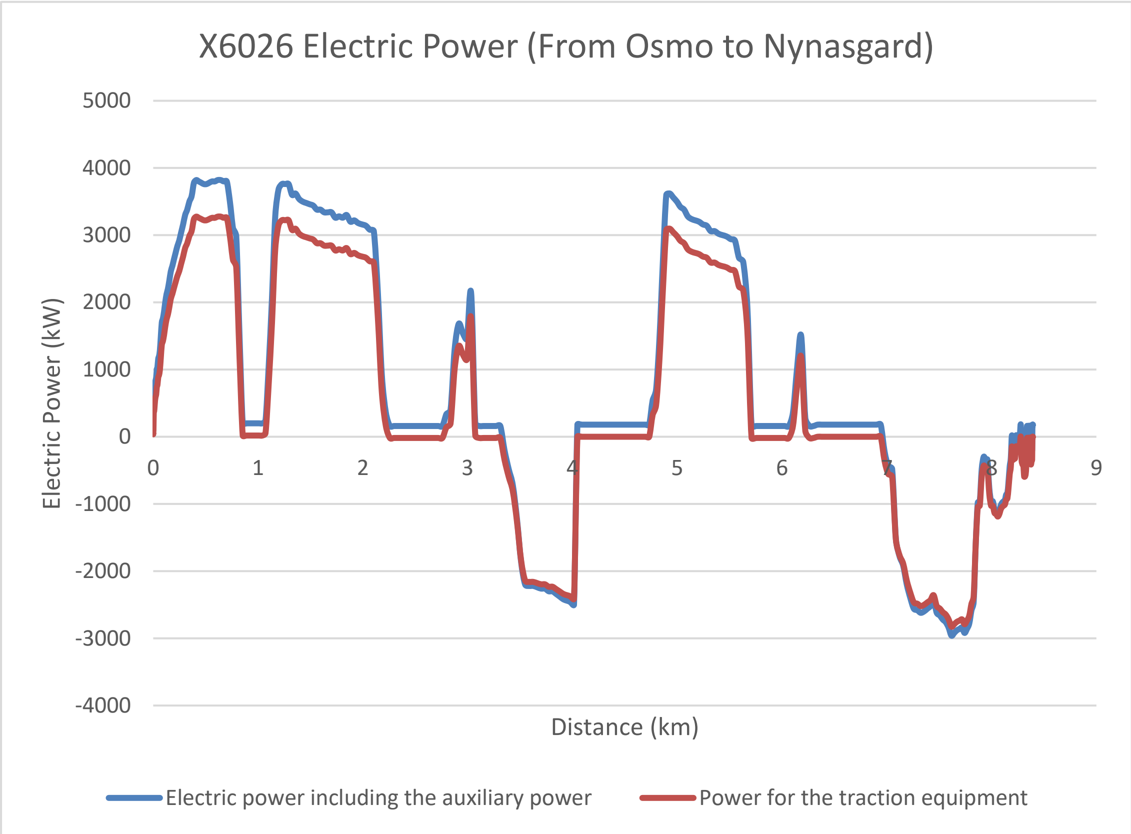

Figure 14 X6026 electric power (from Osmo to Nynasgard)

5. MODELLING

To utilize the simulation tool, the Simulation of Train Energy Consumption software developed by KTH (Royal Institute of Technology) is employed. This software offers a comprehensive platform for conducting traction energy simulations. The following steps outline the process of using this tool for commuter train analysis:

Choose the range of modeling: Determine the scope and extent of the modeling exercise. This involves defining the specific aspects of the commuter train system that will be simulated and analyzed, such as the route, operational scenarios, and time duration.

Build the track profile: Create a detailed track profile that includes information about altitude variations and limited speed sections. These parameters are crucial for accurately modeling the train's energy consumption based on the terrain and track characteristics.

Data processing: Process the available data to ensure compatibility with the simulation tool. This may involve tasks such as formatting the data, integrating relevant breakpoints, and preparing it for input into the software.

Input the train parameters: Define the specific parameters related to the commuter train being simulated. This includes information such as the train's physical characteristics, power supply system, propulsion technology, and any other relevant factors that influence energy consumption.

Iteration for the train's unknown parameters: Some parameters may not be readily available and need to be estimated or iterated through the simulation process. These unknown parameters, such as resistances or efficiencies, can be refined and adjusted iteratively to achieve more accurate results.

Validity check of train & track model: Validate the train and track models to ensure they accurately represent the real-world conditions. This involves comparing the simulated results with actual measurements or known performance data to verify the model's reliability and accuracy.

Run different simulations: Utilize the established train and track models to run various simulations. This involves selecting different scenarios, and analyzing the energy consumption and other important data generated by the simulations.

By following these steps and utilizing the KTH software, it becomes possible to conduct comprehensive simulations of traction energy consumption for commuter trains. The tool takes into account various factors, including operational modes, environmental conditions, passenger loads, and specific train characteristics, providing valuable insights into energy usage throughout the train's operational cycle. These simulations aid in understanding the energy efficiency of the commuter train system and can guide decision-making processes related to energy optimization and sustainability.

5.1. Method of using the simulation tool

The tool being developed is an energy simulation tool designed to calculate energy consumption in the context of rail vehicles. It leverages existing energy simulation tools and incorporates the structure, basic functions, and previous knowledge of energy calculations to create a numerical model. The input and output of the tool will be handled through Excel files, while the actual calculations and modeling will be performed using MATLAB.

Using the simulation tool involves several steps to accurately calculate energy consumption and simulate train behavior. Let's break down the process:

Study and develop a numerical model: Begin by studying existing energy simulation tools, understanding their structure, basic functions, and energy calculation methods. Use this knowledge to develop a custom numerical model that can accurately calculate energy consumption.

Process track data: Track data is often provided in various formats, making it challenging to automate the processing of these files. However, it's not feasible to include every breakpoint in the simulation, as it would result in an excessive number of breakpoints. Upload the track breakpoint data, also known as milestone data, in an Excel file named "track information."

Breakpoints Finder MATLAB script: Use a MATLAB script called "Breakpoints_Finder" to process the breakpoint data. Update the train length information in the script and locate new breakpoints when speed limits change or the consecutive distance between two breakpoints exceeds a specified threshold. The results from the Breakpoints Finder are exported to an Excel sheet named "BreakPoints," which will be used in the energy calculation.

Energy Calculation Setup: Open the Excel file named "Energy_calculation-Test" and add train and track data in different sheets. In the "train_data" sheet, input relevant data such as the braking mass of the train (including vehicle mass and passenger load). The calculations will be performed at the wheel and integrated backward from wheel to catenary, considering all the intermediary systems in between as per the traction topology.

Define topology maps: Define the topology maps in separate sheets of the Excel file. These maps can be 2D or 3D and are functions of speed or other parameters. They help define factors such as maximum mechanical braking, velocity limits for regenerative braking, and other relevant information.

Track, Driving Style, Timing: In the "Track, Driving Style, Timing" sheet of the same Excel file, copy and paste the data of distance, height, and maximum track speed from the previously calculated breakpoints. Additional instructions and details can be found in the same sheet for further customization.

Define driving style: Within the same Excel file, you can manually change the percentage values of Tracon and Braking percentages at specific breakpoints to define the driving style.

Master sheet: In the Excel sheet named "Master," cells are loaded with formulas to populate data from the other sheets. This sheet serves as a central location for collecting and summarizing data from various sources.

Run simulations: To run a simulation, open the MATLAB script "Energy_calculation_NEW." The script allows you to set different modes and parameters. By default, the mode is set to 0. You can run simulations with different parameters, such as applying coatings selectively over a specific period or introducing local driving behavior control. The results of the simulations, including graphs, raw data of key variables in SI units, and summary data, are exported to the Excel sheet named "Results3" and presented in Sheet 2.

Testing and improvement: The simulation tool has been tested with various scenarios, including extreme cases, and has been gradually improved to ensure accuracy and reliability. Real-life data can also be simulated, such as for a commuter train in the north of Sweden.

By following these steps and utilizing the MATLAB scripts and Excel sheets provided, it is possible to perform simulations, calculate energy consumption, and analyze the behavior of commuter trains in various scenarios. More information can be found in the chapter on Addition.

5.2. Build the basic model for commuter train X60

To build a comprehensive basic model for the X60 commuter train, two main components need to be considered: the train model and the track model.

For the train model, the X60 technical manual and other reliable sources are reviewed to gather essential data such as train mass, power supply, traction system, and braking system. This information is carefully collected and verified for accuracy. To organize the data effectively, a table or spreadsheet is created, ensuring that the inputted values are consistent and have the appropriate units. It is important to note that certain parameters may not be directly provided in the technical manual, marked with red X, shown in Table 1 Basic input data for commuter train X60. These parameters may require estimation or iteration through the simulation process to obtain accurate results. The subsequent section will delve into the estimation and parameter guess processing techniques in detail.

Table 1 Basic input data for commuter train X60

Vehicle mass [tonns]	205
Relative mass addition [%]	X
Adhesion mass [tonns]	217
Braked mass [tonns]	340
Load [tonns]	
Max Comfort acceleration [m/s^2]	1.12
Max Comfort deceleration [m/s^2]	1.12
Wheel_diameter [mm]	818
Slip control availability [0/1] [No/Yes]	1
Slip (s = ΩR/v -1) [%]	0.001
Driver Control on brake [0/1] [No/Yes]	1
Running Resistance Coefficients	
A [N]	X
B [Ns/m]	X
C [Ns^2/m^2]	X
Curvature Resistance Coefficients	
a	6.5
b	55
Axle Gear	
Gear ratio (Motor/Axle gear)	10
Efficiency [%] Or (Overall efficiency)	X
Power Components Specification	
No of induction motors [-]	12
Motor Rated Power [kW]	250
Motor Rated Speed [RPM]	5800
Constant Auxiliary Power consumption [kW]	220
Motor efficiency [%]	Map in sheet
Inverter efficiency [%]	Map in sheet
Absorption circuit efficiency [%]	100%
Line converter efficiency [%]	Map in sheet
Transformer efficiency [%]	Map in sheet
Maximum allowed Mechanical brake [%]	100%
Velocity limit on Regenerative brake [km/h]	0

Maximum allowed Regenerative brake [%]	**100%**
Mechanical brake increment step [%]	**10%**
Regenerative brake increment step [%]	**10%**
Adhesion utilization limit while traction α [%]	**45%**
Adhesion utilization limit while braking α [%]	**45%**
Simulation Type	**1**
Inverter Rated Power [kW]	**1000**
Line Converter Rated Power [kW]	**2000**
No of Line Converter [-]	**4**

Regarding the track model for the X60 commuter train, data is sourced from three primary channels: the GPS signals obtained from the Nexala R2M system(Figure 15), information provided by the Swedish Transport Administration(Figure 16), and data from the Swedish land surveyor(Figure 17). By leveraging this diverse range of data sources, a process known as Curve Fitting is performed to construct the track model. Curve fitting techniques allow for the creation of a mathematical representation of the track's geometry, including its curves and gradients. This track model is vital for simulating the train's movement and calculating energy consumption accurately.

By developing both the train model and the track model, a comprehensive understanding of the X60 commuter train's behavior and its interaction with the track can be achieved. This foundational work lays the groundwork for further analysis, optimization, and energy consumption calculations in subsequent stages of the research study.

