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Decision-making based on sensor data from rail and infrastructure - How information from rail vehicles and infrastructure can assist decisions on energy savings and capacity increases

In collaboration with Trafikförvaltningen and MTR Nordic

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1 Introduction

1.1 Background

Urban rail systems as foundational public transport for metropolitan areas play an increasingly important role due to their high capacity, high efficiency and low environmental impact. In Stockholm, the urban rail network is an indispensable component of the city's daily function, serving nearly 900,000 passengers on a daily basis [4]. Aligning with its objective to become the world's most sustainable public transport provider, Stockholm's trains and buses have operated entirely on renewable energy sources since 2017.

Despite the use of green electricity and the inherent efficiency of rail transport, the system's vast operational scale leads to substantial energy consumption. This demand is primarily attributed to two major areas: the traction systems that power the movement of the trains, and the auxiliary systems responsible for ensuring passenger comfort, with the Heating, Ventilation, and Air Conditioning (HVAC) units being the most significant component. Research has indicated that auxiliary power can account for as much as 30% of a train's total energy demand. This issue is particularly pronounced in high-latitude regions such as Stockholm. Concurrently, technological advancements have equipped modern rolling stocks, such as the commuter train X60 and the metro train C30, with an extensive array of sensors. These sensors are capable of recording and transmitting a continuous stream of operational data in real-time, including vehicle speed, power consumption, position, interior and exterior temperatures, and the status of various onboard systems, e.g., doors, air springs and bearings. The availability of this rich dataset creates an unprecedented opportunity to apply a data-driven approach to deeply analyze the relationship between train operation and energy consumption, identify potential savings of energy and operational costs, and ultimately, support more informed and effective decision-making.

It is within this context that the present project was established. As a research initiative funded by the Swedish Innovation Agency's (Vinnova) InfraSweden 2030 program, this project represents a collaborative effort between academia (KTH), the regional transport authority (Trafikförvaltningen, TF), and the train operator (MTR). The primary objective is to develop an intelligent and efficient framework for energy management and decision-making support, designed to address the challenges of rising energy costs and sustainability pressures while pursuing the goal of reducing overall energy consumption in the railway system.

1.2 Problem Formulation

Despite the availability of extensive sensor data and clear energy-saving objectives, the process of translating this data into effective operational strategies is confronted with a series of complex challenges. These issues span the entire chain of activities, from initial technical analysis and economic evaluation to the final decision-making process.

Urban rail transport systems currently in operation were typically built many decades ago. However, rapid urban growth in recent years has significantly increased demands on transport capacity and system availability. This places additional pressure on existing infrastructure and often results in higher energy consumption during operations. At the same time, advances in technology and modern traffic management strategies have created a wide range of opportunities to reduce energy use without compromising service.

Despite this potential, implementing energy-saving measures comes with considerable challenges. These are largely linked to the need for more digitalised and data-driven working processes—both within Public Transport Authorities (PTAs) and Public Transport Operators (PTOs). Moving towards new ways of working, and ultimately introducing new measures, requires a clear demonstration of both business and organisational benefits. In practice, this means showing what cost savings and additional value can be achieved through implementation. As a result, it is not sufficient to focus only on energy-efficiency gains; the broader business case for each measure must also be made explicit.

In addition, a significant economic challenge is the need to establish a fair and unified framework for assessing the cost-effectiveness of different measures. The array of potential energy-saving solutions is diverse, encompassing both operational adjustments with minimal hardware costs, such as modifying HVAC temperature setpoints, and technology-intensive interventions requiring substantial capital investment, like installing onboard batteries or retrofitting switch heating systems. These measures differ fundamentally in their cost structures, life cycles, and the nature of the benefits they generate, which can include direct energy cost savings, reduced maintenance, increased transport capacity, and improved passenger comfort.

Ultimately, the fundamental challenge at the decision-making level is to translate complex technical and economic analyses into a clear, reliable, and actionable process. Faced with dozens of potential improvement initiatives, management needs a structured way to support decision making to help guide the systematic screening, evaluation, and selection of business cases. This framework must not only deliver quantifiable Key Performance Indicators (KPIs) but also clearly articulate the associated risks, implementation complexity, and Technology Readiness Level (TRL) for each proposed measure [4]. Only through such a holistic evaluation can a robust and well-founded strategic investment decision be made.

1.3 Project overview

To systematically address these challenges, the project establishes a comprehensive methodology centred on the development and application of an integrated, data-driven decision-support model. The methodology provides a complete evaluation pathway for any potential energy-saving measure, from early concept development through to the final investment decision.

The project has developed a mixed-method approach to support Public Transport Authorities (PTAs) and Public Transport Operators (PTOs) in identifying and evaluating energy-efficiency measures for urban rail systems. While data and modelling play a central role, decisions are not made solely by algorithms. Implementation must be adapted to local contexts, operational constraints, and organisational processes. Decision-making in public transport is inherently complex, involving multiple stakeholders and competing requirements.

Two quantitative methods form the backbone of the evaluation process: technical modelling, to simulate outcomes before measures are implemented, and economic modelling, to assess total costs and potential savings. These two aspects have been a focus of the project.

To predict the physical effects of proposed measures, the project developed and applied a set of specialised simulation models. A key component is the KTH Rail Vehicle Energy Calculator (also referred to as STEC 2.0), a train energy simulation platform developed in MATLAB. The tool enables simulation of train dynamics, energy flows through traction chain components, HVAC energy use, and includes a model of battery energy storage systems. To analyse system-level electrical effects, a network simulation model of the power supply infrastructure was also developed, enabling precise calculations of voltage distribution, power flow, and the utilisation of regenerative braking energy [5]. In addition, commercial software was used for specific analyses: detailed thermodynamic models of train carriages were developed to simulate HVAC performance, and ANSYS Fluent was used for computational fluid dynamics (CFD) simulations to analyse heat losses from infrastructure components [2].

The economic model translates technical results into financial metrics. The model developed in this project is grounded in the principles of Life Cycle Cost (LCC) analysis and systematically accounts for all costs associated with a measure across its full lifespan, including investment and installation, operation and maintenance, and end-of-life decommissioning and disposal. To enable consistent comparison of business cases with different timelines, the model applies financial evaluation tools such as Net Present Value (NPV), discounting future costs and benefits to present-day value [4].

To support practical implementation and decision-making beyond purely quantitative assessment, the methodology also incorporates the Business Model Canvas (BMC) as a qualitative tool for strategic analysis.

The overall evaluation is structured around a standardised five-step decision flow (D1–D5). The process begins with the identification and prioritisation of potential energy-saving measures (D1), based on workshops and preliminary data analysis. Promising measures then progress to modelling and simulation (D2), where they undergo detailed techno-economic assessment. Measures that show significant potential are recommended for real-world testing (D3) through controlled pilots to validate performance under operational conditions. Based on test results, a plan for full-scale implementation (D4) is developed to support the final investment decision. After implementation, a continuous follow-up and evaluation process (D5) is established to monitor long-term performance and identify opportunities for further optimisation.

2 Application area

The application area for this project is focused on the urban rail transport system of the Stockholm region, with a specific emphasis on its commuter train (Pendeltåg) and metro (Tunnelbana) networks.

Collaborative Framework

The project is built on close collaboration between research, public administration, and operations.

KTH Royal Institute of Technology (KTH) led the research and developed the core technical and economic models, including train energy simulations, power infrastructure modelling, and cost–benefit analysis. KTH also carried out detailed studies of selected measures, such as heat losses linked to switch heating and ice melting processes [2].

Stockholm Public Transport Administration (Trafikförvaltningen, TF) managed the project and represented the end-user perspective. TF defined operational needs, supported coordination, and facilitated access to data across operators. Its role was also to ensure that the results could be translated into decisions and actions aligned with long-term sustainability goals [10].