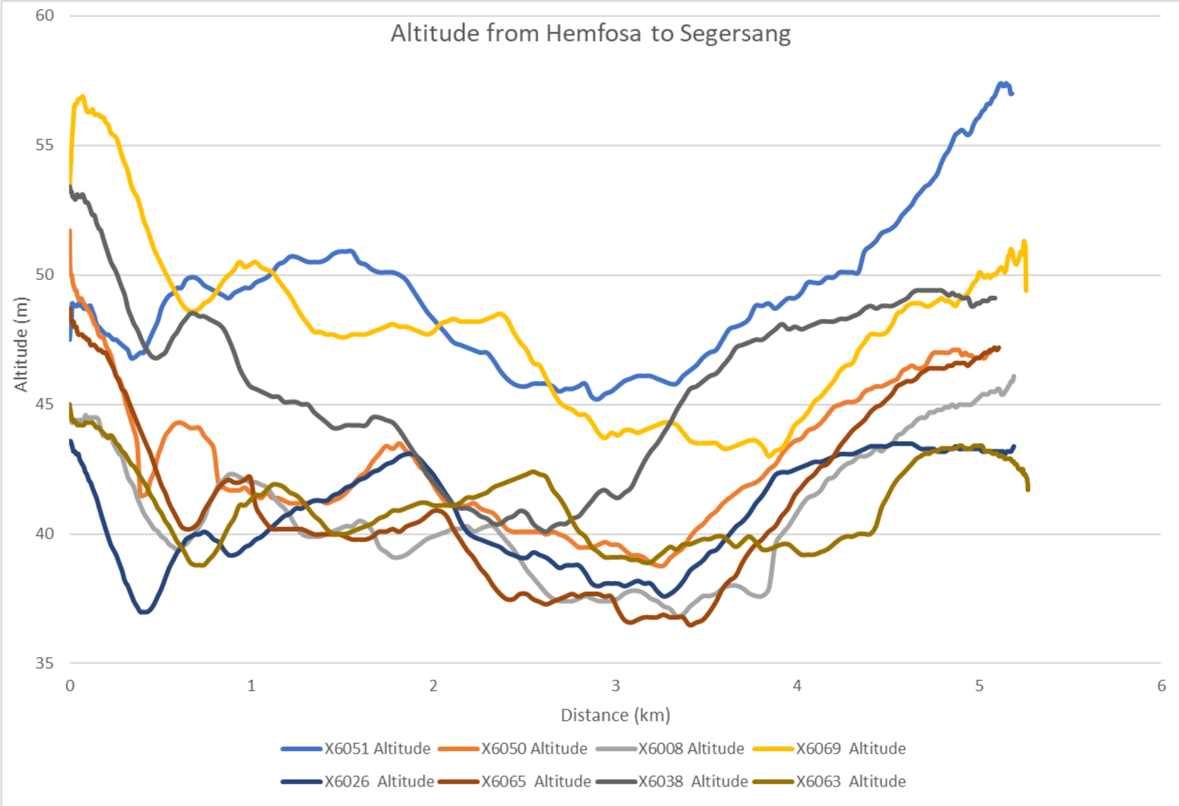

Figure 15 Altitude from Hemfosa to Segersang

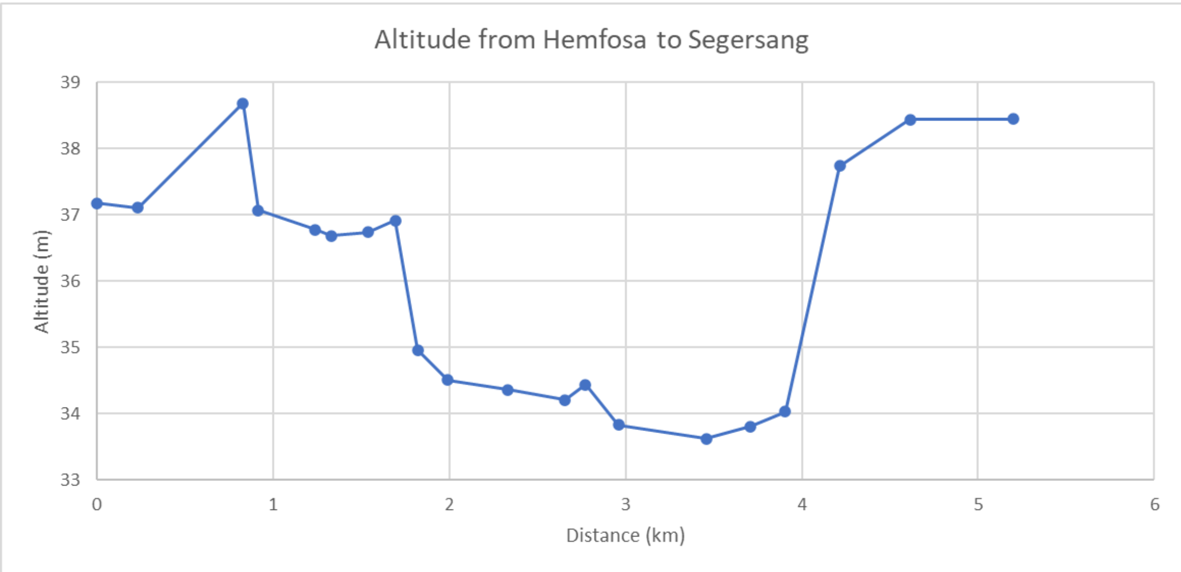

Figure 16 Altitude from Hemfosa to Segenrsang

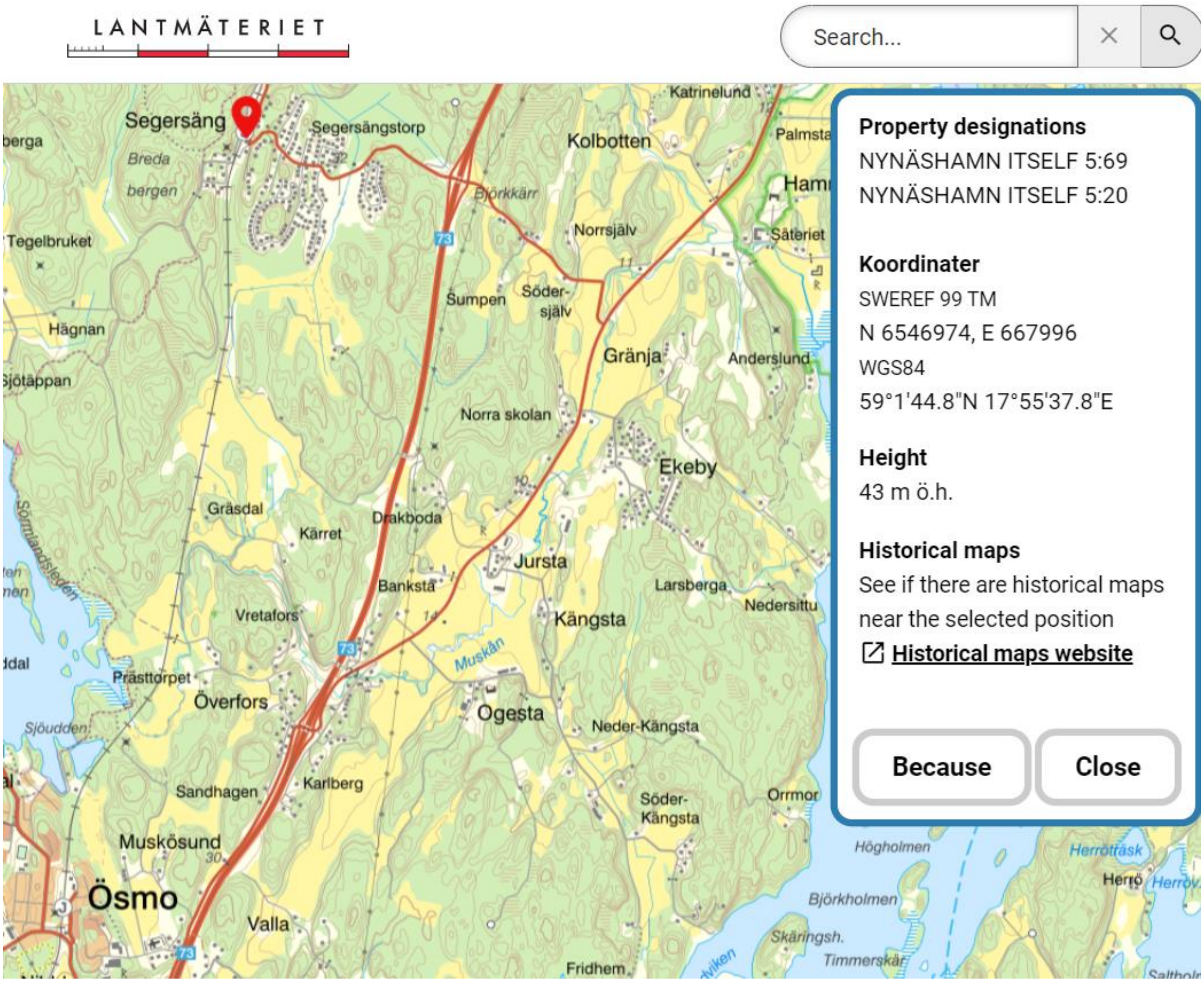

Figure 17 Altitude at Segersang station (Lantmateriet)

5.3. Estimation and parameter guess

When estimating initial values for the unknown parameters of the X60 commuter train model, several approaches can be taken. Engineering principles, available data, industry standards, and educated guesses can all contribute to determining suitable starting points for the simulation process. The basic parameters guess is shown in Table 2.

One crucial parameter that significantly impacts the simulation results is the Relative mass addition [%]. This parameter, which accounts for the additional mass added to the train during operation, typically falls within the range of 4.2% to 4.5% according to industry standards. It directly affects the traction force required throughout the entire journey.

The Running Resistance Coefficients (A [N], B [Ns/m], C [Ns^2/m^2]) are another set of important parameters. These coefficients quantify the resistance experienced by the train while moving, including factors such as air resistance, rolling resistance, and track conditions. Erik's research study, "Energy use in the operational cycle of passenger rail vehicles," provides valuable insights for setting the initial values of these coefficients, ensuring a realistic representation of the train's behavior in the simulation.

Additionally, the Overall efficiency of the train is a crucial parameter to consider. It represents the efficiency of the train's traction system and accounts for energy losses during operation. As a starting point, an Overall efficiency value of 98% can be used, although this value can be refined through the simulation process to achieve more accurate results. It is important to note that the simulation tool may have default values for certain parameters, including Overall efficiency.

By estimating initial values for these important parameters based on engineering principles, available data, industry standards, and previous research findings, the simulation process can commence with reasonable starting points. As the simulation progresses and further analysis is conducted, these initial estimates can be refined and adjusted iteratively to improve the accuracy of the energy consumption calculations for the X60 commuter train.

Table 2 Basic parameters guess

Train	
Relative mass addition [%]	**4.2%**
Load [tonns]	**20**
Running Resistance Coefficients	
A [N]	**1400**
B [Ns/m]	**20**
C [Ns^2/m^2]	**4.5**

Efficiency	
Efficiency [%] Or (Overall efficiency)	**98.00%**

5.4. The ideal model for validation

After constructing the basic model for the commuter train X60 and estimating its parameters, the next step involved selecting an ideal model for validation purposes. The selection criteria focused on identifying a smooth graph with minimal interference from external factors, as this would aid in building an accurate ideal model. Additionally, the chosen graph should have fewer braking points, as this would help streamline the iterative process, as braking points significantly impact the iterations.

After careful consideration, the final ideal model selected for validation was the train X6063, shown in Figure 18, Figure 19 and Figure 20, specifically the journey from Hemfosa to Segersang. This particular train model exhibited the desired characteristics, aligning with the requirements of the validation process. By utilizing this ideal model, the simulation tool could be verified and validated against real-time data, ensuring its accuracy and reliability in predicting energy consumption for the X60 commuter train.

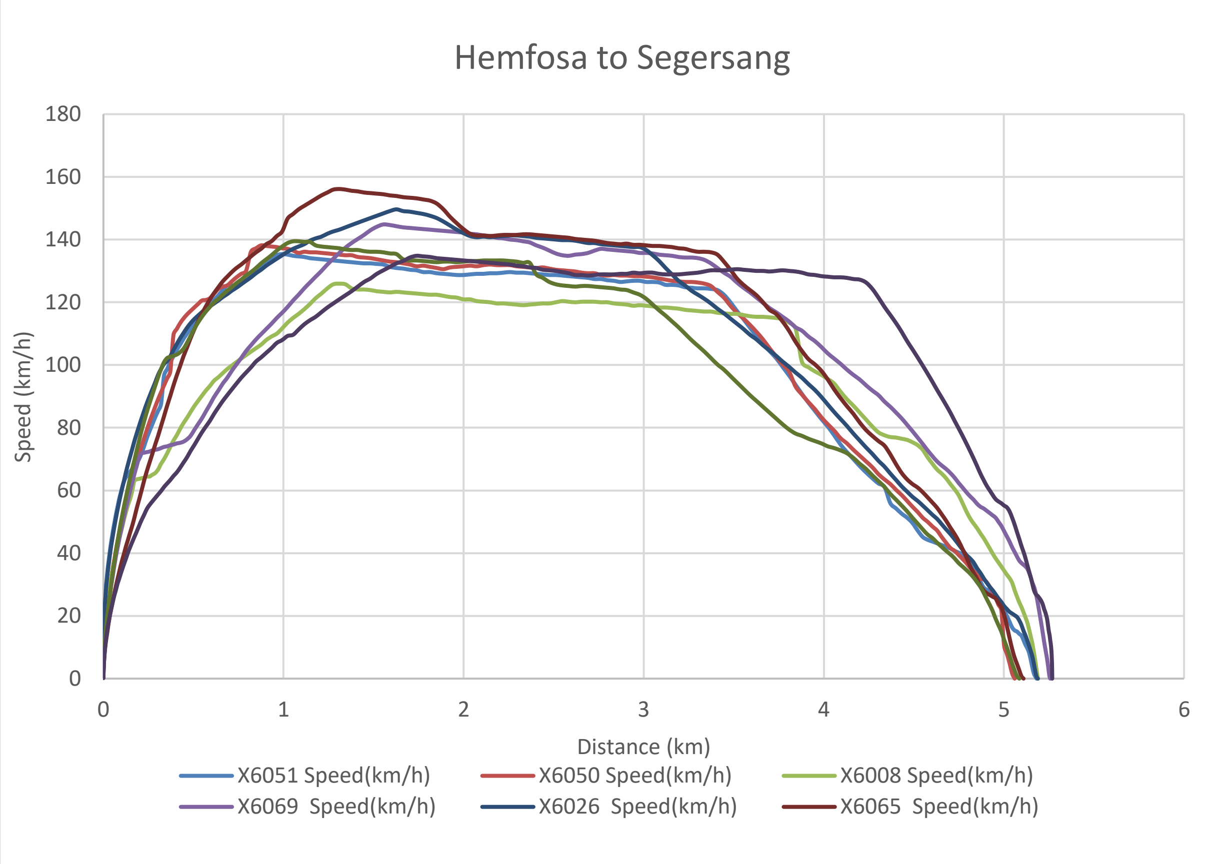

Figure 18 Hemfosa to Segersang

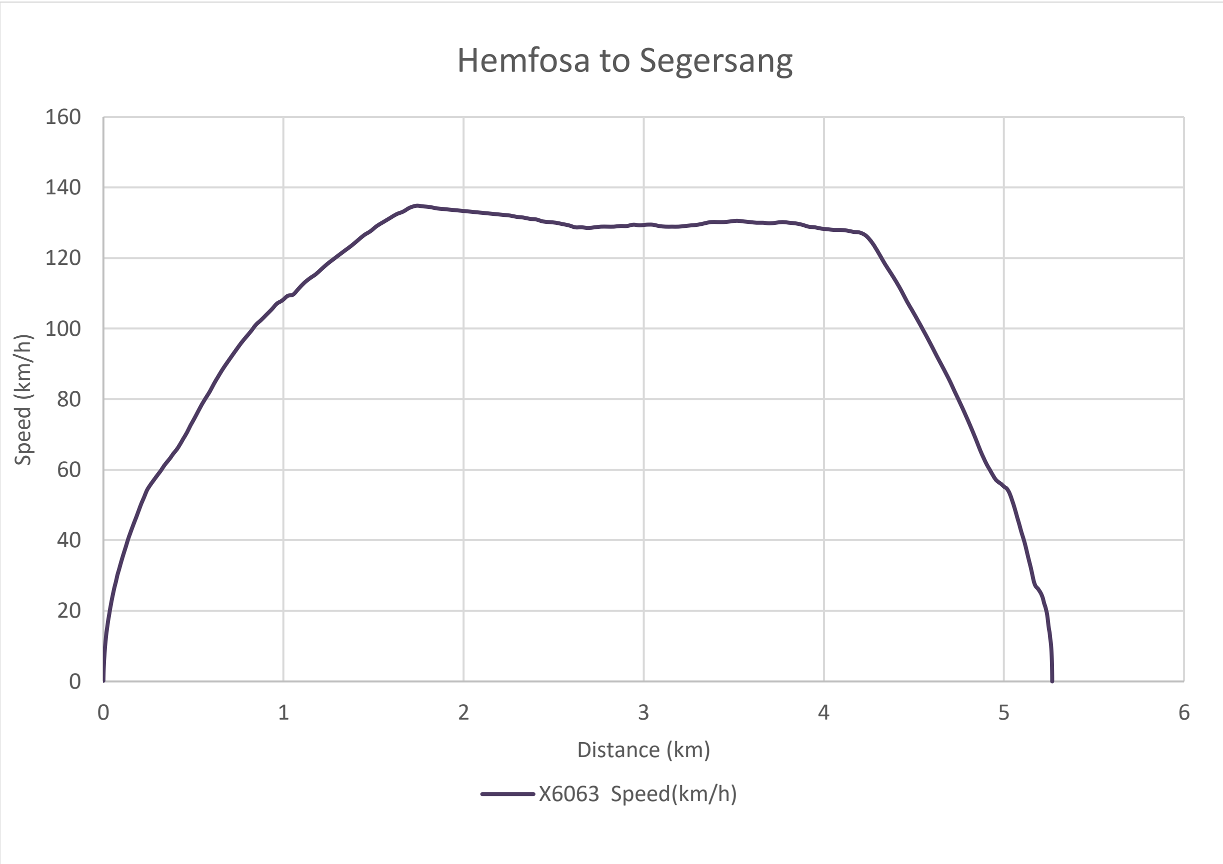

Figure 19 Hemfosa to Segersang

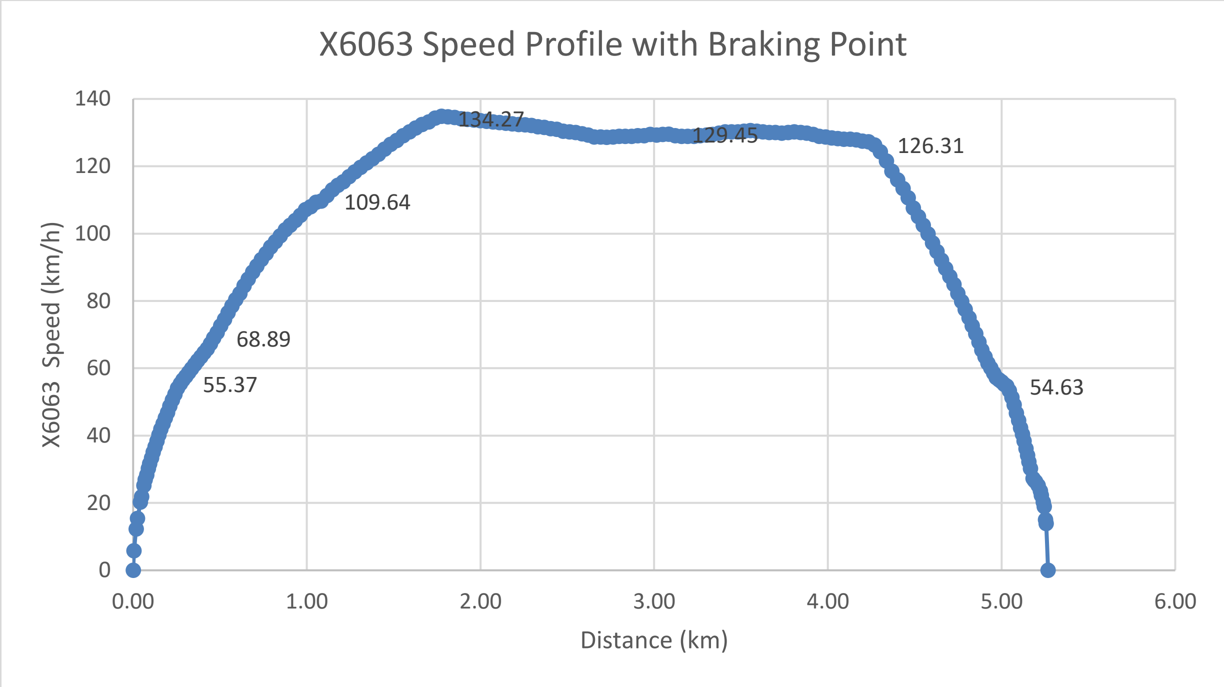

Figure 20 X6063 speed profile with braking point from Hemfosa to Segersang

5.5. Simulation and iterative process

According to the methodology outlined in the previous section, the simulation tool utilizes input data from the train and track, along with the estimated parameters, to run the simulation. The simulation process, which involves iterations, can be divided into two steps.