MTR Nordic, as the train operator, provided access to the fleet, operational data, and the ability to adjust equipment parameters.

2.1 Data

The project is built on a range of data sources from real-world rail operations. This data is used for analysis and modelling, and support for decision-making.

The main data source comes from onboard train sensor systems, collected and accessed through the real-time remote diagnostic monitoring platform NEXALA R2M. The platform gathers data from multiple subsystems and provides two key types of information: digital signals, which describe the status of equipment (for example, door opening events or high-voltage system activation), and analog signals, which provide continuous measurements such as electricity use, speed, temperature (inside and outside), voltage, and current [1]. Together, these streams provide the core dataset for detailed energy and operational analysis.

To understand the data, analyse it and build reliable simulation models, detailed technical information about the vehicles is also required. The project focuses on the Stockholm commuter train X60 and the metro train C30. Key vehicle parameters were primarily taken from technical documentation provided by the manufacturer Alstom. Where specifications were missing, published studies on related vehicles in the same series were used to fill gaps through reasonable extrapolations [3].

External data was also gathered and used from Trafikverket and Lantmäteriet, including elevation profiles, gradients, curve radii, and legal speed limits along each track section [3].

Together, these datasets – real-time sensor streams, detailed vehicle specifications, and high-resolution track information – provide the foundation for the quantitative analysis done in the project.

3 Generic method discussion

3.1 Sensor-based decision-support method for energy efficiency in urban rail

An important aim of this project was to develop a generic method that uses sensor data as a decision-support system to improve energy efficiency in rail traffic. The result is the D3-Rail method (Data-driven Decision-support system).

At its core, the project advances the digital transformation of energy-efficiency work. Today, there are significant data gaps in how the public transport sector follows up on energy use, while vehicles generate large volumes of sensor data that could be harnessed, provided the right systems are in place.

Digital transformation requires more than a technical framework for data management and analysis; it also demands changes to processes, a clear understanding of business needs, and robust business cases to enable the shift.

To make the lessons from this project repeatable within trafikförvaltningen in Region Stockholm, and transferable to other public transport agencies, we address both qualitative and quantitative dimensions. Accordingly, D3-Rail is a mixed-methods approach that combines quantitative analytics with qualitative insights to support the implementation of data-driven energy-efficiency measures. Without the qualitative aspects and consideration of how work is done in practice, then it is difficult to gain energy efficiency and costs savings that are the ultimate aim.

Context for the method

To be practicable, a shift to data-driven working practices cannot happen all at once. It is necessarily a gradual process, and it is essential to develop working methods that are aligned with the current organisational and institutional context.

At present, public transport operators (PTOs) are responsible for their own energy planning, implementation of measures, and follow-up. Within commercial agreements with public transport authorities (PTAs), PTOs are required to report their energy consumption and to provide plans for improving energy efficiency. These reporting obligations are imposed by the PTA and are also embedded in the broader EU legislative framework, including forthcoming requirements under the Energy Efficiency Directive. Typically, this information is delivered to PTAs through static reports. At the same time, PTAs have their own energy-efficiency objectives, and in principle all actors are expected to be moving in the same strategic direction.

In practice, however, energy efficiency is rarely regarded as a business-critical issue by either PTAs or PTOs. As a result, the work is often limited to fulfilling minimum formal requirements, and sufficient resources are rarely allocated to energy-efficiency efforts within PTO organisations. Relationships between PTAs and PTOs can also be strained due to strict commercial agreements, concerns about competition, and fears of losing competitive advantage. Together, these factors create an environment in which:

- data is not readily shared
- generally only the bare minimum is delivered from PTOs to PTAs in order to ensure formal compliance
- analysis is carried out in organisational silos, leading to repeated mistakes and limited sharing of good practices

Against this backdrop, several considerations are particularly important for the D3-Rail model. A central aspect is the need to explicitly address the business case, ensuring that data-driven energy management is perceived as relevant and valuable rather than as a purely administrative burden. In addition, the model must balance being generic with being practically useful. This implies that:

- the business model and incentives for both PTAs and PTOs need to be considered
- the model must remain sufficiently generic, meaning that not all details can or should be predefined
- feedback and learning should be facilitated through the PTA, enabling knowledge and experience to be shared across all PTOs

The target group and starting point

The aim of the D3-Rail decision support method is to support stakeholders working with energy efficiency in public transport in identifying and implementing data-driven energy efficiency measures in rail-based public transport. The method can be understood both as a structured process and as a practical guide that helps users identify relevant elements, assess current practices, and move step-by-step towards more systematic, data-driven ways of working. It is intended for stakeholders within public transport authorities (PTAs) and public transport operators (PTOs), including both strategic and operational roles.

A necessary starting point for applying the D3-Rail method is an initial scoping and preparation phase. In this phase, the method is presented, including the five decision steps which are the main part of the method. This phase establishes the conditions for the work and ensures that the method is applied in a way that is realistic and relevant to the organisational context. It includes defining the scope of the application, such as which parts of the rail system are covered, which energy-efficiency objectives are prioritised, and over what time horizon improvements are sought. It also involves identifying and engaging the relevant stakeholders from PTAs and PTOs, clarifying their roles and responsibilities, and agreeing on how collaboration, and decision-making will be organised.

An important part of defining the baseline is to map the data that is currently available. Ideally, an energy mapping (for example using a Sankey diagram) should be developed for the relevant systems based on sensor data. However, at the outset data availability and quality may be limited. In such cases, the energy mapping should initially be produced using existing knowledge and supporting documentation, at a lower level of detail, and refined as improved data becomes available.

Five decision steps

The core of the model is a set of five decision steps that guide the journey from an initial idea to a sustained and scalable energy-efficiency practice. First, promising measures are identified and prioritised. Next, the required analysis or simulation is defined, along with the data and competencies needed to carry it out. The next step is to design and plan a real-world test, including clear KPIs and a strategy for managing risks. Based on the results of that test, a decision is then made about implementation, supported by both evidence and a complete business case. Finally, the model emphasises follow-up: evaluating outcomes, making adjustments, and scaling up what works.

At each step, the method combines quantitative analysis and business modelling with qualitative process and stakeholder insights, producing a concrete go/no-go decision and a practical plan—making it repeatable within Trafikförvaltningen and transferable to other agencies.

The following five decision steps are included in the model, and described in detail below:

- D1: Identify the measures
- D2: Calculate theoretical potential
- D3: Verify the potential
- D4: Implement
- D5: Follow-up

An overview of the method is presented in the figure below. The method relies on collecting sensor data from vehicles and infrastructure, which is then analysed through a range of approaches to provide decision support. The system does not make decisions autonomously; rather, it enables informed decision-making by integrating data-driven insights with expert knowledge and adapting to the processes and contextual conditions in which it is applied.

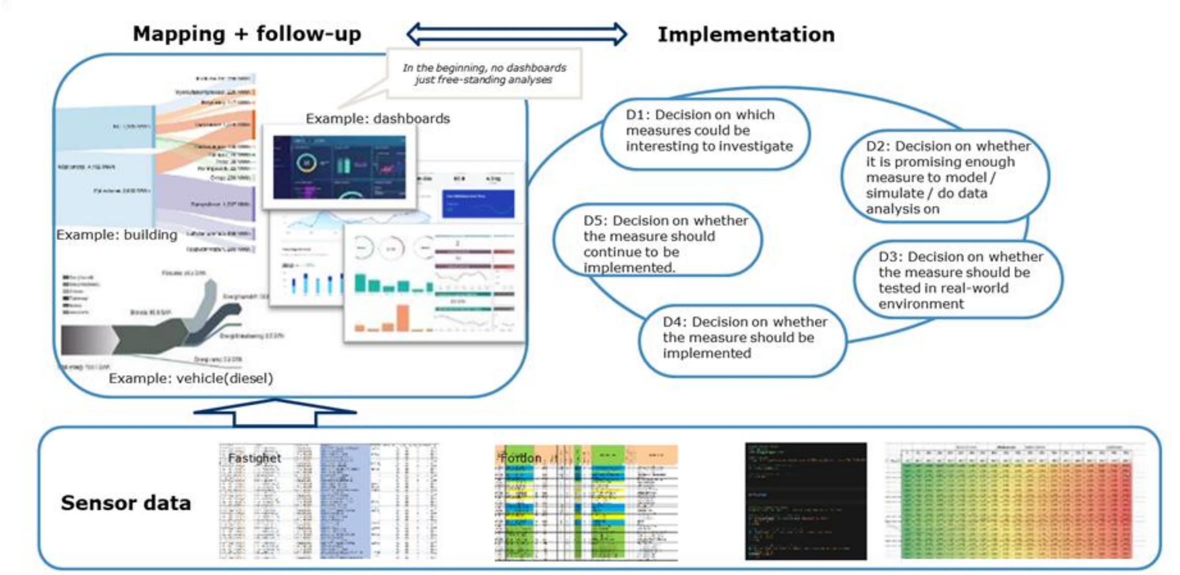

Figure 1 Overview of the method. The sensor data from vehicles and infrastructure is gathered and analyses – as standalone analysis, or through dashboard solutions and used as decision support ("mapping and follow up") to support implementation and evaluation of measures.

What is a ***data-driven measure***?

In the context of this project, a data-driven measure is a measure that has been identified based on an analysis of data and followed up through collecting and analysing relevant data.

D1: Identify and prioritise measures

Overview of this step:
This step decides which measures are interesting enough to explore. You run a joint workshop with relevant stakeholders (in our case in the project, all project partners) and based on previous work and priorities produce a longlist of measures: which data-driven measures to consider, what data needs collecting, and how to prioritise the work. The output is a documented and prioritised longlist that becomes the starting point for later analysis. The longlist should be updated at a regular interval (e.g. once every 2 years) – inline with update of internal strategies for PTA/PTO.

Completed work before this step:
Before this step, the initial scoping, definition of which stakeholders to involve and a basic mapping of the data availability and description of the energy use from the system(s) of relevance should be completed.

What's done in this step?
Create a longlist of measures which will be the basis for the energy efficiency plan.

Who's involved?
The relevant stakeholders should be included, based on the stakeholder analysis and scoping. For example, for metro system: include energy strategist from PTO and PTA, IT/data expert and technical experts (academics, or inhouse expertise from PTA or PTO).

What's done in practice?
A workshop is held with relevant stakeholders to define a long list of potential measures. Preparatory work prior to the workshop includes:

- Overview of energy use in the system in scope – preferably Sankey diagram if available.
- Initial longlist of measures to support brainstorming exercise.

In our case, the longlist looked at the following criteria:

- Name + short description of the measure
- Potential + barriers to implementation
- Value data (sensor data needed)
- Previous study / study in project
- Status in actual context
- Priority for measure: scoring 1-5 based on expert judgement in room

The workshop should result in a long list of measures that everyone has agreed on and some kind of priority regarding these measures. It is possible that more than one workshop is needed.

Result / decision

Long list of potential measures and priority for them.

Data-driven component

Preferably there will be a Sankey diagram created from sensor data to form a detailed basis and discussion. In any case, some basic data availability and mapping of access to data will be made in this step, and the data needed for each of the measures.

D2: Pre-study: decide whether to analyse/model

Overview of this step

For the priority measures from previous step, here you decide if a measure is promising enough to warrant analysis, simulation, or both. The work clarifies the analysis type, checks what data exists, and verifies whether suitable models already exist (and what calibration and effort would be needed). You note data requirements, scan any prior impact results, confirm sensor data availability, draft a very early "back-of-the-envelope" cost-benefit (CBA), sketch the first Business Model Canvas, and list the resources/competences needed. The decision is whether to proceed with analysis and exactly which analysis to do; the result is a defined set of cases for modelling or analysis and access to the data needed. This is a theoretical phase.

Completed work before this step

Result from step 1 – long list of measures and priority.

What's done in this step?

Review the priority measures and decide which should be analysed further.

Who's involved?

The same stakeholders as in the previous step should be involved. Potentially also OEM or other modelling competence can be included.

What's done in practice?

This step includes a review of existing knowledge, data availability, access to modelling and simulation tools, and relevant previous work. In practice, the prioritised measures are evaluated and the available evidence for their applicability and potential impact is discussed. Prior to implementation, robust evidence is required to confirm the expected effect of each measure. In many cases, this requires advanced theoretical analysis to quantify potential outcomes—for example, estimating the energy-saving potential of optimised driving strategies for trains.

Since implementation also requires a clear business case for implementation, a first draft of a business model canvas is also implemented at this stage. More on the business model canvas methodology is included later in this report.

In our project, several measures were analysed by researchers at KTH, thesis students supervised by the project team as well as analysts in TF.

Result / decision

The results from this step are:

- Which measures to do further analysis on, and documentation of these
- Documentation of data availability
- First version of business model canvas for chosen measures.

Data-driven component

It is preferable to use real-world data to perform the modelling / verification if available.

D3: Pre-implementation: design the real-world test

Overview of this step

This step decides whether to test the measure in a real environment and, if so, how. You base the plan on the modelling/analysis results, develop a more detailed CBA and Business Model Canvas, identify and mitigate risks, set up the decision framework for the test, weigh practicalities and costs, and lock down data requirements and KPIs for evaluation. The decision is whether to run a live test and the test design; the result is a concrete pre-implementation plan.

In our project, the measures that we started to look at for real-world testing were:

- setpoint temperature (X60, C30)
- energy-save/parking mode (X60, C30)
- door opening strategies (X60)
- CDAS for X60

Completed work before this step

Completed modelling work to show potential impact of chosen measures, and start of business model canvas for the measure.

What's done in this step?

Review modelling / simulation work and results and business model canvas and if prepare implementation plan for promising measures.

Who's involved?

Relevant stakeholders required to conduct the test should be engaged in the development of the test design. The stakeholders involved will vary depending on the measure. It is therefore advisable to treat each measure as a separate project, with clear objectives, responsibilities, and implementation planning.

What's done in practice?

Detailed planning of the test is carried out, including the timeline, budget, evaluation plan, arrangements for data access and analysis, and a risk management plan. The planning should be aligned with the requirements and procedures for implementing measures in the relevant application area.

Result / decision

Documentation of the test plan, followed by a decision on whether to proceed with the test based on the test protocol.

Data-driven component

The data plan as part of the test including access to the data and relevant data and protocol for evaluation of the test.

A note on monitoring signals and KPIs across steps

Across D3–D5, monitoring focuses on energy-use signals and relationships that matter for decisions: energy over time and driving cycle, the gap between setpoint (or optimal) and actual values, links to temperature and door openings, and alerts for excessive energy use. This feeds the follow-up of implemented measures and the refinement of KPIs as you move from testing into sustained operation.

D4: Implementation decision

Overview of this step

After testing, you decide whether to implement the measure. You use test results, a final CBA, and a concrete implementation plan, together with a practicality/cost review, and you confirm the data requirements and KPI definitions for roll-out. The output is a go/no-go decision and, if "go", a plan describing how to implement in practice.

Completed work before this step

Completed test and evaluation from test.

What's done in this step?

A decision about whether the measure should be implemented in larger scale / in practice.

Who's involved?

The project manager for the test and relevant experts for input – CBA experts, energy strategists, vehicle and / or technical experts, data management experts. The decision will ultimately lie with upper management, so the right decision maker needs to be involved with the relevant data and documentation delivered to expedite the decision.

What's done in practice?