The first step focuses on adjusting the traction power within the system to simulate the ideal model speed profile and travel time. By carefully controlling the traction power, the simulation aims to replicate the expected performance of the commuter train, ensuring that it follows the desired speed profile and completes the journey within the desired time frame. This step allows for fine-tuning and optimization of the traction power settings to achieve the desired simulation results. As an example, a speed profile (Figure 21) is shown below, illustrating the variation of speed over the distance traveled during the simulation. As there are many simulations, the results are not all saved. The x-axis is the travel distance(m), and the y-axis is the speed(km/h).

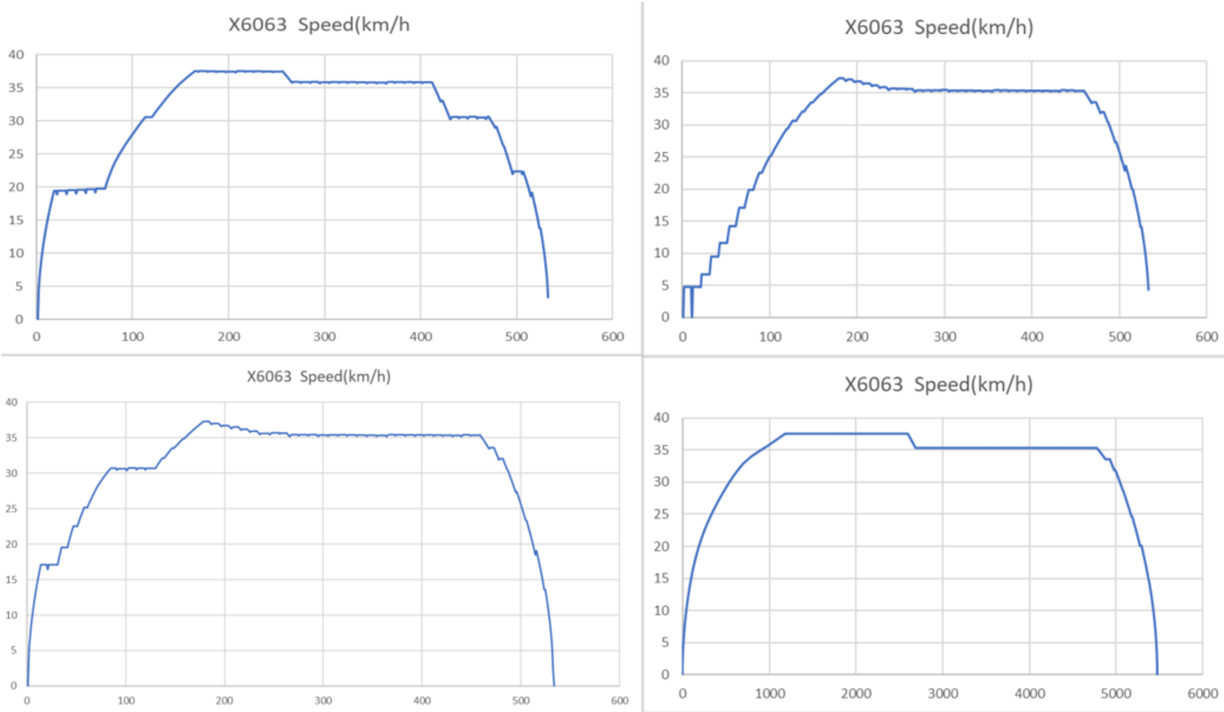

Figure 21 Examples of speed profile during the simulation

Once the ideal speed profile and travel time are achieved, the simulation moves on to the second step. In this step, the input parameters mentioned in the previous chapter are modified to obtain the same energy consumption as the real-world commuter train. The parameters that are adjusted include running resistance coefficients (A, B, and C), relative mass addition, load, and overall efficiency. By iterative refining and adjusting these input parameters, the simulation aims to replicate the energy consumption patterns observed in the actual train.

The simulation and iterative process of running resistance is the first part of adjusting the input parameters. It primarily focuses on the acceleration phase of the commuter train, as the train force is primarily utilized to overcome the running resistance and achieve acceleration. The running resistance is estimated using the Davis equation, $FR = A + B \cdot v + C \cdot v^2$, where A, B, and C are coefficients specific to the train and operating conditions. The initial values for these coefficients are determined in the previous chapter.

In the Davis equation, the coefficient A represents the constant component of running resistance, which includes factors such as bearing friction and other mechanical losses. The coefficient B captures the linear component of running resistance, associated with factors like air resistance and rolling resistance. The coefficient C accounts for the quadratic component of running resistance, which considers additional factors like wheel-rail interaction and train aerodynamics.

To analyze the effects of each coefficient, adjustments are made individually. For coefficient A, its parameter is modified to observe changes in energy consumption at speeds of 20 km/h, 40 km/h, and 60 km/h. Similarly, for coefficient B, adjustments are made to analyze energy consumption changes at speeds of 80 km/h and 100 km/h. Lastly, for coefficient C, changes are made to observe energy consumption variations at speeds of 120 km/h and 130 km/h. The total energy consumption trend of the commuter train is compared during these adjustments.

The graphs presented below partially illustrate how changes in the input parameters mentioned in the previous chapter can result in obtaining the same energy consumption as the real-world commuter train. These graphs provide insights into the impact of individual coefficients on energy consumption and aid in fine-tuning the simulation to achieve accurate results.

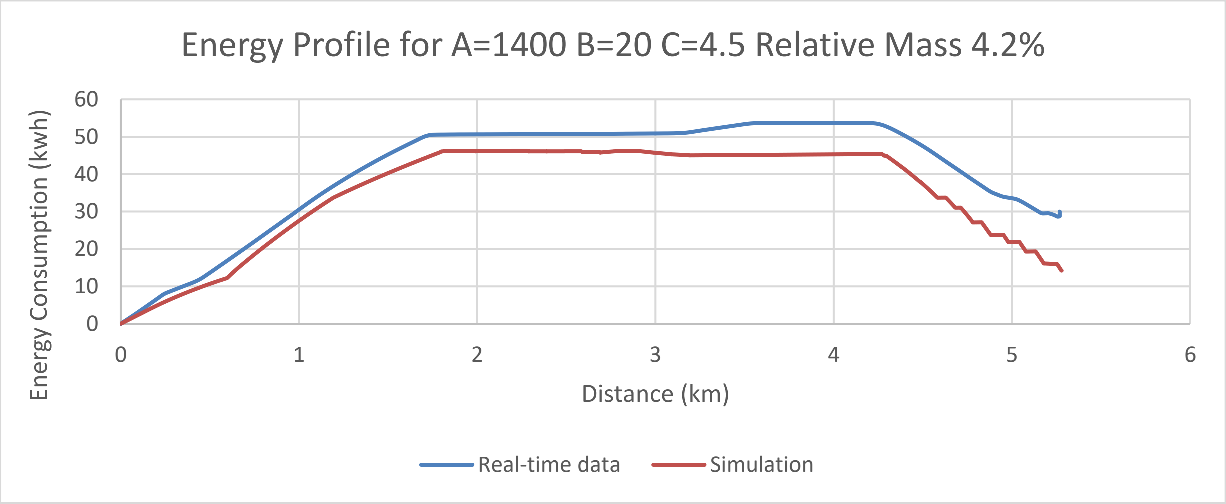

Figure 22 Energy profile for A=1400 B=20 C=4.5 relative mass 4.2%

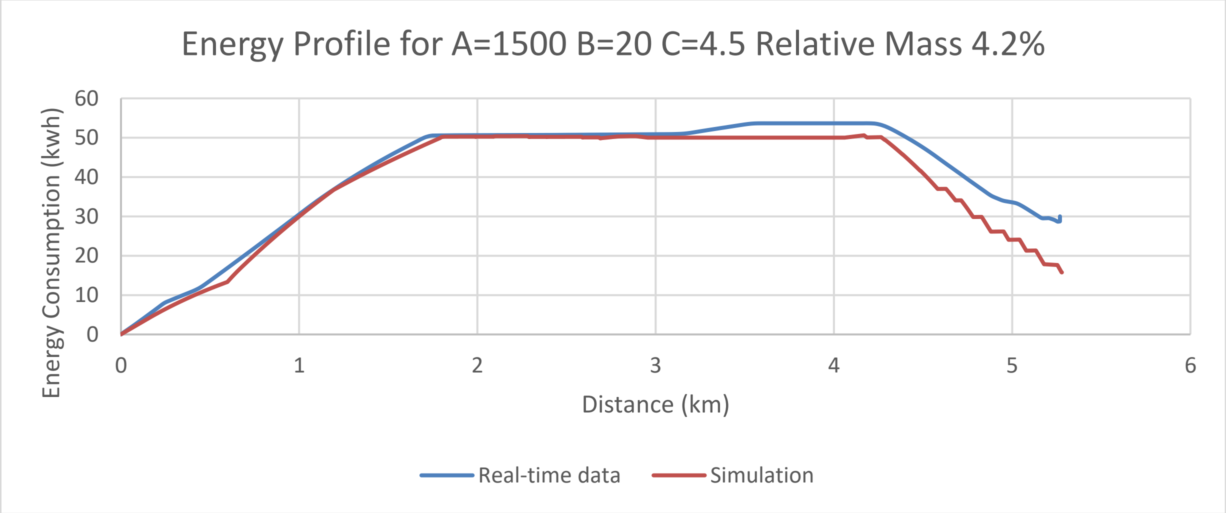

Figure 23 Energy profile for A=1500 B=20 C=4.5 relative mass 4.2%

5.6. **Validation**

The results of the validation process confirm the accuracy of the simulation model for the X60 commuter train. The speed profile generated by the simulation closely matches the real-time data profile, indicating that the model can effectively replicate the train's speed behavior. However, it is important to note that due to the minimum simulation running distance of 1m, there are some imperfections when applying braking, resulting in a jagged shape in the speed curve during braking. This issue can be addressed in future updates of the simulation tool to improve the accuracy of deceleration reproduction.

The overall travel distance is 5.2km. The overall travel time obtained from the simulation is 222s, while the real-time data records a travel time of 224s, resulting in a difference of 2s. This small discrepancy falls within the acceptable margin of error, further validating the simulation's ability to accurately reproduce the train's travel time.

Regarding energy consumption, the simulation's energy profile aligns well with the real-time data profile, indicating that the model can effectively predict the train's energy consumption. However, due to the minimum simulation running distance of 1m, there is a difference in energy consumption compared to the real-time data. The real-time data records an energy consumption of 27kWh, while the simulation shows a similar energy consumption of 23kWh. This disparity can be attributed to the fact that auxiliary energy is not always constant during the train's journey, introducing some error into the simulation results.

To address the potential impact of altitude differences on the gradient force and avoid significant errors in the validation, the next section of the chapter focuses on validating the model using two stations with flatter ground. By considering different terrains, the validation process aims to provide a more comprehensive assessment of the simulation model's accuracy.

Overall, the validation results demonstrate that the simulation model for the X60 commuter train is capable of accurately reproducing its speed profile, travel time, and energy consumption. The minor discrepancies observed can be further refined in future updates of the simulation tool, enhancing its effectiveness in predicting the train's performance under various conditions. The speed profile (Figure 24), travel time profile (Figure 25), the energy consumption profile and altitude profile from Hemfosa to Segersang (Figure 26) are shown below.

Figure 24 X6063 speed profile (Hemfosa to Segersang)

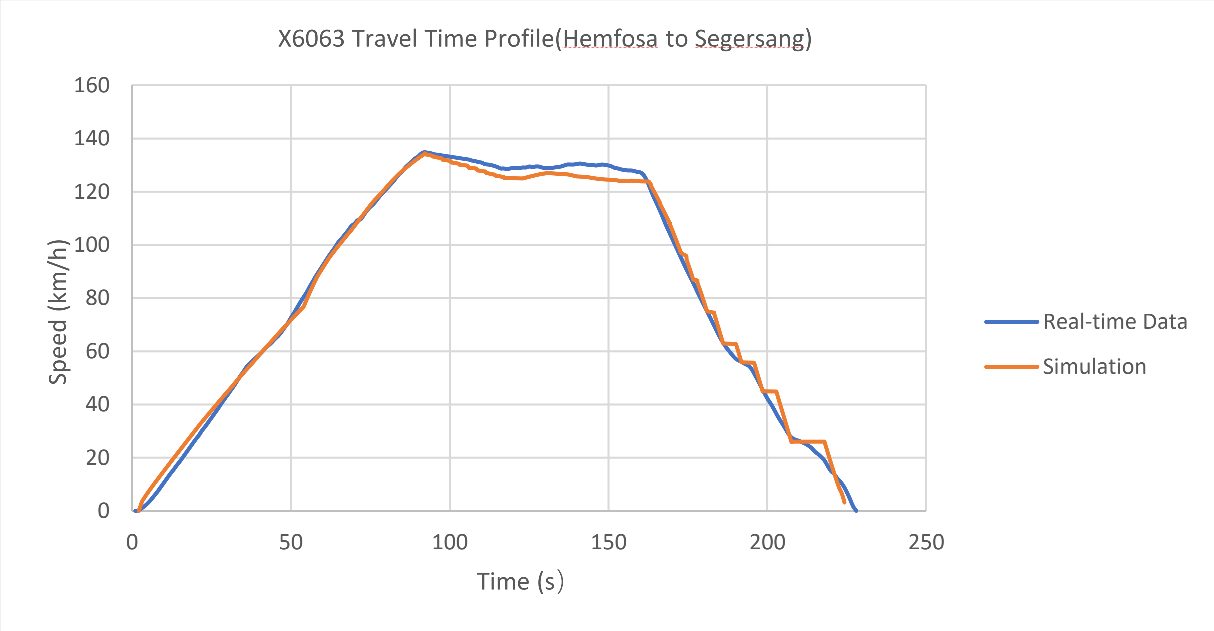

Figure 25 X6063 travel time profile (Hemfosa to Segersang)

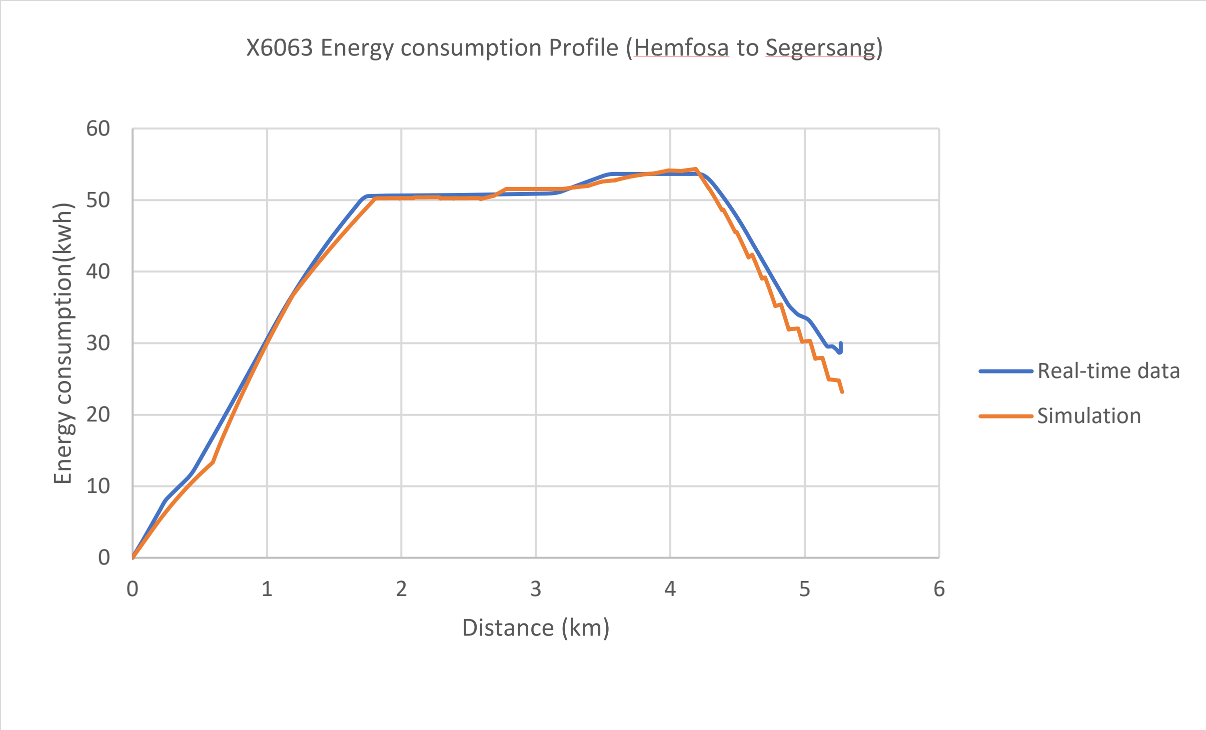

Figure 26 X6063 energy consumption profile (Hemfosa to Segersang)

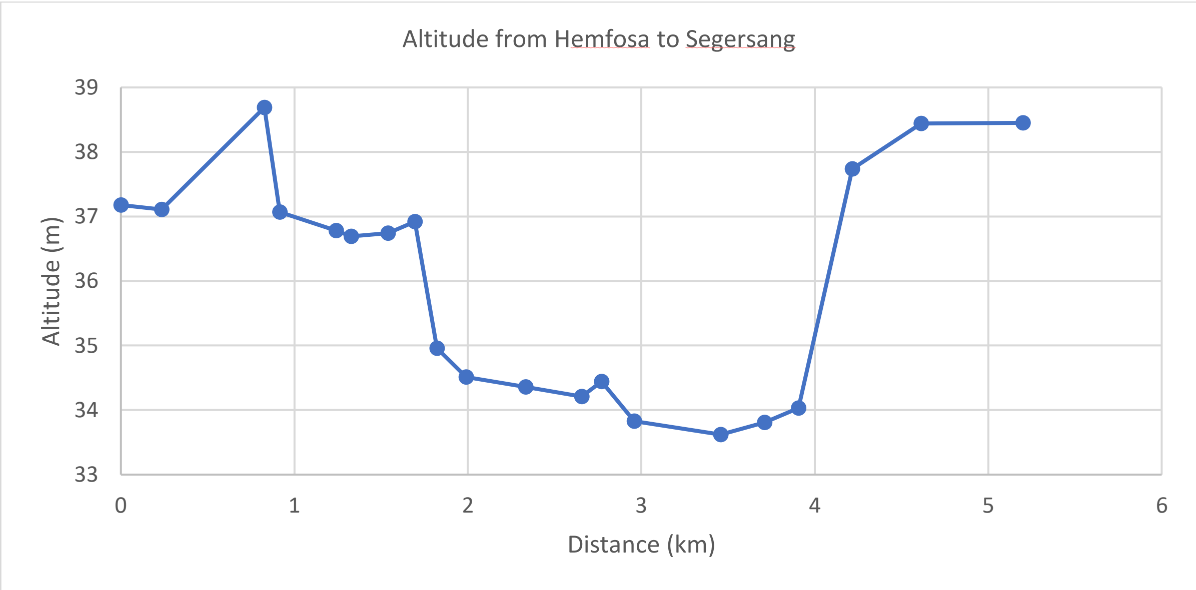

Figure 27 Altitude from Hemfosa to Segersang

5.7. Second validation

During the second validation, the train simulation model was tested using two stations, Tungelsta and Hemfosa, where the ground was relatively flat. The altitude profile for this section revealed a maximum difference of 13 meters over a distance of 5.1 kilometers. The speed profile (Figure 28), travel time profile (Figure 29), the energy consumption profile and altitude profile from Tungelsta to Hemfosa (Figure 30) of second journey are shown below.

The simulation's overall travel time was calculated to be 213 seconds, while the real-time data recorded a travel time of 214 seconds, resulting in a discrepancy of only 1 second. This small difference falls within the acceptable margin of error, further confirming the simulation's accuracy in reproducing the train's travel time.

The speed profile of the simulation closely matched the real-time data, except for a small section in the acceleration phase. This indicates that the simulation accurately captures the train's speed behavior throughout most of the journey.

In terms of energy consumption, the simulation's energy profile aligned well with the real-time data profile. However, due to the minimum simulation running distance of 1 meter, there was a slight disparity in energy consumption compared to the real-time data. The real-time data recorded an energy consumption of 27 kilowatt-hours (kWh), while the simulation showed a similar energy consumption of 26 kWh. This difference can be attributed to the fact that auxiliary energy is not always constant during the train's journey, introducing some error into the simulation results.

In conclusion, the train simulation model demonstrated its accuracy in replicating the travel time and speed profile of the train. While there was a small disparity in energy consumption, it can be attributed to the fluctuating nature of auxiliary energy during the journey. Overall, the validation results support the reliability and effectiveness of the train simulation model.

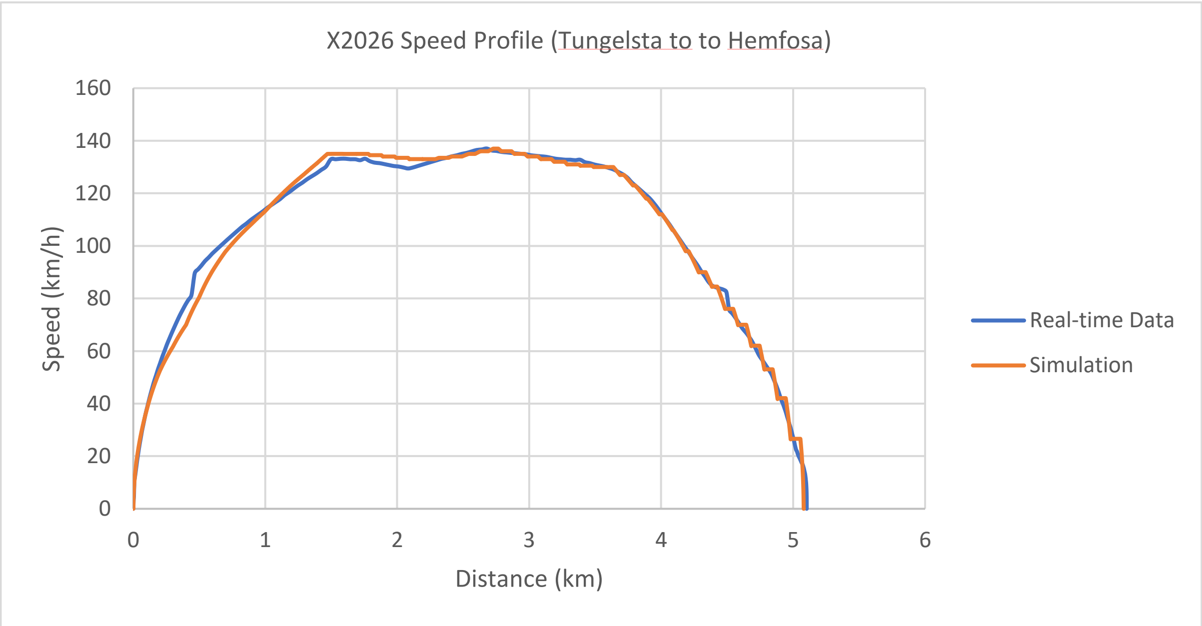

Figure 28 X2026 speed profile (Tungelsta to Hemfosa)

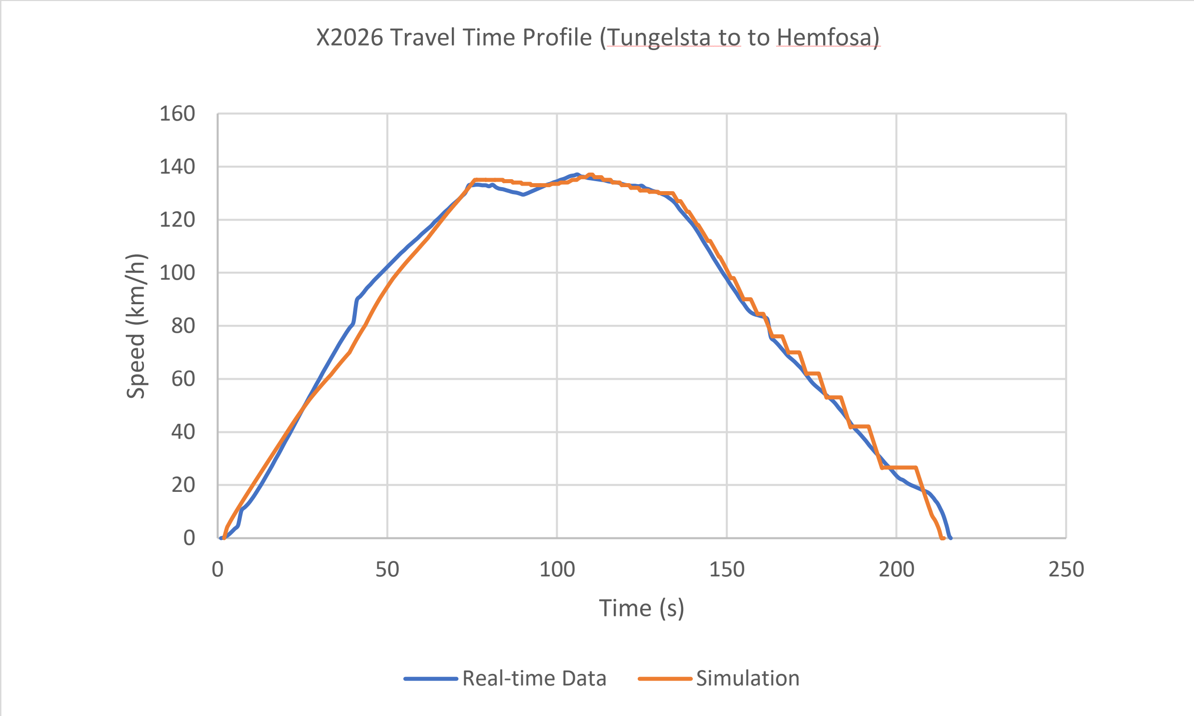

Figure 29 X2026 travel time profile (Tungelsta to Hemfosa)

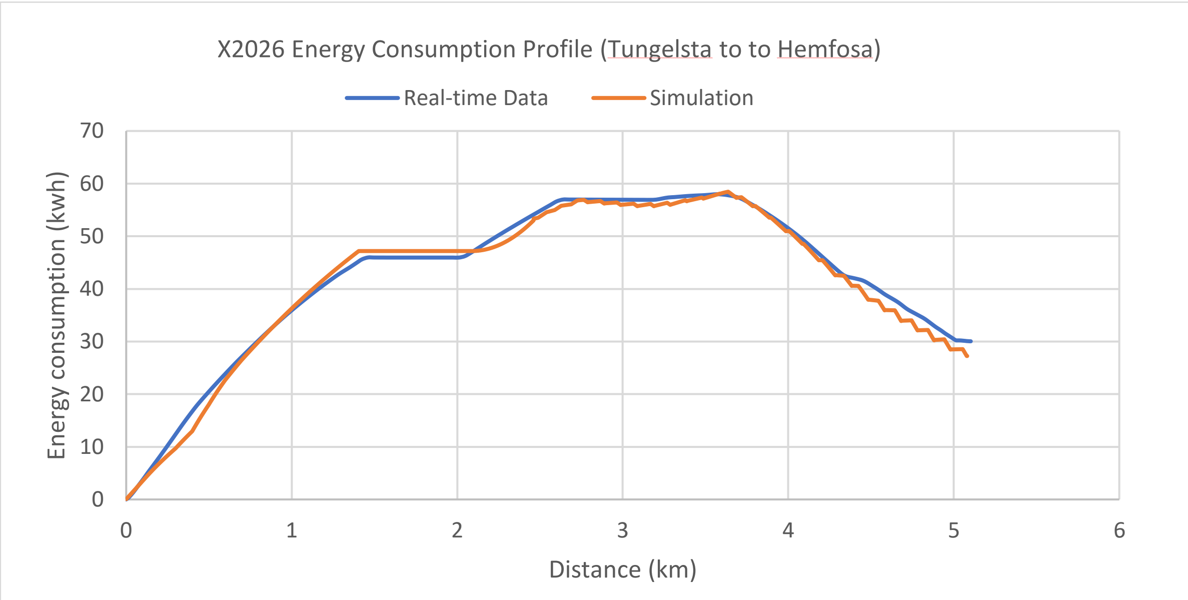

Figure 30 X2026 energy consumption profile (Tungelsta to Hemfosa)

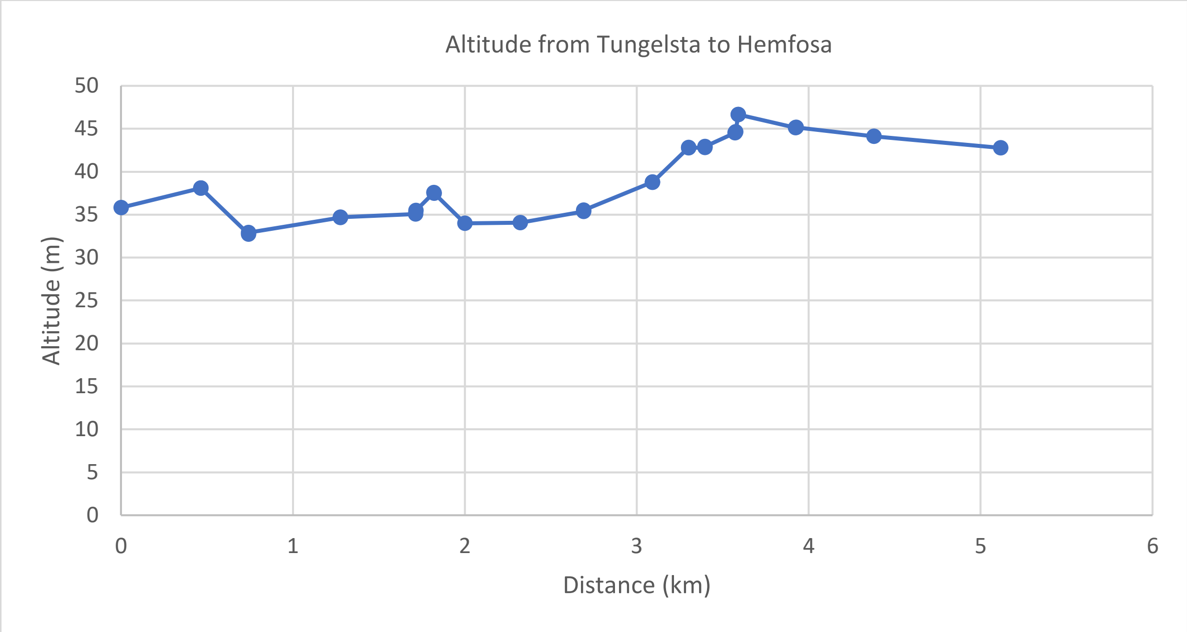

Figure 31 Altitude from Tungeslta to Hemfosa

The table below shows the final parameters for train X60.