The full cost benefit analysis is performed in this step and final business model canvas. A plan is developed for implementation including costing and plan for follow-up.

Result / decision

Decision on and plan for implementation including final business model canvas.

Data-driven component

Data for evaluation and relevant KPIs for follow-up / monitoring.

D5: Continuation and scaling

Overview of this step

Finally, you decide whether the implemented measure should continue, be adjusted, or be scaled. You follow up on KPIs, update the implementation plan as needed, and reassess costs/practicalities; KPI definitions can be revised based on what the monitoring shows. The decision is whether to keep going and how.

Completed work before this step

Implementation completed.

What’s done in this step?

A decision about whether the measure should continue being implemented and / or scaled.

Who’s involved?

The project manager for the implementation and relevant experts for input – energy strategists, business area managers, vehicle and / or technical experts, data management experts. As with the previous step, the decision will need to be taken by upper management.

What’s done in practice?

Evaluation of the implementation and KPIs and analysis with respect to other parts of strategy. New / updated plans for implementation drafted for decision.

Result / decision

Decision on whether to keep going and how.

Data-driven component

Data for evaluation and relevant KPIs for follow-up / monitoring.

3.2 Core Components – technical and economic modelling

The generic decision-support methodology is built upon two complementary pillars: technical models and economic models.

The *technical models* serve as the theoretical foundation in D2 with their purpose being to predict and quantify the physical effects resulting from any technical or operational change.

This project developed and integrated a series of specialized simulation models for the case of rail transport. Among these, the single train driving model takes inputs such as vehicle parameters, track data, capacity constraints, and driving styles to calculate the train's power intake, regenerated feedback power, and running time, ultimately determining the net energy consumption for an individual train. The train comfort function model calculates the auxiliary power and energy required to maintain a comfortable environment, based on factors like interior and exterior temperatures, ventilation rates, and door opening schedules. For infrastructure-specific analysis, the switch heating model estimates the energy needed to maintain normal switch operation under specific system settings and outdoor temperature conditions. The outputs from these sub-models are then fed into the electric power supply model for system-level integration, allowing for the analysis of total power demand, net energy consumption, and overall line capacity. The integrated application of these technical models makes it possible to translate a proposal, such as reducing the HVAC setpoint temperature by 2°C, into a series of concrete, measurable physical outputs, including the annual heating energy saved and the impact on the total line load [7].

The *economic model* acts as the bridge between the technical analysis and business decisions, represented in the roadmap as the final cost calculation stage. It is designed to convert the physical outputs from the technical models, such as kilowatt-hours saved or capacity increased, into economic value and to conduct a comprehensive cost-benefit assessment for each measure. This model is based on the principles of Life Cycle Cost (LCC) analysis, which systematically accounts for all costs incurred by a measure throughout its entire lifespan. This includes not only the initial capital costs, such as equipment procurement and installation, but also the long-term recurring costs associated with energy consumption, inspection, maintenance, and administration, as well as the final disposal costs related to asset decommissioning. To allow for a fair comparison between business cases with different timelines for costs and benefits, the model incorporates financial analysis tools such as Net Present Value (NPV) to discount future costs and benefits to their present-day value [4].

3.3 Integration of Business Model Canvas

The Business Model Canvas [11] is a visual tool for describing, designing, and refining a business model. It provides a shared “one-page” overview of how an organisation creates value, delivers it to customers, and captures value in return. The canvas is structured into nine building blocks, covering customers, value proposition, channels, relationships, revenue streams, key resources, key activities, partners, and cost structure.

The canvas is typically used as a collaborative working tool, often in workshops, where teams map out assumptions, align on priorities, and identify gaps or risks in the business model. It supports both early-stage idea development and more mature strategy work, helping organisations compare alternative business models, test hypotheses, and guide strategic decisions. Rather than being a static document, the canvas is often updated iteratively as new insights emerge from customer research or pilots.

Energy efficiency measures cannot be implemented without a viable business case. The Business Model Canvas methodology provides a structured way to assess and develop this business case, both at an early stage when data is limited and later as evidence and data become available. For this reason, the Business Model Canvas has been integrated into the model as a core component for decision-making. For more information on the Business Model Canvas, please visit: https://www.strategyzer.com/library/the-business-model-canvas

4 Choice of measures and analysis of measures in the project

4.1 Framework for Measure Identification and Analysis

One of the core tasks of this project was the systematic identification, analysis, and evaluation of a series of measures aimed at enhancing the energy efficiency and transport capacity of the Stockholm rail system. This process followed the generic methodology detailed in Chapter 3. The work began with a broad measure identification phase, conducted through workshops with relevant stakeholders, including the transport authority (TF) and the operator (MTR). This initial effort produced a long list of potential measures to implement covering [7].

The long list of measures is shown below in the figure.

Möjlighet till snabb realisering (1-5)	Nr	Åtgärdskategori	Kort Beskrivning	Value data (data to be collected / to make data-driven decisions)	Studeras av	Kommentar om sannolik implementerbarhet	Update - where are we now?	Look further at?
3	1	Resenärsstyrd dörrkontroll – Passöppning	Resenären öppnar själv dörrparet för att gå av eller på fordonet, året runt. Används redan under sommaren.	.- Temperature inside and outside. - Doors open / closed.	Exjobb 1: Optimization of comfort-related energy of Stochholm commuter trains (Jimmy)	MTR - most interesting. , KTH finds this interesting and has idea on how to research.	Small savings, quite difficult to implement in metro. Easy to implement technically. Already implemented to some extent, but not in real-time based on actual temperature. Good knowledge about this measure	
3	2	Behovsstyrd Ventilation	Bygga om HVAC så att man styr återcirkulation av luft beroende på behov.	.- luftkvalité? - funktion HVAC?	Exjobb 1: Optimization of comfort-related energy of Stochholm commuter trains	MTR-interesting.	C30 already has this. C20 does not. Already been done and decision made. Not much room to make big upgrade of C20 (currently 70% transport). About 20-30 % heating can be saved annually.	
5	3	Börvärde temperatur	Sänkning av börvärde värme - termiska förutsättningar behöver vara anpassad och "rimlig" för bibehållen/förbättrad kundnöjdhet och energieffektivitet	.- Temperatrue inside and outside - Customer satisfaction - thermal comfort can be measured in a number of ways. Which are most relevant? (• Solar radiation (direct and diffuse) and solar incidence angle. • The heat emission from passengers (latent and sensible) – Internal gains • Exterior temperature • Relative humidity • Wind speed • Air infiltration/exfiltration • Heat transfer through envelope • Ventilation air supply (recirculated and fresh air) • Lighting • Clothing)	Exjobb 1: Optimization of comfort-related energy of Stochholm commuter trains	MTR - intersting. KTH finds this interesting and has idea on how to research.	Easy to implement. Medium impact energy consumption. Modelling done - simulation modelling. (pendeltåg)	x
4	4	Motorinställningar	Optimera motor/körsystem för maximal verkningsgrad		Exjobb 2: Optimization of traction energy of Stochholm commuter trains (Yijing)	Mest intressant enligt MTR	Best would be to have collaboration with Alstom. Difficult due to business reasons.	
5	5	Värme olika källor / Intern värmelast	Optimal användning av olika värmekällor		Exjobb 1: Optimization of comfort-related energy of Stochholm commuter trains	KTH - no clear idea on how to research.	Not to focus on now.	
2	6	Förbättra aerodynamiken	Behöver göras en luftflödesanalys			Troligen svår att realisera på befintlig flotta men ger input till nya fordon/uppgraderingar		
1	7	Öka isolering av väggar/dörrar/fönster	Behöver göras en kartläggning		Exjobb 1: Optimization of comfort-related energy of Stochholm commuter trains	Troligen svår att realisera på befintlig flotta men ger input till nya fordon/uppgraderingar		
4	8	Tryckluftsläckage	Fynd och tätning av eventuella läckage				Not to focus on now.	
1	9	Tågvikten	Behöver göras en kartläggning		Exjobb 2: Optimization of traction energy of Stochholm commuter trains	Troligen svår att realisera på befintlig flotta men ger input till nya fordon/uppgraderingar		
5	10	Energi-effektiv körstrategi	1. Energieffektivi tidtabell jämfört med… 2….. Regularitet istället för tidtabell		Exjobb 2: Optimization of traction energy of Stochholm commuter trains	Mest intressant enligt KTH	Depending on how much willing to delay, approx 10% reduction energy (must also work with driver style). Interesting to look at to understand tradeoffs in costs and benefits and how to evaluate them	
4	11	Energysavemode	Hur hantera fordonens energianvändning under stillestående i depå, eller under uppställning i banan?	.- location vehicle and time -energy consumption vehicle (and which component) - energy consumption depot - information on which vehicle and which elements to turn on / off (temperature setpoint - see also "parking mode in exjobb 1"	Exjobb 1: Optimization of comfort-related energy of Stochholm commuter trains	Important. Can look into data during study, but unclear how much impact it has. No changes detected, how to study. New/more data needed. MTR - large potential, literature to students. It would be enough to analyse to se potential saving in-outdoor. Solution is reprogramming….May be out of scope for student.	Huge potential for pendeltåg. C30 not yet estimated, probably quite substantial. NB C30 all parked inside. Havn't looked at it in this project.	x
5	12	Uppkopplat förarstödsystem (C-DAS) relativt Eco-driving	Uppkopplade förarstödsystem ger fördelar vid störning, möjlighet att ge dynamiskt stöd till föraren baserat på trafikintensitet och stöd till nr 13 (regularitet/tidtabell), ökad återmatning mm		Exjobb 2: Optimization of traction energy of Stochholm commuter trains	Mest intressant enligt KTH- A study has been made based on data analysis - new angle needed. Verifying model possible, New model from KTH will focus on simulation more than data analysis.	About 10 % reduction based on previous trials. Driver support system - as time keeping tool rather than energysaving tool. But can beused for both. Another aspect is to give feedback back to drivers regarding their performance wrt energy performace (being implemented, other project)	
4	13	Identifiera optimera energi- och effektpåverkande tidstjuvar	Bla minska problem med fri bredd på perrong, dörröppning och ev rörligt fotstagssekvens, effektivitet i på och avstigning, hastighetsbegränsningszoner, stationer med ev vinst med "vägg mot spårområdet"		Exjobb 2: Optimization of traction energy of Stochholm commuter trains		For the benefit, the effort is quite high. Not to focus on now…	
4	14	Accelerationsstöd i anläggningen	Delsträckor i anläggningen med behov/potential för ökad återmatning/avlastning av elinfrastruktur i anläggning, för optimerad energieffektivitet och eller acceleration mm. Placering av batterilager i anläggning, för optimal påverkan acceleration mm.			Need to provide some solutions that concern infrastructure - can we identify some weaknesses to limitations in infrastructure and suggest improvements. In the project, focus on trains and infrastructure.	Linked to 17	
4	15	Modellens utveckling för att passa in i TFs "systemvärld"	Säkra att det analysverktyget som KTH ska bygga kan hantera data i TFs Data och analysplattform, men också kan tillgodose det vi lovat i form av att verktyget ska vara spårfordonsoberoende.		Exjobb1&2, TFs DAI siencelab.		Not a measure. But important to consider	
	16	Braking control and infrastructure	Local on the vehicle. Raising voltage when brake kicks in. Means that the power can be returned to the system. (linked to 17)			unsure about whether the system can take the line voltage. Need to look t how different vehicles / trains (including work vehicles) can take on board the voltage. Quite extensive investigations required. Alstom would need to be involved	Ongoing project in TF (Erik in charge with Alstom). Some modelling will be done over hte summer (thesis). Modelling related to driving style. Simulating how affects other vehicles. (thesis finished in August). Follow-up project using data and AI modelling. How can technical model support decision making. The real-world data and real-world modelling is quite extensive and complex. Meeting with student (Kangli), end June, to align the modelling done with what has already been done by Siemens as well as what is most useful to look at now.	Ricardo?
	17	Energy supply	Using regenerative braking. Currently engine cannot take power from trains. Can upgrade systems to take advantage of this. Savings up to 25 %. Rectifier is the interesting solution here. NB. C20 and C30 can already use regenerative braking			Quite difficult to implement. Unsure. Need to check with power supply specialist. Don't just change, but need to tune. Need to be clear about the savings and whether it makes sense to do it.	Ongoing projects in TF (Christine). Siemens are currently working on simulations. This will probably be enough to make decisions moving forward. Siemens simulatiosn already accepted by TF - easy for business case here. Need to have an idea on the timeframe to knokw if it's somkething that needs to be brought in now…	

Figure 2 Screenshot of Excel file showing the potential measures.

The measures on the long list were organized into three categories:

1. Auxiliary power measures: focuses on the non-traction energy consumption of the train, particularly the Heating, Ventilation, and Air Conditioning (HVAC) system, which is critical for passenger comfort.
2. Traction and operational measures: aiming at reduce traction energy consumption by optimizing the train's driving profile and operational schedule, often with low implementation costs.
3. Infrastructure measures: involving the modification or upgrading of fixed assets such as the power supply network and trackside equipment. These measures typically require higher capital investment but have the potential to deliver fundamental improvements in system performance [7].

Specific examples of measures studied in the project are described in more detail below, following these three categories. Some results from the modelling work are included in these descriptions.

4.2 Measures for auxiliary power systems

The auxiliary power systems, and particularly the HVAC system, represent a significant portion of a train's energy budget, accounting for approximately 30% of total consumption [1]. The analysis of measures in this category is centered on achieving substantial energy savings while maintaining, or even enhancing, passenger comfort. This project conducted in-depth investigations into three key measures within this domain.

Setpoint temperature optimization

This measure aims to conserve energy by moderately reducing the target temperature setpoint for the cabin's heating system during winter operation, for instance, from the standard 20°C to 18°C. To precisely assess its impact, a detailed thermodynamic model for the Stockholm commuter train (specifically the X60 model) was developed using the specialized building energy simulation software, IDA ICE. The accuracy of this model was rigorously calibrated and validated against field measurement data collected during the winter season, which included thermal imaging, air velocity readings, and temperature measurements at passenger level [1].

The simulation results provided definitive quantitative outcomes. The study found that lowering the setpoint temperature from 20°C to 18°C can reduce annual heating energy consumption by 16.5%. Importantly, this adjustment also produced an unexpected positive effect on passenger comfort. The lower heating output reduced the vertical temperature gradient within the cabin—the difference between the warmer air near the floor-level heating outlets and the cooler air near the ceiling-mounted sensors. This resulted in a more uniform temperature distribution throughout the passenger space, leading to an improved thermal environment. Quantitative data showed that this change not only avoided a decrease in passenger comfort but actually reduced the Predicted Percentage of Dissatisfied (PPD) from 7.2% to 5.3%, thereby decreasing the number of passenger-dissatisfaction-hours (PDH) by 10% [9]. This finding demonstrates that setpoint temperature optimization is a readily implementable "soft" measure that can achieve a win-win outcome of both energy savings and enhanced passenger comfort.

Energy-Saving Parking Mode

This measure addresses the energy consumption of trains during non-operational periods, such as overnight stabling in depots or open-air yards. The core concept is to activate a dedicated energy-saving mode, which primarily involves lowering the interior temperature setpoint to 15°C or below, increasing the proportion of recirculated air to minimize heat exchange with the cold exterior, and reducing the fresh air intake rate while ensuring air quality standards are met [1].