Table 3 Final parameters after validation

Vehicle mass [tonns]	**205**
Relative mass addition [%]	**4.2**
Adhesion mass [tonns]	**217**
Braked mass [tonns]	**340**
Load [tonns]	
Max Comfort acceleration [m/s^2]	**1.12**
Max Comfort deceleration [m/s^2]	**1.12**
Wheel_diameter [mm]	**818**
Slip control availability [0/1] [No/Yes]	**1**
Slip (s = ΩR/v -1) [%]	**0.001**
Driver Control on brake [0/1] [No/Yes]	**1**
Running Resistance Coefficients	
A [N]	**1500**
B [Ns/m]	**20**
C [Ns^2/m^2]	**4.5**

Curvature Resistance Coefficients	
a	**6.5**
b	**55**

Axle Gear	
Gear ratio (Motor/Axle gear)	**10**
Efficiency [%] Or (Overall efficiency)	**89**
Power Components Specification	
No of induction motors [-]	**12**
Motor Rated Power [kW]	**250**
Motor Rated Speed [RPM]	**5800**

Constant Auxiliary Power consumption [kW]	**220**
Motor efficiency [%]	**Map in sheet**
Inverter efficiency [%]	**Map in sheet**
Absorption circuit efficiency [%]	**100%**
Line converter efficiency [%]	**Map in sheet**
Transformer efficiency [%]	**Map in sheet**

Maximum allowed Mechanical brake [%]	**100%**
Velocity limit on Regenerative brake [km/h]	**0**
Maximum allowed Regenerative brake [%]	**100%**

Mechanical brake increment step [%]	**10%**
Regenerative brake increment step [%]	**10%**

Adhesion utilization limit while traction α [%]	**45%**
Adhesion utilization limit while braking α [%]	**45%**

Simulation Type	**1**

Inverter Rated Power [kW]	**1000**
Line Converter Rated Power [kW]	**2000**
No of Line Converter [-]	**4**

6. SCENARIO STUDY

6.1. Scenarios description

In the scenario studies conducted to investigate traction-related energy consumption in the commuter train X60, various approaches are explored to identify energy-saving opportunities.

The first scenario focuses on drive strategy optimization. The selected station for this scenario is Hemfosa to Segersang, covering a distance of 5.2km. The average traveling time for this route is 222s. In this scenario, different strategies and techniques are employed to optimize the train's drive strategy, aiming to minimize energy consumption while maintaining efficient performance.

The second scenario involves adjusting the timetable of the commuter train. The same station and distance as the previous scenario are considered. The average traveling time remains 222s, but the study explores a range of time changes from -10% to +10%. By modifying the timetable, potential energy-saving opportunities can be identified, considering the impact of different travel durations on the overall energy consumption of the train. The total energy consumption, which includes energy used for acceleration and energy recovered during deceleration, is analyzed in this scenario.

The third scenario investigates the concept of planned motor switch during cruising. It also takes place on the Hemfosa to Segersang route with a traveling time of 222s. In this scenario, the maximum train traction force is set at 343 kN. The study examines the feasibility and potential benefits of implementing a planned motor switch strategy during cruising to optimize energy usage and reduce overall energy consumption.

These scenario studies provide valuable insights into optimizing traction-related energy consumption in the commuter train X60. By analyzing and comparing the results of each scenario, it becomes possible to identify effective strategies for energy-saving and sustainable operation of the train.

6.2. Scenario 1 Drive strategy optimization

In Scenario 1, which focuses on drive strategy optimization, the analysis is divided into two parts to gain a deeper understanding of energy consumption dynamics during different stages of the journey.

The first part of the analysis focuses on the acceleration phase and partial cruising. During this stage, energy consumption is at its highest. By examining various acceleration strategies separately, it becomes possible to assess their impact on energy consumption. This allows for the identification of the most energy-efficient acceleration approach for short-distance commuter trains.

The second part of the analysis considers partial cruising, coasting, and braking. Notably, during the braking phase, energy consumption becomes negative as the train regenerates energy through regenerative braking. This part of the analysis is crucial for understanding energy regeneration and optimizing energy usage during coasting and braking periods.

To illustrate the results of the analysis, Table 4 is provided, presenting different cases for the acceleration phase and their corresponding energy consumption for the distance of 0-2 km, which is the segment where energy consumption is at its highest for the entire journey.

Case 1	Accelerate constantly to max velocity
Case 2	Accelerate to a certain speed and keep a while and accelerate to max constant velocity
Case 3	Accelerate inconstantly to max velocity
Case 4	Accelerate inconstantly to 90% of max velocity
Case 5	Accelerate smoothly to max velocity

Table 4 Different cases for the acceleration phases

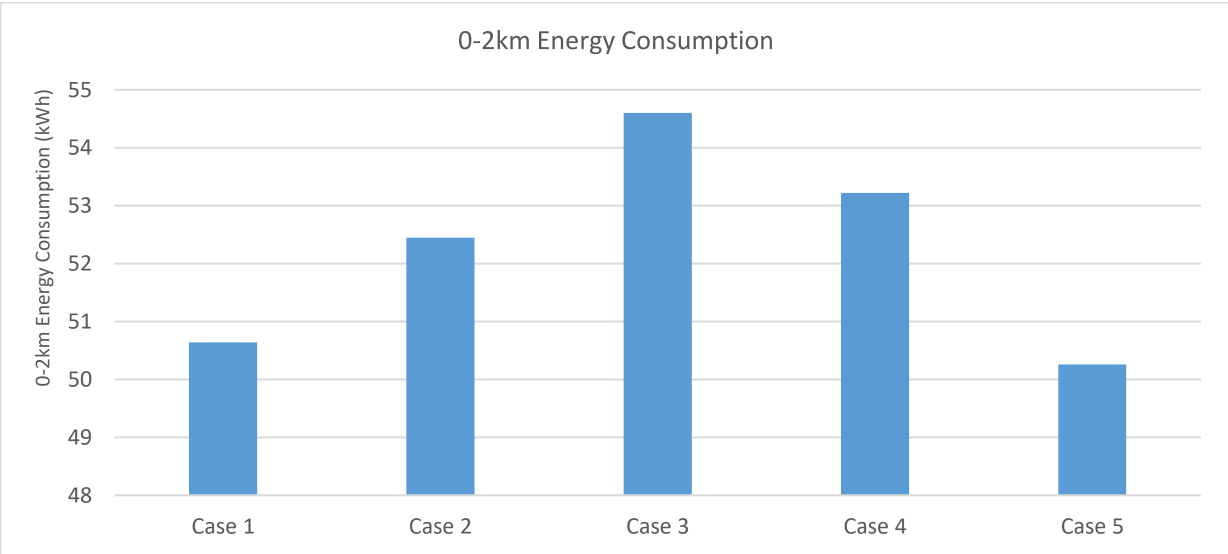

Figure 32 0-2 km energy consumption

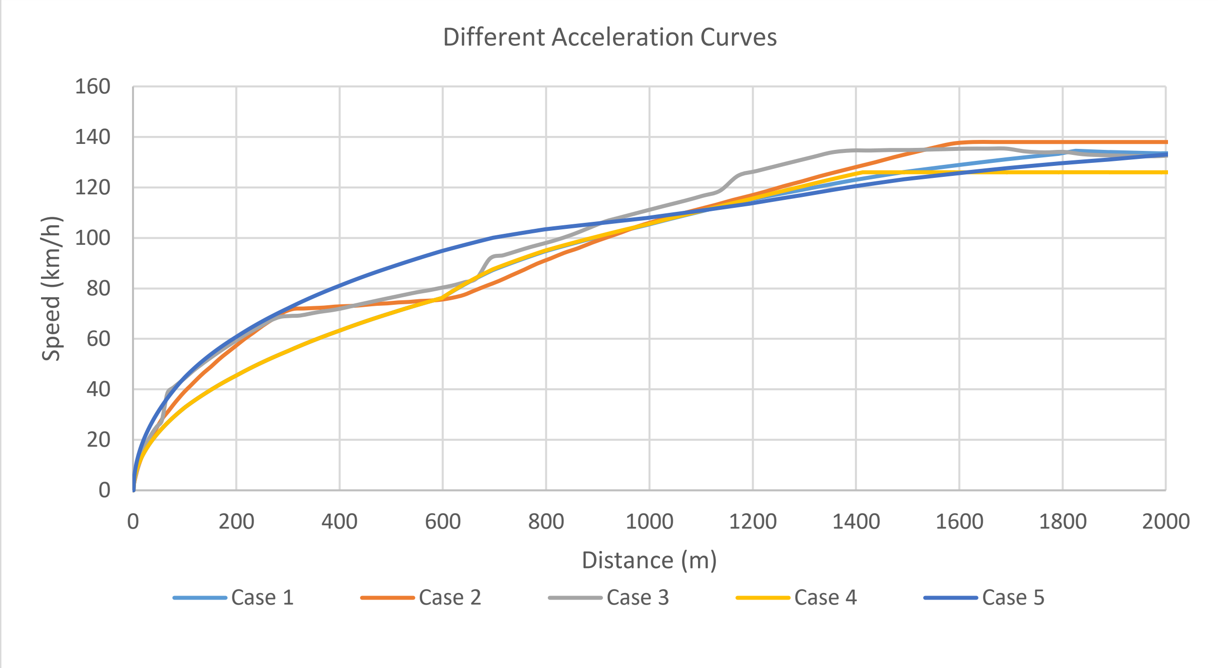

Figure 33 Different acceleration curves

The Figure 32 and Figure 33 show the following cases and their respective energy consumption values in the acceleration phase. By examining these different cases and their associated energy consumption values, it becomes evident that the smooth acceleration approach (Case 5) yields the lowest energy consumption, indicating it as the most energy-efficient drive strategy for the commuter train X60 during the acceleration phase. These insights aid in optimizing drive strategies to minimize energy consumption and promote sustainability in short-distance commuter train operations.

In the deceleration phase, Table 5 illustrates various cases that involve braking strategies and their corresponding energy consumption values for the commuter train X60. It is noteworthy that the difference in energy consumption during deceleration is greater than that during acceleration, shown in Figure 34 and Figure 35. The most significant difference is observed between Case A, where the train brakes at 4400m, and Case E, where the train applies constant braking at 3800m. This difference amounts to a significant 14 kWh in energy consumption. These findings suggest that initiating braking earlier and maintaining a constant braking approach can result in greater energy savings during the deceleration phase. This highlights the importance of optimizing the deceleration strategy to maximize energy regeneration and minimize energy wastage in the context of drive strategy optimization for the commuter train X60.

Table 5 Different cases for the deceleration phase

Case A	Brake at 4400m
Case B	Brake at 4000m
Case C	Brake at 3700m
Case D	Brake inconstantly at 3800m
Case E	Brake constantly at 3800m

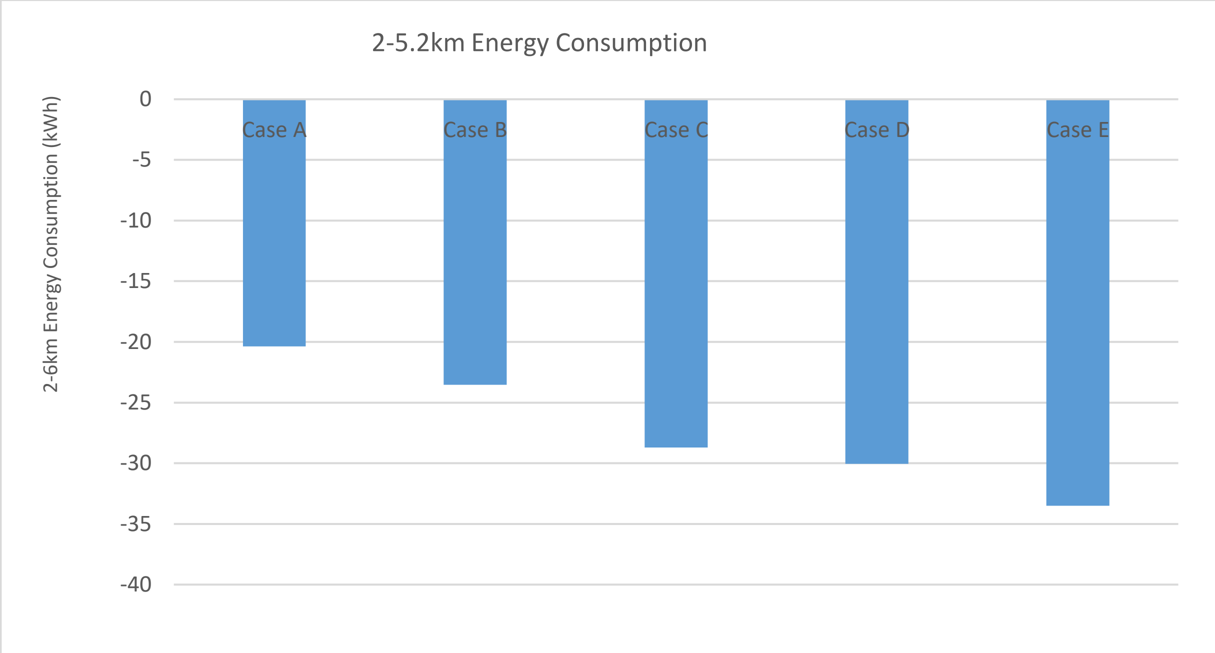

Figure 34 2-5.2 km energy consumption

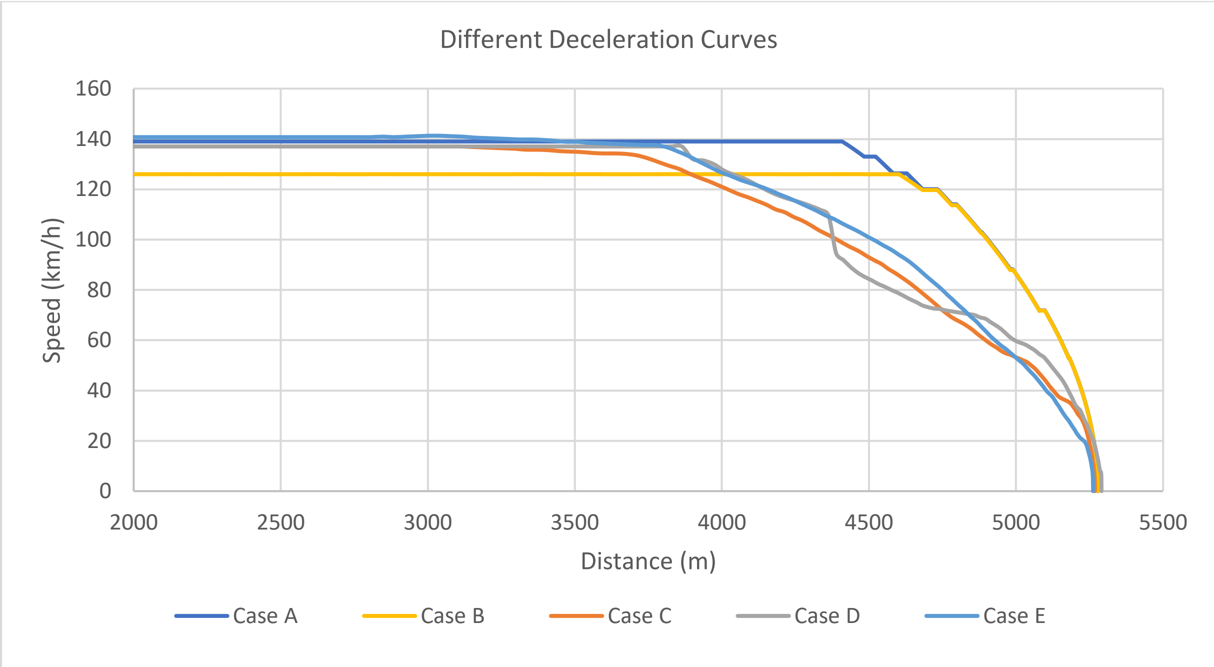

Figure 35 Different deceleration curves

The provided data presents the energy consumption in different combinations of acceleration and deceleration cases for the commuter train X60. It compare, explain, and analyse the energy consumption in these different case combinations.