A full-year simulation using the IDA ICE model revealed the significant potential of this measure. The results indicated that merely setting the overnight parking temperature to 15°C could save 13.2% of the annual heating energy per train [9]. When this was combined with an optimized strategy that included shutting down ventilation for a few hours to allow for natural vehicle cooling and increasing air recirculation, the potential energy savings increased to as much as 34% [1]. The Business Model Canvas analysis for this measure identified a clear value proposition with the transport authority (TF) as the main beneficiary. The successful implementation of this measure hinges on the operator's (MTR) access to vehicle parameter settings and potential software support from the vehicle manufacturer, Alstom. At present, this measure has completed the detailed modeling and business case analysis and has been advanced to the D3 stage of the project, with a real-world test being planned for late 2024 or early 2025 [10].

Door Opening Strategy Optimization

For commuter trains with frequent stops at closely spaced stations, door openings are a major source of thermal loss in winter and heat gain in summer, directly impacting both HVAC energy consumption and passenger comfort. This measure aims to reduce unnecessary door opening times and frequency during off-peak hours by shifting from a fully automatic door opening mode to a passenger-activated, on-demand system [1].

To quantify the energy-saving potential of this measure, a precise schedule of door opening events, based on a real train's daily operational timetable, was implemented in the IDA ICE model. The simulation analysis demonstrated that during periods of lower passenger flow, such as weekdays from 9:00 to 15:00 and evenings from 18:00 to 22:00, a strategic 60% reduction in unnecessary door opening time could save approximately 11,000 kWh of heating energy per train annually [1]. At the same time, the analysis revealed an interesting trade-off: during the morning and evening peak hours with high passenger density, frequent door openings, while causing heat loss, also contribute to improved air exchange within the cabin, helping to lower carbon dioxide concentrations and thus partially improving air quality. Therefore, the implementation of this measure requires a dynamic and intelligent control strategy that is linked to passenger load and overall ventilation performance.

4.3 Measures for Traction and Operation

The train's traction system is the largest consumer of energy in the rail system, typically accounting for 60% to 80% of the total energy usage [3]. Therefore, optimizing the driving and operational methods of the trains is a key strategy for achieving significant system-wide energy savings. Measures in this category are often characterized by low implementation costs and rapid returns, as they are primarily realized through software upgrades (supporting eco-driving) or adjustments to operational procedures rather than large-scale hardware modifications. This project's research focused on a detailed analysis of three core measures related to traction and operation.

Driving Strategy Optimization

The driving strategy, which is the combination of acceleration, cruising, coasting, and braking profiles used by a train between stations, directly dictates the energy consumption of the traction system. To quantify the impact of different driving strategies, researchers utilized the KTH-developed comprehensive train simulation platform to create a detailed model of the Stockholm commuter train X60 operating over a typical 5.2-kilometer inter-station segment from Hemfosa to Segersang [3].

The study was designed to compare various combinations of acceleration and deceleration strategies. In the acceleration phase, different modes were tested, including constant acceleration, phased acceleration, inconsistent acceleration, and smooth acceleration. In the deceleration phase, the analysis tested different braking points as well as constant versus inconsistent braking profiles. The simulation results revealed the profound impact of driving behavior on energy consumption. The study found that a driving strategy combining smooth acceleration to the maximum allowed speed, followed by an early transition to coasting and concluding with constant braking, was the most energy-efficient approach, referred to in the study as Case 5+E. When compared to the most aggressive baseline strategy of rapid acceleration and late braking (Case 1+A), this optimized driving profile was able to reduce the net traction energy consumption for the segment from 30.28 kWh to 16.76 kWh, representing an energy saving potential of up to 44%, with a negligible impact on the total travel time of only one to three seconds [3]. This significant finding demonstrates that enormous, near-zero-cost energy savings can be realized by integrating optimized driving curves into the train's Automatic Train Operation (ATO) software or by providing drivers with visualized eco-driving guidance.

Timetable Adjustments

The train's operational timetable directly constrains the total travel time between stations, which in turn profoundly influences the choice of driving strategy and the resulting energy consumption. To investigate the quantitative relationship between travel time and energy use, the project utilized the aforementioned simulation model to analyze the energy impact of adjusting the total travel time by plus or minus 10% from a baseline value of 222 seconds for the same inter-station segment [3].

The results clearly identified a critical trade-off: a modest increase in travel time can yield very significant energy savings. The simulation data showed that extending the total travel time by 10%, which corresponds to approximately 22 seconds, could reduce net traction energy consumption by nearly 45%. Conversely, attempting to shorten the travel time by 10% would cause a drastic increase in energy consumption of almost 90% [3]. This finding has important practical implications for transport authorities. It indicates that during off-peak hours or at less critical stations where passenger demand is lower, making minor adjustments to the timetable that are nearly imperceptible to passengers can result in substantial energy savings. Therefore, energy efficiency should be considered a key factor in the development and optimization of train timetables, rather than solely pursuing maximum operational speed, in order to find an optimal balance between service quality and sustainable operation.

Planned Motor Switch-off During Cruising

During the constant-speed cruising phase of a train's journey, the required traction force is only that which is needed to overcome running resistance, a demand that is far below the maximum available traction force. In this state, all motor groups operate at a low load, which is often a less efficient point in their performance curve. This measure aims to improve efficiency by intentionally switching off some of the motor groups during this phase, thereby forcing the remaining active motors to operate at a higher load, which corresponds to a more efficient point on their performance curve [3].

For the X60 train, which is equipped with three independent traction motor groups, the study simulated the energy-saving effects of switching off one and two of these groups during the cruising phase. The theoretical feasibility of this method was first confirmed by analyzing the motor's efficiency map, which shows that at a constant rotational speed, a higher torque output corresponds to a higher motor efficiency. The simulation results then quantified this effect: under an optimized driving strategy (Case 5+E), switching off one motor group during cruising saved 1.4 kWh, while switching off two motor groups saved 4.1 kWh of energy. Although the absolute energy saving per trip is smaller than that from a full driving strategy optimization, the cumulative benefit is still significant, given the large number of cruising phases in a train's daily operation. The implementation of this measure primarily depends on modifications to the train's control software to add the necessary control logic, making it a technically feasible and effective complementary energy-saving measure.

4.4 Infrastructure Measures

In addition to operational optimizations for the trains themselves, upgrading and modifying the fixed infrastructure is another critical pathway to achieving systemic, large-scale improvements in energy efficiency. Measures of this type typically require higher capital investment, but the benefits they yield are often more profound and durable. This project's research covered infrastructure optimization solutions ranging from the power supply network to key trackside equipment.

Increasing Voltage Level of Brake Chopper

In a DC-powered metro system, a sufficiently high voltage potential is required for the effective feedback of regenerated braking energy into the grid. If the line voltage is low due to the power consumption of other trains, this regenerated energy can be readily absorbed. However, if the line voltage is already high or if there are no other trains nearby to consume the energy, its utilization is impeded. To protect the onboard electrical equipment from overvoltage under all conditions, trains are equipped with a voltage limit, for example, 780V.

Once the onboard system voltage exceeds this limit during regenerative braking, the excess energy is forced to dissipate as heat through onboard braking resistors.

The core idea of this measure is to moderately increase the permissible voltage limit of the onboard inverter during braking, for example, from 780V to 900V, following a thorough technical assessment. To quantify the impact of this change, researchers developed a dynamic simulation model of the Stockholm Metro's power system in MATLAB, encompassing multiple trains and substations, which accurately simulates the bidirectional flow of energy between the trains and the grid.