Case 1+A: The combination of constant acceleration (Case 1) with braking at 4400m (Case A) results in an energy consumption of 30.28 kWh.

Case 2+B: Combining acceleration with a certain speed and braking at 4000m leads to an energy consumption of 28.91 kWh.

Case 3+C: The combination of inconstant acceleration and braking at 3700m yields an energy consumption of 25.91 kWh.

Case 4+D: In this combination of inconstant acceleration to 90% of the maximum velocity and inconstant braking at 3800m, the energy consumption decreases to 23.18 kWh.

Case 5+E: The most energy-efficient combination involves smooth acceleration to the maximum velocity and constant braking at 3800m, resulting in the lowest energy consumption of 16.76 kWh.

Comparing the different case combinations, it is evident that Case 5+E, which combines smooth acceleration with constant braking, exhibits the most efficient energy utilization, shown in Figure 36 and Figure 37. This combination significantly reduces energy consumption compared to the other combinations, almost halving the energy consumption of Case 1+A. This highlights the importance of optimizing both acceleration and deceleration strategies to achieve energy savings in the commuter train X60.

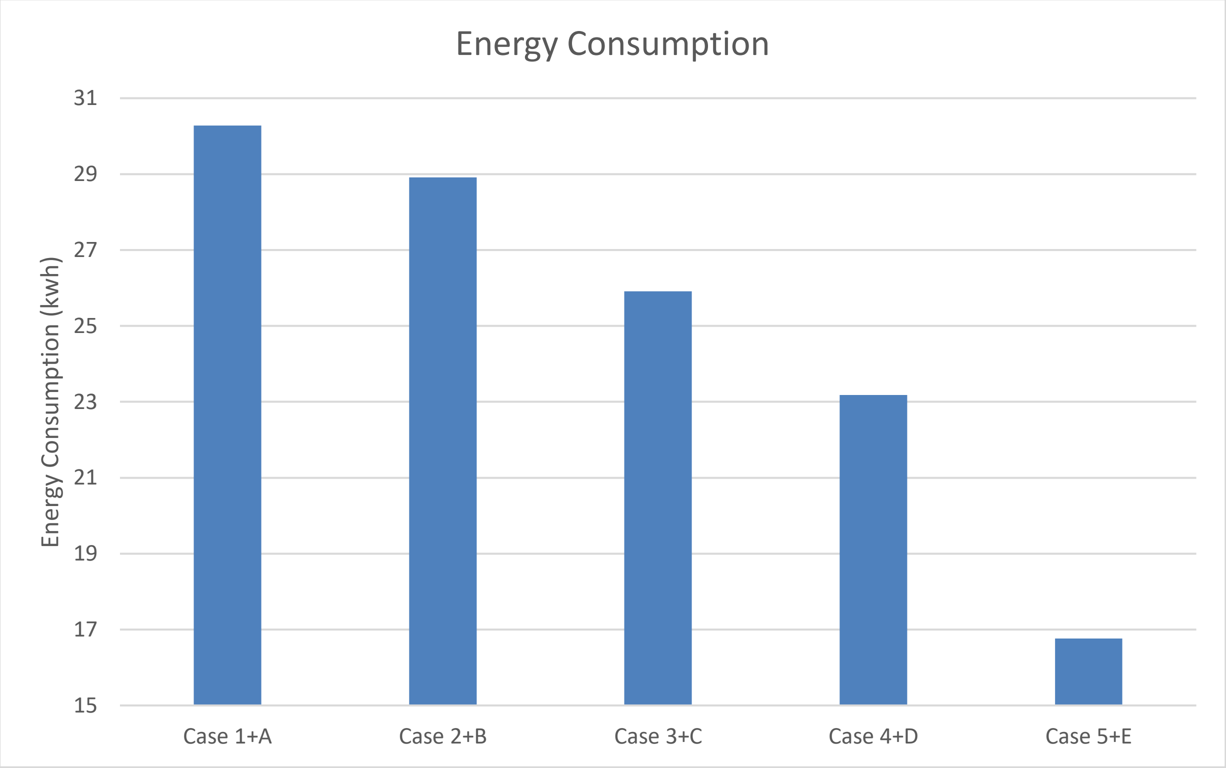

Figure 36 Energy consumption in different cases combinations

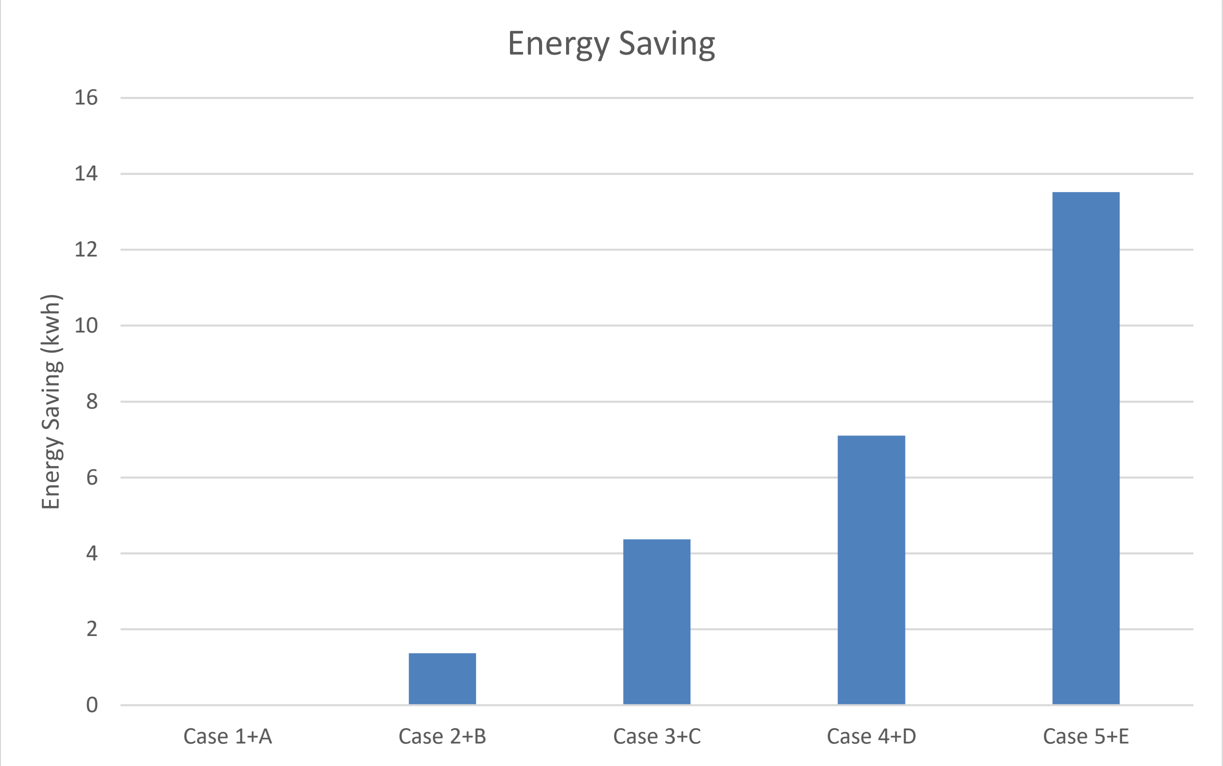

Figure 37 Energy saving potentials

6.3. Scenario 2 Timetable adjustments

Considering the potential drawbacks discussed in the literature review regarding changes to the train travel table, it was important to limit the time difference in Scenario 1 (drive strategy optimization). The objective was to optimize the energy consumption of the commuter train X60 while minimizing the impact on travel time.

In Scenario 1, the average travel time was approximately 222 seconds. The table provided in the previous text indicates that the maximum overall travel time difference among the different case combinations was 3 seconds (Table 6). This difference falls within the acceptable margin of error, suggesting that the energy-saving strategies implemented in Scenario 1 do not significantly impact the overall travel time of the commuter train X60.

Moreover, based on the data presented (Figure 38), the energy-saving potential of the commuter train X60 can reach up to 44% compared to the reference case (Case 1+A). This highlights the effectiveness of the drive strategy optimization approach in achieving substantial energy savings. By carefully selecting the appropriate combination of acceleration and deceleration strategies, it is possible to significantly reduce the energy consumption of the train without compromising travel time.

Table 6 Travel time in different cases

0-2 km Travel time in different cases

	Case 1	Case 2	Case 3	Case 4	Case 5
Travel Time (s)	98	97	99	101	98
2-5.2 km Travel time in different cases					
	Case A	Case B	Case C	Case D	Case E
Travel Time (s)	124	128	125	121	125
0-5.2 km Travel time in different cases					
	Case 1+A	Case 2+B	Case 3+C	Case 4+D	Case 5+E
Travel Time (s)	222	225	224	222	223

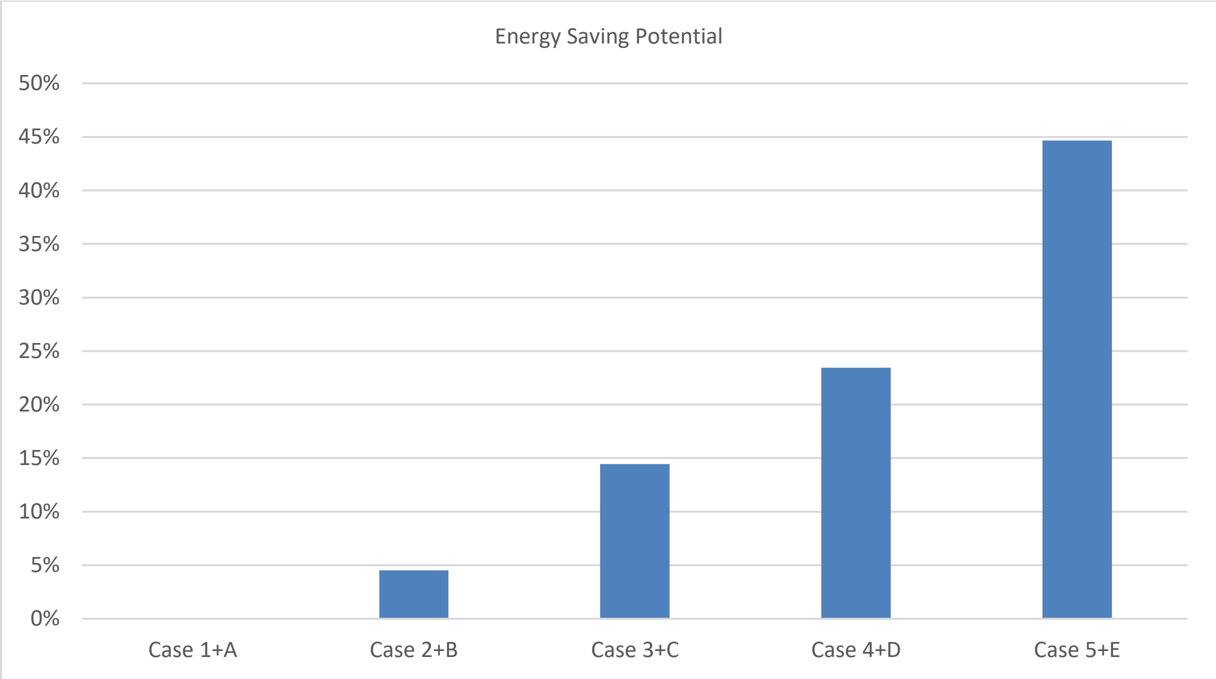

Figure 38 Energy saving potential

Building upon the success of Scenario 1, Scenario 2 focuses on adjusting the train timetable within a range of -10% to +10%. The objective is to evaluate the impact of slight timetable adjustments on energy consumption while considering the feasibility of maintaining the train schedule.

Real-time data analysis revealed that travel time changes of less than 10% do not significantly affect the timetable of the commuter train X60. This provides confidence that slight adjustments can be made without compromising the overall train schedule.

To assess the energy-saving potential, a graph was constructed to visualize the relationship between total travel time and energy consumption. The graph indicates that increasing the total travel time by 10% can result in nearly 45% reduction in total energy consumption (Figure 39 and Figure 40). This implies that the trade-off between travel time and energy consumption favors longer travel times for the purpose of achieving substantial energy savings.

Considering the relatively high energy consumption levels, it is deemed not worthwhile to prioritize travel time reduction over energy efficiency. The results suggest that optimizing the train timetable to prioritize energy savings can yield significant benefits without significantly impacting the overall train schedule. This finding is important for transportation planners and operators seeking to strike a balance between energy efficiency and maintaining an efficient train service.

In summary, Scenario 2 demonstrates that minor timetable adjustments within the range of -10% to +10% have minimal impact on travel time. Furthermore, increasing the total travel time can lead to substantial energy savings, highlighting the importance of prioritizing energy efficiency over minimal travel time reductions.

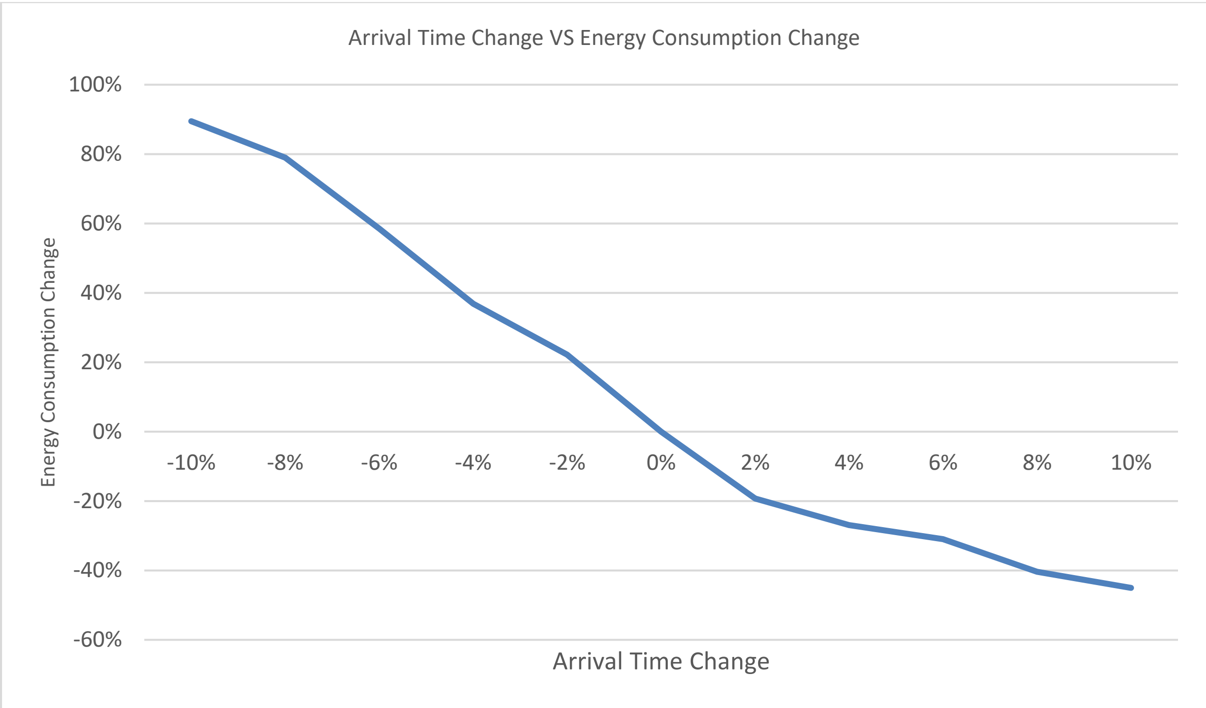

Figure 39 Arrival time change versus energy consumption change

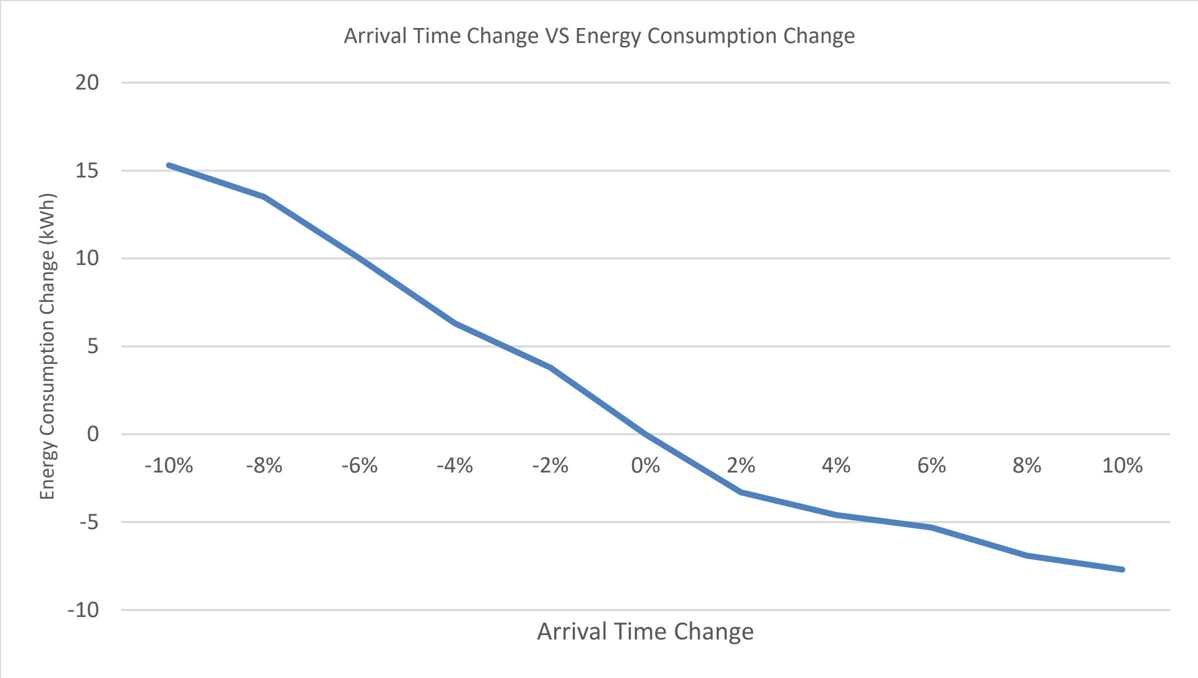

Figure 40 Arrival time change versus energy consumption change

6.4. Scenario 3 Planned motor switch-off during cruising

The energy-saving potential of a commuter train is influenced by its specific efficiency map, which can vary between different train models. In the context of this scenario, the efficiency map for the commuter train X60 is not directly provided. However, an analyzed efficiency map from the OPEUS (Energy Simulation Of Train Operation) simulation tool is used for the analysis.

OPEUS, developed by the European Union, is a simulation methodology and modeling tool designed to evaluate, improve, and optimize the energy consumption of rail systems, with a particular focus on in-vehicle innovation.[19] By leveraging the efficiency map provided by OPEUS, shown in Figure 41, the analysis of the commuter train X60's energy-saving potential can still yield reliable results.

It is important to note that while the efficiency map used in this scenario is reliable, a more accurate analysis could be conducted by utilizing the specific efficiency map for the Stockholm commuter train X60. By having access to the train's dedicated efficiency map, a more precise assessment of energy-saving opportunities and optimization strategies can be performed.

The utilization of accurate efficiency maps allows for a deeper understanding of energy consumption patterns and the identification of specific areas where improvements can be made.

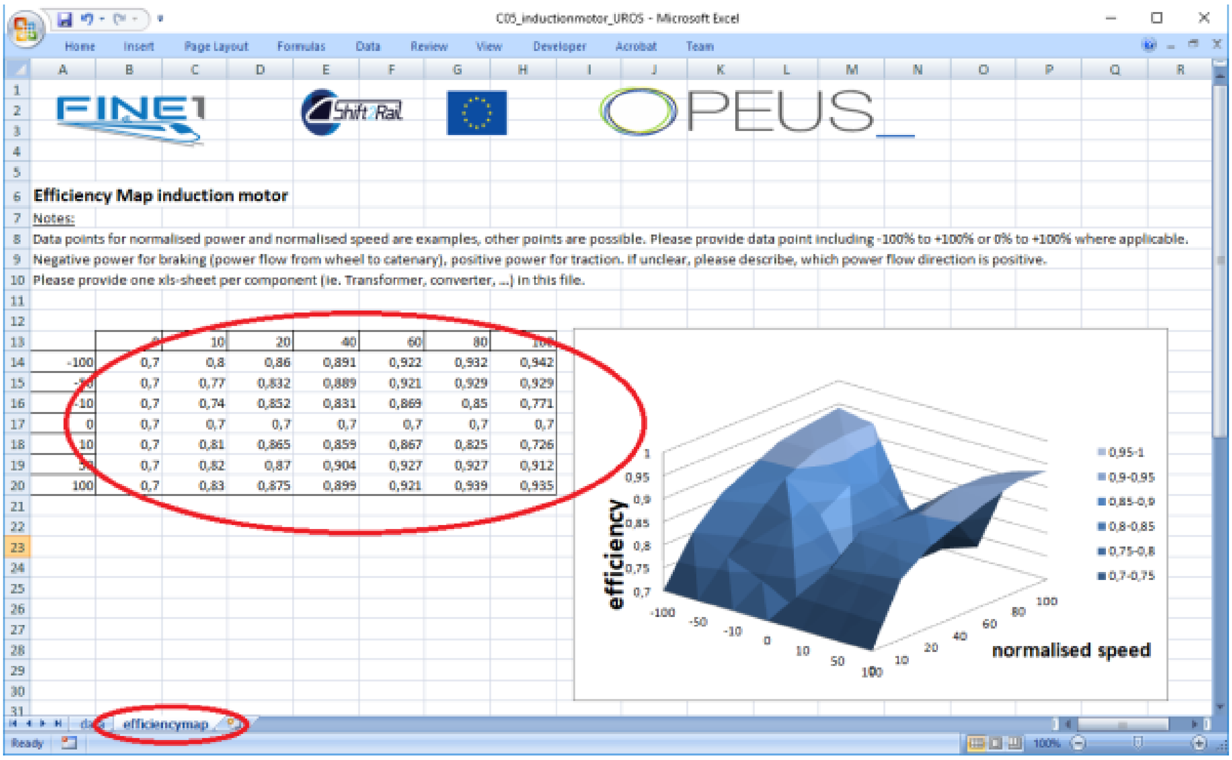

Figure 41 Screenshot of the efficiency sheet of the motor component file

During the cruising phase of the train's running cycle, the speed remains constant, and the force generated by the motors matches the running resistance force, with no acceleration involved. This constant traction force ensures that the train maintains a steady speed throughout this phase. At a consistent rotation speed of the motor, different continuous torque values demonstrate varying motor efficiencies. Consequently, at this constant rotation speed, different force levels exhibit distinct motor efficiencies. More detailed information about the planned motor switch-off methodology during cruising can be found in the corresponding chapter on methodology.

In the case of the commuter train X60, the traction force is provided by three groups of motors distributed among the train's wagons. The wagons within a unit of the commuter train X60 are identified as A1, M1, M2, M3, M4, and A2. Refer to Figure 42 and Figure 43 for a visual representation. According to the traction circuits for the commuter train X60, bogies 1 and 2 share motor group 1, bogie 3 is not connected to any motors, and bogies 4 and 5 utilize motor group 2 to supply the required traction force. Bogies 6 and 7 use motor group 3 for the same purpose.

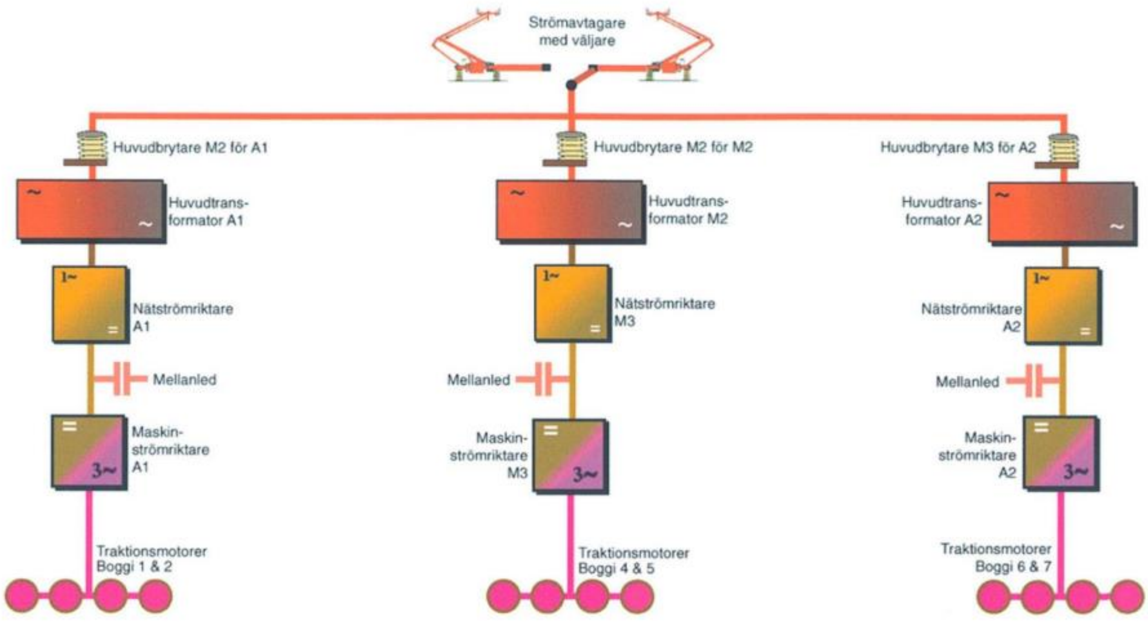

Figure 42 Traction circuits for commuter train X60

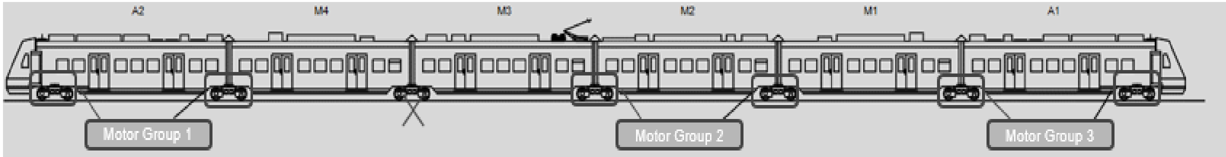

Figure 43 Traction motor groups for commuter train X60

In this scenario, the goal is to maintain the same rotation speed while providing the necessary traction force for the entire train using only two groups of motors or even a single group. Original traction force is powered by three groups of motors (Figure 44). This implies that the force output of the two motor groups must be increased to power the train. At the same rotation speed, the efficiency of these motor groups improves in proportion to the force. Similarly, utilizing only one group of motors can enhance the train's force efficiency.

The traction curve illustrates the effect of switching off one group of motors. In this case, the traction force is taken by the remaining two groups of motors, with a maximum of 171 kN, shown in Figure 45. During cruising, where the speed is approximately 128 km/h, assuming the motor speed matches the speed of the commuter train, the total traction force provided by the two groups of motors is 114 kN. This redistribution of force results in increased efficiency. All of these adjustments and calculations are performed within the system. Same for switching off two groups of motors, see Figure 46.
By strategically managing the motor groups during cruising, the commuter train X60 can achieve higher efficiency and optimize energy consumption. The system ensures that the remaining motor groups operate at their most efficient levels while delivering the required traction force for maintaining a steady speed. These efforts contribute to reducing energy waste and enhancing the overall sustainability of the commuter train's operation.