The simulation results show that increasing the braking voltage is a simple yet effective energy-saving measure. A higher voltage limit allows the train to feed more of its regenerated energy back into the grid even when the line voltage is high, rather than wasting it. The quantitative analysis demonstrated that raising the voltage limit to 900V could increase the utilization rate of regenerated energy from a baseline of 16.0% to 17.6%, resulting in an approximate 10% reduction in the average net energy consumption per vehicle, from 52.8 kWh to 47.4 kWh [5]. Given that this measure primarily involves software parameter adjustments rather than extensive hardware modifications, it is considered a cost-effective, compatible, and readily implementable short-term optimization solution.

Reversible Substation Upgrade

The rectifiers in traditional traction substations, typically diode bridges, only permit a unidirectional flow of current from the AC grid to the DC traction network. They are incapable of feeding surplus energy from regenerative braking back into the upstream AC grid. This leads to significant energy wastage, particularly in situations where there are no nearby trains to absorb the regenerated power. The reversible substation upgrade measure aims to enable bidirectional energy flow through technological retrofitting.

In the power system simulation model, this upgrade was modeled by adding a controllable inverter, such as an IGBT or thyristor-based system, in parallel with the existing rectifier. When the DC-side voltage is detected to be rising due to regenerative braking, the inverter activates, converting the surplus DC power into AC power and feeding it back into the grid [5].

The simulation results show that this is the single most effective of all the infrastructure modification measures. After upgrading to reversible substations, the utilization rate of regenerated energy dramatically increased from a baseline of 16.0% to 75.3%. This means that the vast majority of the braking energy that would otherwise have been wasted was effectively recovered. In terms of final energy consumption, the average net energy use per vehicle plummeted from 52.8 kWh to 20.6 kWh, an energy saving of over 60%. Although the initial capital investment for this measure is substantially higher than for other solutions, and the construction work could temporarily affect normal operations, its enormous long-term energy savings and its supportive effect on the power grid make it a highly valuable strategic investment. The project recommends that pilot upgrades could be prioritized at key locations where regenerative braking is frequent, such as on long downhill gradients or before terminal stations.

Onboard Battery Energy Storage System

Within a rail transport system, an Onboard Energy Storage System (ESS) using batteries is a technological solution with multifaceted potential. Its core functions are twofold: first, to efficiently capture and store the electrical energy generated during regenerative braking that might otherwise be wasted; and second, to provide catenary-free traction power in specific areas, such as depots, maintenance yards, or aesthetically sensitive zones.

This project did not conduct a dedicated empirical study on onboard batteries but instead focused on establishing a robust theoretical model to serve as a foundation for future parametric analysis and feasibility studies. This theoretical model, known as the generic battery cell model, was integrated into the KTH-developed comprehensive train energy calculator. This model abstracts a complete battery pack as an array of individual cells configured in series and parallel. By inputting the key parameters of a single cell, such as rated voltage, capacity, internal resistance, and polarization voltage, the model can accurately simulate the voltage and State of Charge (SOC) of the entire battery pack during charging and discharging cycles.

Using this model, researchers can simulate a variety of scenarios. For example, for a specific catenary-free line, the model can calculate the minimum battery capacity (in kWh) and power (in kW) required to meet operational demands by inputting track data and service requirements. Similarly, the model can be used to evaluate what size battery would be most cost-effective for absorbing the majority of regenerative braking energy on a conventional line. Although this project does not provide specific hardware selections, its associated cost analysis frameworks [4] and power systems models [5] offer a comprehensive simulation tool for conducting more in-depth feasibility studies of onboard ESS for specific lines in the future.

Switch Heating System Optimization

The reliable operation of railway switches during winter is critical for the fluidity of the entire network. To prevent ice and snow from freezing the switch and rendering it inoperable, key switches in the Stockholm region are equipped with electrical heating systems. However, the existing systems predominantly use a continuous resistive heating method with rudimentary control, leading to massive energy consumption, estimated at 130-200 GWh annually.

To address this issue, researchers conducted an in-depth modeling analysis of the ice-melting process and heat transfer in the switch area. First, a mathematical model for the non-steady-state contact melting of ice and snow on a heated surface was established to accurately calculate the melting time and required power under various conditions. Subsequently, the professional computational fluid dynamics (CFD) software ANSYS Fluent was used to perform a detailed simulation of the heat loss from a standard UIC 60 rail under different wind speeds and ambient temperatures [2]. This foundational research provides the theoretical basis for designing a more intelligent and efficient on-demand heating control strategy.

Furthermore, the research points out from a thermodynamic perspective that using high-grade electrical energy for low-temperature heating, as is the case with resistive heating, is a highly inefficient use of energy. To this end, the project proposes a revolutionary alternative: using Ground Source Heat Pumps (GSHPs) to provide heat for the switches. The widespread granite bedrock in Sweden provides excellent geological conditions for installing deep borehole heat exchangers. Simulation analysis shows that a 300-meter deep borehole heat pump system, requiring only about 7.5 kW of electrical power to run its compressor, can extract enough heat from the ground to produce up to 22.5 kW of thermal power, corresponding to a Coefficient of Performance (COP) of approximately 3. This is sufficient to heat one switch. This means that compared to traditional resistive heating, the GSHP solution can achieve the same heating effect with only one-third of the electricity consumption. This not only offers enormous energy-saving potential but also provides a highly feasible technological path for achieving localized and even off-grid energy supply for critical infrastructure.

5 Analysis and further work

This project has systematically explored multiple pathways for enhancing the energy efficiency and transport capacity of the Stockholm urban rail system through the use of sensor data. This concluding chapter aims to synthesize the core findings of the project, discuss the difficulties encountered and the potential barriers to future implementation, and on this basis, chart a course for the next phase of research and application.

5.1 Summary of the main research findings

The research findings from the various master's theses represent the core outputs of the D2 modeling and simulation phase. A summary of the key discoveries from this body of work is presented below.

In the area of auxiliary power systems, the research conducted by Jimmy Lidén demonstrated that a combination of measures could yield substantial energy savings. The study quantified that an optimized energy-saving parking mode could reduce annual heating energy consumption by up to 34%. Lowering the winter setpoint temperature from 20°C to 18°C was found to save 16.5% of heating energy while simultaneously improving passenger comfort. Additionally, optimizing the door opening strategy could save approximately 11,000 kWh per train annually. When these readily implementable measures were combined, the total potential savings in heating energy reached as high as 59%, with an additional potential reduction of 12,000 kWh per train per year in fan power consumption [1].

Regarding traction and operational energy savings, the research by Yijing Pang revealed the decisive impact of driving behavior and operational planning. The simulation results showed that adopting an optimal driving strategy, characterized by smooth acceleration, early coasting, and constant braking(referred to as Case 5+E), could save up to 44% of traction energy without significantly affecting the total travel time. The study also quantified the significant potential of timetable adjustments, finding that a modest 10% increase in travel time could lead to a nearly 45% reduction in energy consumption. Furthermore, the strategy of switching off motor groups during cruising was proven to be an effective supplementary measure, saving up to 4.1 kWh of energy under an optimal driving profile [3].

For electrical infrastructure, the model developed by Kangli Chen provided a system-level simulation of the entire metro power supply network to evaluate several hardware upgrade measures. The research clearly identified that upgrading to reversible substations was the most effective solution, capable of increasing the utilization rate of regenerated energy from 16% to 75.3%. This, in turn, would reduce the average net energy consumption per vehicle by over 60%. A lower-cost alternative, increasing the braking voltage level, was also shown to be effective, with simulations indicating a potential energy reduction of approximately 10% [5]. These findings provide a clear quantitative basis for both long-term investment in and short-term optimization of the power infrastructure.

In the domain of fixed assets, the research by Siddharth Sumathi (as part of the project's broader work on wayside equipment) focused on the high-energy-consuming switch heating systems. By quantifying thermal losses through CFD simulations, the study proposed an innovative solution of replacing traditional resistive heating with ground source heat pumps. The analysis indicated that these heat pumps could achieve a Coefficient of Performance (COP) of approximately 3.0, meaning they could deliver the same heating effect using only one-third of the electricity. This not only offers significant energy savings but also provides a viable path toward localized and more resilient energy supply for critical infrastructure [2].