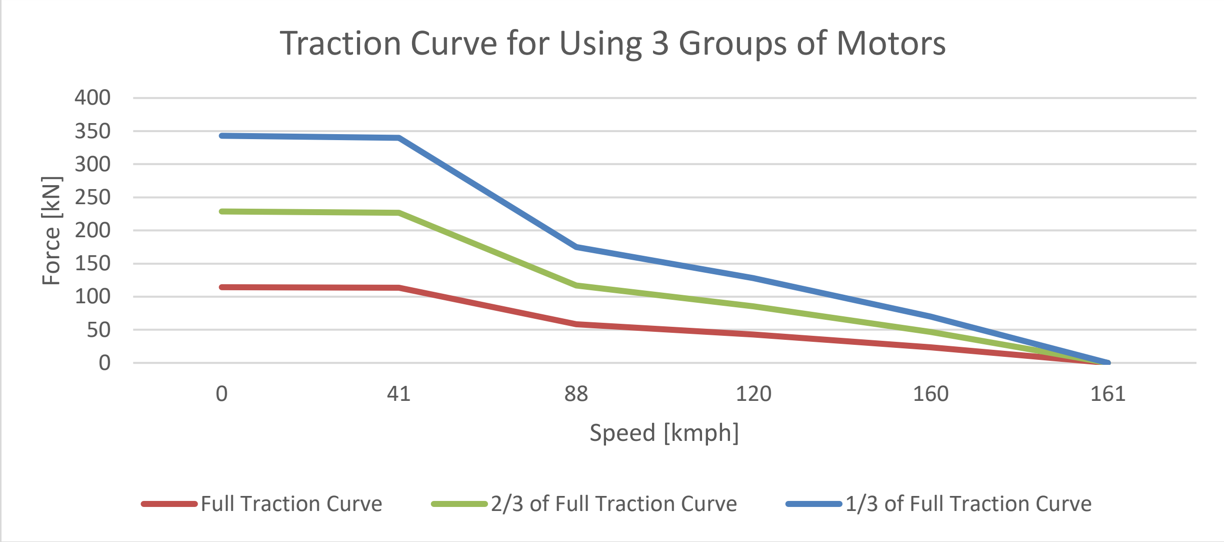

Figure 44 Traction curve for using 3 groups of Motors

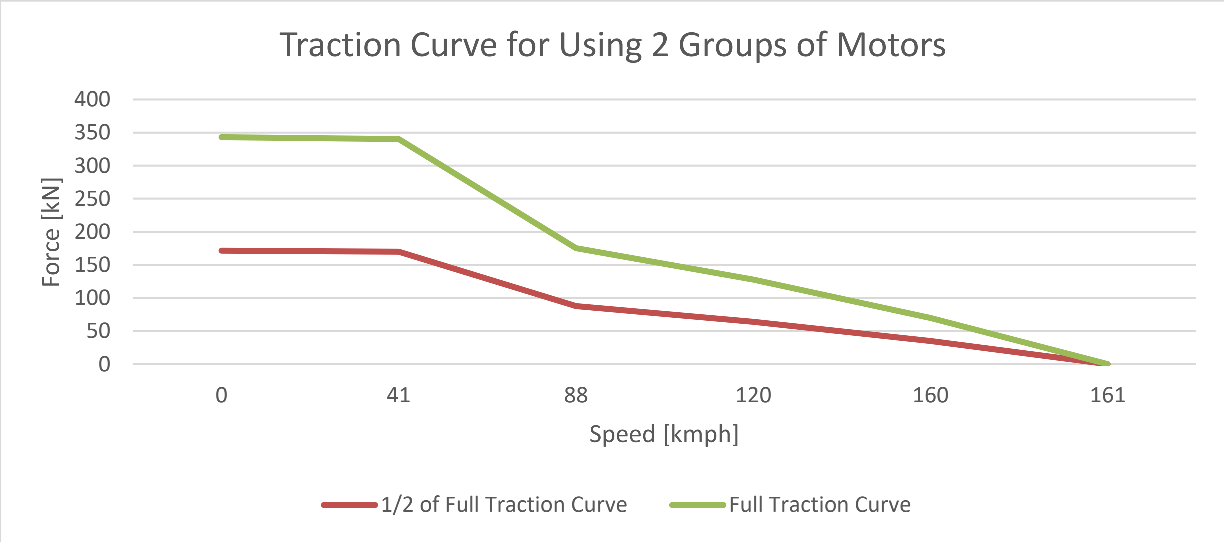

Figure 45 Traction curve for using 2 groups of motors

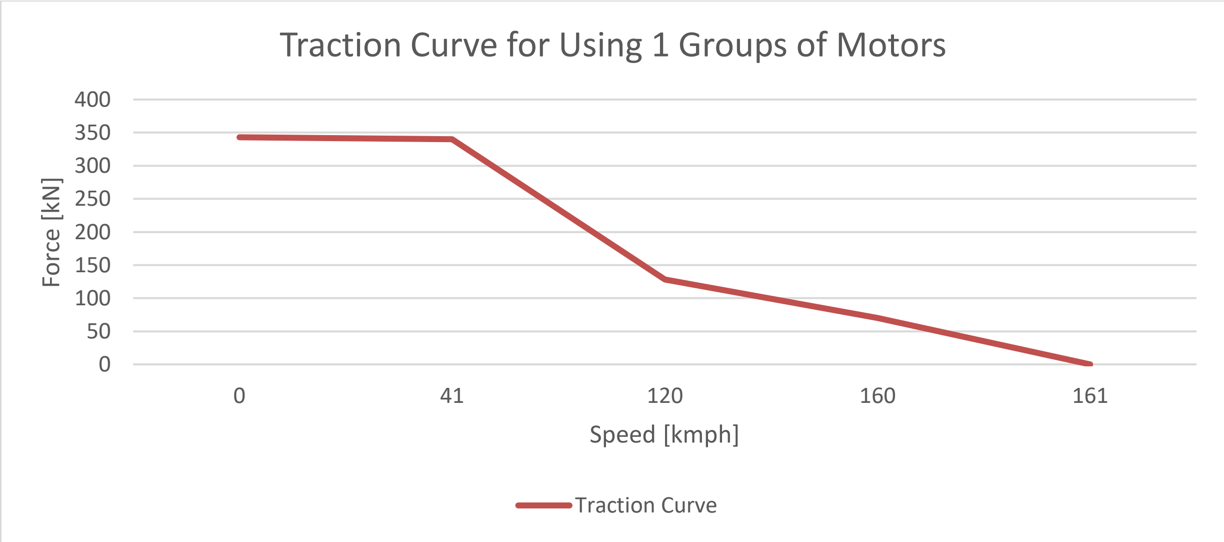

Figure 46 Traction curve for using 1 groups of motors

The scenario is based on the drive strategy combinations of Case 1+A and Case 5+E, shown in Figure 47. As depicted in the figure below, it is observed that switching off 1 group of motors during cruising in both Case 1+A and Case 5+E results in energy savings of 0.9 kWh and 1.4 kWh, respectively. Although these savings are lower than initially anticipated, they still contribute to reducing energy consumption. On the other hand, switching off 2 groups of motors during cruising in Case 1+A and Case 5+E leads to higher energy savings of 2.5 kWh and 4.1 kWh, respectively. While these savings are also slightly below the expected levels, they represent an improvement compared to the previous method of switching off only 1 group of motors. These findings highlight the potential of optimizing energy efficiency through strategic motor group management during the cruising phase of the commuter train X60.

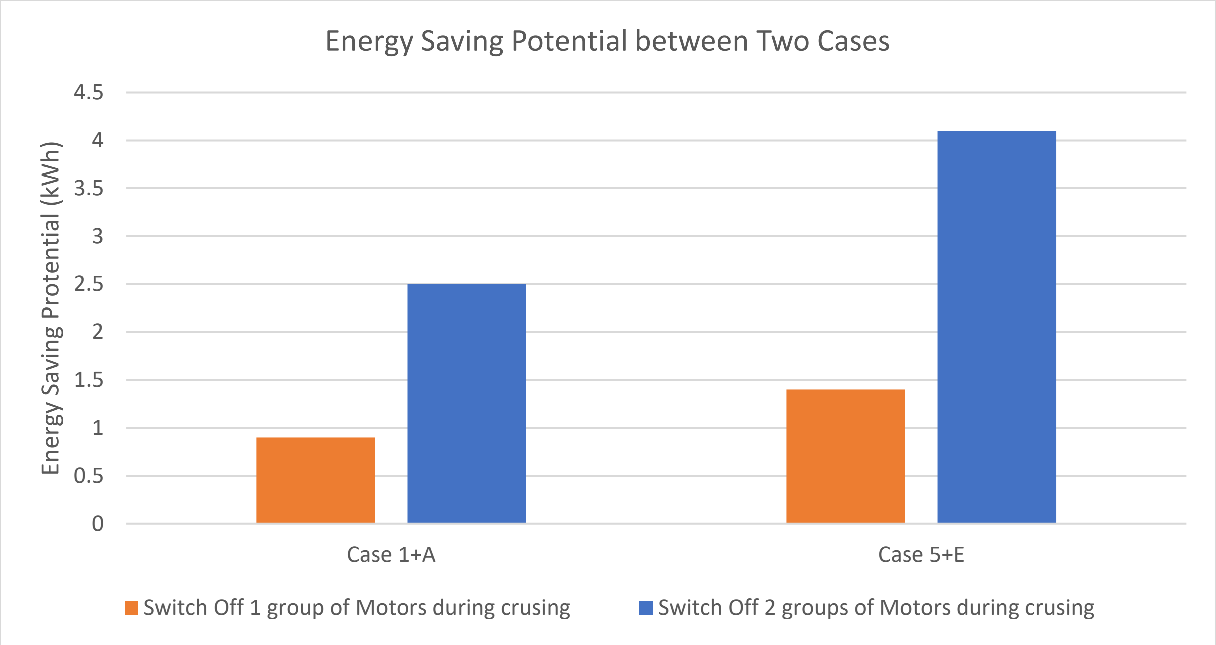

Figure 47 Energy saving potential between two cases

6.5. Results and discussion

The three scenarios investigated in this study demonstrate different approaches to optimizing energy consumption in the commuter train X60. Each scenario provides valuable insights into the potential energy savings and highlights the importance of considering multiple strategies in combination.

Scenario 1: Drive Strategy Optimization
The analysis of different drive strategy combinations reveals significant variations in energy consumption. Case 5+E, which involves smooth acceleration and constant braking, emerges as the most energy-efficient combination, reducing energy consumption by nearly 44% compared to Case 1+A. This highlights the importance of carefully selecting acceleration and deceleration profiles to minimize energy usage. By optimizing the drive strategy, substantial energy savings can be achieved in the operation of the commuter train X60.

Scenario 2: Timetable Adjustments
The findings of Scenario 2 demonstrate that minor adjustments to the train

timetable within the range of -10% to +10% have minimal impact on travel time. Interestingly, increasing the total travel time by 10% results in significant energy savings of nearly 45%. This emphasizes the trade-off between travel time and energy consumption, suggesting that prioritizing energy efficiency can lead to substantial benefits. By considering energy-efficient timetabling strategies, rail systems can achieve notable reductions in energy consumption without significantly compromising travel time.

Scenario 3: Planned Motor Switch-Off During Cruising
The analysis of planned motor switch-off during cruising reveals potential energy savings. Switching off 1 group of motors during cruising in Case 1+A and Case 5+E leads to modest energy savings of 0.9 kWh and 1.4 kWh, respectively. While these savings are slightly below expectations, they still contribute to overall energy reduction. Switching off 2 groups of motors during cruising in the same cases results in higher energy savings of 2.5 kWh and 4.1 kWh, respectively. These findings suggest that strategic motor group management during the cruising phase can further enhance energy efficiency. By optimizing motor usage and minimizing unnecessary power consumption, energy savings can be achieved.

Combining Strategies for Better Energy Saving
The results of the three scenarios highlight the potential for combining strategies to achieve even greater energy savings in the commuter train X60. By optimizing the drive strategy, adjusting the timetable to prioritize energy efficiency, and implementing planned motor switch-off during cruising, rail systems can effectively reduce energy consumption. The combination of these strategies allows for a comprehensive approach to energy optimization, resulting in significant reductions in total energy usage.

7. CONCLUSIONS & FUTURE WORK

Based on the real-data analysis and analysis of the three scenarios, several conclusions can be drawn for the commuter train X60.

Drive strategy optimization plays a crucial role in minimizing energy consumption. The combination of smooth acceleration and constant braking (Case 5+E) proves to be the most energy-efficient, leading to a significant reduction of up to 44% in energy consumption compared to other drive strategy combinations. It is recommended to incorporate this optimized drive strategy into the train's software and provide guidance for drivers to adopt energy-efficient driving habits.

Timetable adjustments can contribute to energy savings without compromising travel time significantly. Minor changes within the range of -10% to +10% have minimal impact on travel time, while increasing the total travel time by 10% can result in substantial energy savings of nearly 45%. This highlights the importance of prioritizing energy efficiency over minimal travel time reductions. Rail operators should consider modifying the train schedule during off-peak hours or at non-busy stations to optimize energy consumption.

Planned motor switch-off during cruising presents another avenue for energy savings. Although the observed energy savings from switching off 1 or 2 groups of motors during cruising were slightly lower than anticipated, they still contribute to reducing overall energy consumption. It is recommended to implement a planned motor-switch-off system in the train's software, allowing for strategic motor group management during the cruising phase to further enhance energy efficiency.

While this study provides valuable insights into energy optimization for the commuter train X60, there are several areas that warrant further investigation.

Tracking regenerative energy flow: It would be beneficial to monitor and analyze the regenerative energy flow within the train system. This would help identify areas where regenerative braking can be maximized and energy can be effectively captured and utilized.

Engine performance under different conditions: Conducting a detailed analysis of the engine's performance under various conditions can provide valuable information for reducing energy consumption. This analysis could involve examining the engine's efficiency at different speeds, loads, and environmental conditions to identify opportunities for energy savings.

component weight reduction: Exploring the possibility of replacing certain components with lighter alternatives can lead to significant energy savings. Conducting a thorough assessment of different components and quantifying the potential energy savings associated with their replacement can guide future efforts in optimizing the train's energy efficiency.

By addressing these areas of further work, rail operators and engineers can continue to enhance the energy efficiency of the commuter train X60 and contribute to the development of sustainable and eco-friendly transportation systems.

Q&A

- Is there an optimal route for energy savings between Hemfosa and Segersäng?

The combination of smooth acceleration and constant braking (Case 5+E) proves to be the most energy-efficient, leading to a significant reduction of up to 44% in energy consumption compared to other drive strategy combinations.
And the strategy can be combined with increasing the total travel time by 10% can result in substantial energy savings of nearly 45%. The strategy can be considered to modify the train schedule during off-peak hours or at non-busy stations to optimize energy consumption.

- What do we need to look at in order to understand how and whether we can implement the measures on more or all sections?

Firstly, for Drive Strategy Optimization, we can develop models for different stations along the rail network. By analyzing this data, we can provide speed guidance to train drivers through a user-friendly screen interface. This guidance will help drivers adopt energy-efficient driving habits, optimizing acceleration and deceleration profiles for each section of the track, thereby reducing energy consumption.

Additionally, for the implementation of Planned Motor Switch-Off during Cruising, by understanding the circuitry and power distribution system, we can design and integrate a switch system in the train's control system. This switch system can be programmed to automatically detect specific conditions, such as reaching certain speed thresholds or cruising phases, and subsequently switch off one group of motors to conserve energy. Implementing such a system would require thorough testing and validation to ensure safety and efficiency.

Furthermore, to assess the feasibility of implementing these measures on a broader scale, a detailed cost-benefit analysis should be conducted. This analysis would evaluate the economic implications, including initial investment costs, potential energy savings, and the payback period. It would also be crucial to assess the impact on the overall train schedule and whether timetable adjustments are needed to accommodate the optimized drive strategies.

- Can the method and conclusions also be used for other rail transport modes such as Roslagsbanan or the Metro?

The method and conclusions presented in this study are specific to the commuter train X60 and may not directly apply to other rail transport modes such as Roslagsbanan or the Metro. Each rail transport mode may have unique characteristics, operating conditions, and energy consumption patterns. Therefore, adapting the method and conclusions for these modes would require adjusting the relevant parameters and considering the specific travel distances and operational factors.

While the model developed for the commuter train X60 can serve as a foundation, it would need further refinement and additional modeling with appropriate parameters specific to Roslagsbanan or the Metro to obtain meaningful results. This could involve gathering data on the energy consumption patterns, load factors, and operational characteristics of the respective rail systems.

In summary, while the general approach of the study can be used as a starting point for analyzing energy-saving measures in other rail transport modes, it would necessitate customizing the model and conducting further research to ensure accurate and relevant results for each specific rail system.

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APPENDIX
A1 Abbreviations

Abbreviations used in the text are here listed in their order of appear acne:
SL - Storstockholms Lokaltrafik
MTR - Mass Transit Railway Corporation
HVAC - Heating Ventilation and Air Conditioning
OPEUS - Energy Simulation Of Train Operation
ESI Analysis - economic, sustainability, and implementation analysis

A2 Commuter train X60 vehicle description

Type	6-piece electric motor cart
Length	107 100 mm
Width	3,258 mm
Height	4,280 mm
Gauge	1,435 mm
Service weight	206.1 t
Max. weight (5 persons/m2)	272.8 t
Dynamic weight	217 h
Brake weight	340 t
Max. shoulder load	20 h
Maximum permitted speed	160 km/h
Multiple coupling	2 X60
radius on line length	150 m
Minimum drivable curve radius in the railway yard and depot area	100 m
Passenger capacity Seats Standing places	 374 pcs 565 pcs. (at 5 people/m2)
Supply voltage/frequency	15 kV/16.7 Hz
Drive device Type Effect	 Three-phase asynchronous motors 12 x 250 kW
Voltage auxiliary power system	±400 V DC 400 V AC/50 Hz
Train control and monitoring systems Vehicle interior Vehicle-wide WTB network	 main computer (MPU) MVB and FIP networks
Bogie wheelbase End bogie Jacobs bogie	2,400 mm 2,700 mm
Bogie center distance Bogie 1-2/6-7 Jacobs bogie	 15,500 mm 16,400 mm
Wheel diameter Max. My.	 850 mm 780 mm
Driving performance Max. acceleration 0 to 80 km/h Average deceleration 120 to 0 km/h Average deceleration during emergency braking	 1.12 m/s2 0.85 m/s2 1.2 m/s2
Floor height Transistion Low floor area Step in	 approx. 850 mm approx. 790 mm approx. 760 mm