Finally, the work of Zekeriya Gökmen Dursun provided the overarching framework for all technical analyses. He developed a decision-making matrix that incorporates multiple dimensions, including costs, benefits, and risks, and introduced economic analysis tools such as Life Cycle Cost (LCC) and Net Present Value (NPV). By assigning weights to different Key Performance Indicators (KPIs) and using visualization tools like radar charts, this framework translates complex technical parameters into intuitive business cases that can be compared by managers, thereby providing a scientific and systematic process to support final investment decisions [4].

5.2 Conclusions and lessons learned

The project demonstrates that there is substantial potential to reduce energy consumption in urban rail systems, but that realising this potential depends as much on organisational and data-related factors as on technical solutions.

Significant energy-saving potential exists

The analyses show that considerable energy savings can be achieved across a range of measures, many of which do not require new hardware investments. A large share of the potential lies in software-based and operational measures, such as timetable optimisation, driving strategies, HVAC control (including temperature setpoints, parking modes, and door opening strategies), and improved use of existing equipment. These measures can often be implemented using current systems and infrastructure, making them particularly attractive from a cost and risk perspective.

At the same time, hardware-intensive measures can deliver the largest absolute savings. The most prominent example is the introduction of reversible substations, which enable regenerative braking energy to be fed back into the grid. While this measure offers very high energy-saving potential, it also requires significant capital investment and system-level modifications, making the implementation process more complex.

Table 1 summarises the key measures studied in the project, together with their estimated energy-saving potential.

Together, these results indicate that meaningful energy savings can be achieved through a combination of low-cost operational measures and more capital-intensive infrastructure upgrades, depending on system context and investment capacity.

Table 1 Overview of measures and potential energy savings.

Measure	Short description	Achievable energy saving	Reference
Reversible substation	Upgrading the existing or building new substations to allow bidirectional energy flow, feeding regenerative braking energy back to the AC grid.	> 60% reduction in net energy consumption of DC power system	5
Timetabling + driving strategy	Optimizing driving profiles (e.g., smooth acceleration, coasting) and/or extending travel times modestly.	45% reduction in traction energy of the studied case.	3
HVAC – combined measures	Combining optimizations for parking mode, setpoint temperature, and door openings.	59% reduction in total heating energy of the studied case.	1
HVAC – setpoint temperature	Lowering the winter indoor setpoint temperature (e.g., from 20°C to 18°C).	16.5% reduction in annual heating energy.	1
HVAC – Parking mode	Activating an optimized low-temperature and air-recirculation mode during non-operational periods	34% reduction in annual heating energy	1
HVAC – door opening control	Using passenger-activated, on-demand door opening during off-peak hours to reduce unnecessary opening times.	11,000 kWh per train, per year.	1
Switch heating	Replacing traditional electric heating with geothermal heat Pumps	67% reduction in electricity consumption (COP ≈ 3.0).	2

Digitalisation and the role of qualitative aspects

A central lesson from the project is that energy efficiency is not only a technical optimisation problem. While technical models make it possible to quantify energy-saving potential with a high degree of confidence, implementation depends on digital maturity, organisational readiness, and stakeholder acceptance.

Existing working practices tend to be conservative, and introducing new data-driven ways of working can be challenging. There is often a gap between research results and real-world implementation: measures that show clear benefits in simulations are not always easy to deploy in practice. One way to bridge this gap is through demonstrations and pilot testing, including virtual demonstrations. For example, the development of a driving simulator makes it possible to test and illustrate the effects of different driving strategies in a realistic but controlled environment before moving to real-world trials.

From a business perspective, it is rarely sufficient to present technical energy savings alone. Business cases need to be developed iteratively, improving as more data and experience are gained through modelling, testing, and pilots. Equally important are qualitative aspects: who benefits from a measure, which stakeholders need to be involved, how responsibilities are distributed, and which benefits matter most to each actor. A strong business case therefore combines quantitative results with a clear understanding of organisational impacts and incentives.

Data quality, access, and integration remain major challenges

Although large volumes of operational data are available, data quality and accessibility remain significant barriers. Common issues include incomplete documentation, unclear sampling rates, unknown data processing steps, and misalignment between different data sources. These challenges complicate the use of operational data for calibrating and validating theoretical models.

Access to data is often restricted due to security classifications or organisational caution, where it is easier to deny access than to assess actual risks. In addition, data lock-in and guarding by different private actors can further limit the ability to use data effectively across organisational boundaries.

As a result, there is a clear need for structured data governance, better documentation, and early dialogue on data access. Small-scale tests and demonstrations also play an important role in building trust, validating data, and increasing confidence in both the models and the proposed measures.

The project shows that achieving energy efficiency in urban rail systems requires more than identifying technically optimal solutions. Success depends on combining robust data and modelling with iterative business-case development, stakeholder involvement, and practical demonstrations. Having the right people engaged, aligned, and willing to work differently is as critical as the availability of data and technology.

5.3 Limitations

Although the project successfully used operational data and developed robust modelling tools, several challenges emerged that are important for future work.

A key limitation was data availability, quality, and interpretability. Even when large volumes of data were accessible through platforms such as NEXALA R2M, many channels lacked clear naming conventions and documentation, which made it difficult to interpret signals and assess their reliability. In addition, data sources did not always align well with one another, which complicated model calibration and validation.

Another limitation concerns missing or indirectly measured parameters. Some variables that are highly relevant to energy use—such as passenger load in real time—are not directly measured, and therefore had to be estimated through indirect indicators. This introduces additional uncertainty and limits the precision of certain analyses.

Finally, although many measures show strong potential in modelling, translating results into operational practice remains challenging. Implementation requires overcoming barriers related to conservative working practices, system integration complexity, and stakeholder coordination. A further obstacle is that some advanced strategies depend on upgrades to control systems and digital infrastructure, which may not be feasible in the short term. In all cases, operational safety and reliability remain overriding priorities, and any new measure must be implemented in ways that do not compromise system stability.

5.4 Future work

Future work should focus on moving from modelling results to practical implementation, while also improving the modelling framework and strengthening the business and organisational case for key measures.

At the application level, a priority is to move more measures with high potential from the D2 (Modelling and simulation) stage into the D3 (Testing and verification) stage. Structured pilots on operational lines would provide two major benefits: (1) validating the simulation results under real conditions, and (2) generating high-quality empirical data that can improve calibration and reduce uncertainty. This would also strengthen cost–benefit estimates and support investment decisions for the D4 (Implementation) stage [4]. Virtual demonstrations—such as driving simulators—can also play an important role in bridging the gap between technical potential and operational confidence.

At the technical level, further work is recommended in two directions. One is to refine existing models through targeted measurements and improved calibration. For example, longer-term measurements of in-carriage CO_2 levels and vertical temperature gradients could improve HVAC model accuracy. The second direction is to develop more advanced control strategies, such as integrated energy management systems that optimise driving profiles and HVAC settings in real time. These could take advantage of external and operational inputs such as electricity price signals, weather conditions, train position, and passenger load forecasts [3].

At the economic and strategic level, more detailed business-case development is needed for the most promising investment-heavy measures, such as reversible substations and ground-source heat pumps. This should include refined Life Cycle Cost (LCC) analyses, ROI calculations, and careful consideration of how costs and benefits are distributed across stakeholders [4]. Finally, future work should focus on how successful measures can be standardised and scaled—so that validated solutions can be replicated across vehicle types, lines, and ultimately the wider rail network.

References

[1] Jimmy Liden, Master thesis: Optimization of comfort-related energy of Stockholm commuter trains, 2023.

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