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How Sensor Data from Rail Vehicles to Support Decision-Making for Energy Saving

W. Liu[1], A. Clark[2], S. Kapoor[1], M. Berg[1], E. Dunkars[2] and J. Forsberg[3]

[1]Rail Vehicles, Department of Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden
[2]Trafikförvaltningen, Sweden
[3]MTR Nordic, Sweden

Abstract

Urban rail systems are important to metropolitan mobility but are also major energy consumers, particularly in cold-climate regions like Stockholm. Growing availability of high-resolution sensor data from modern fleets gives new opportunities to analyse energy use, identify efficiency measures and support evidence-based decision-making for energy saving. This paper presents a structured, data-driven decision-support method developed through a close collaboration between university, transport administration and train operator. The method integrates quantitative modelling which consists of train traction simulation, thermodynamic modelling, infrastructure heating analysis, and power-supply network simulation, and qualitative tools, like the Business Model Canvas. It organizes the evaluation of candidate measures into a five-step flow covering identification, pre-study, test planning, implementation decision and continued follow-up. Case study on the Stockholm commuter trains demonstrates substantial energy-saving potential across multiple domains: thermodynamic measures, e.g., optimizing setpoint temperature and implementing energy-saving parking mode to reduce heat loss; operational strategies, e.g., eco-driving driving and modest timetable slack to reduce traction energy. Together, these results show that sensor-data-driven analysis can enable targeted, cost-effective and scalable improvements in energy efficiency of urban rail systems, providing a practical pathway from analytics to implementation.

Keywords: urban rail systems, decision-making, energy saving, sensor data, traction energy, auxiliary energy.

1 Introduction

Urban rail systems play a critical role in supporting mobility, accessibility, and economic activity in metropolitan regions. Their high transport capacity, operational efficiency, and low emissions make them a foundation of sustainable urban transport. At the same time, the large scale and high frequency of rail operations result in substantial energy consumption. This is a big challenge, especially in cold-climate regions such as Stockholm, where auxiliary loads for heating and ventilation constitute a significant share of total energy use. Previous studies have shown that auxiliary systems can account for up to 30% of the energy demand of a commuter train, making them a key target for efficiency improvements. The energy for traction has a big potential to be further reduced. The increasing cost of electricity, coupled with regional sustainability objectives, has intensified the need for transport administrations and operators to identify cost-effective strategies that reduce energy consumption without compromising service quality or passenger comfort.

Recent generations of rolling stock, such as commuter trains and metro trains, are equipped with many sensors capable of capturing high-resolution data on traction power, temperature, speed, equipment status, and numerous subsystem interactions. These datasets provide many opportunities for data-driven analysis of operational energy use. However, transforming raw sensor data into actionable insights remains difficult in practice. Challenges related to data quality, accessibility, organizational issues, and differing stakeholder priorities often limit the systematic use of data in energy-related work. As a result, promising technical measures are not always translated into implementation, and decision-makers in many cases lack a clear, structured process for evaluating measures with varying costs, risks, and benefits.

Addressing these challenges requires more than some specific technical studies. It demands an integrated approach that combines quantitative modelling, qualitative assessment, and structured decision-making workflows that are in line with the decision-making procedure of the urban rail transport. To meet this need, a collaborative project involving a university, local transport administration, and train operator developed a generic, sensor-data-driven decision-support methodology for identifying, analysing, and implementing energy-efficiency measures for urban rail systems. The method, known as D3-Rail (Data-Driven Decision Support for Rail), provides an evaluation pathway extending from early energy-efficiency measure identification to long-term follow-up.

A key feature of the method is the integration of multiple quantitative modelling tools. These include traction energy simulation, thermodynamic modelling of auxiliary functions, and modelling of infrastructure energy losses for evaluating system-level effects. These technical analyses are complemented by qualitative tools, i.e., Business model canvas, which help clarify stakeholder incentives, value distribution, implementation barriers, and additional requirements from the stakeholders. The method is structured into a five-step process covering measure identification, pre-study, test planning, implementation decision, and follow-up plan.

This paper presents the D3-Rail methodology and illustrates its application through a case study on a Stockholm commuter train system. The results demonstrate substantial energy-saving potential across thermodynamic, operational, and infrastructure domains. Overall, the findings highlight how sensor-data-driven analysis can support targeted, cost-effective, and scalable improvements in the energy efficiency, providing a practical pathway from analytics to implementation.

2 Methodology

The methodology developed in this study provides a structured, data-driven approach for identifying, assessing, and implementing energy-efficiency measures for the urban rail systems. The D3-Rail method integrates quantitative modelling with qualitative business-oriented evaluation. It is designed to address the gap between technical potential and real-world implementation by combining analytics with stakeholder perspectives, organizational constraints, and long-term considerations.

A key foundation of the methodology is its use of high-resolution operational sensor data. In daily operation, modern trains generate rich datasets through their onboard systems, including status signals (e.g., door openings, HVAC modes, high-voltage system activation) and analogue measurements (e.g., power consumption, voltage, current, speed, interior and exterior temperature). These data are collected via the remote-monitoring platform, which enables continuous access to real-time operational conditions. Additional information can be extracted from documentation provided by manufacturers and infrastructure managers. Together, these datasets support model calibration, identification of efficiencies and understanding of the impact of driving behaviour, climate, and infrastructure conditions.

To assess the technical effects of candidate measures, the methodology integrates three pillars. The first pillar is a single-train traction simulation, performed using the KTH Rail Vehicle Energy Calculator (STEC 2.0). This model evaluates traction energy consumption by simulating driving strategies, acceleration and braking patterns, regenerative energy use, and constraints imposed by timetables. It is used to analyse operational measures, e.g., eco-driving, timetable adjustments, and traction-motor control. The second pillar is thermodynamic modelling of HVAC performance. The thermal models simulate heating loads, interior temperature distribution, and the impact of dooropening events, providing insight into measures, e.g., setpoint optimisation and energy-saving parking modes. The third pillar consists of infrastructure energy loss, e.g., switch heaters and power-supply network to study voltage levels, regenerative-energy utilisation, and the system-level impact of changes such as raising braking-voltage limits or introducing reversible substations.

While the modelling pillars quantify technical potential, implementation also depends on organizational constraints, resource availability, and stakeholder alignment. Therefore, the D3-Rail methodology incorporates life-cycle economic analysis to evaluate investment, operation, maintenance, and end-of-life costs. Measures with different lifespans and cost structures can thus be compared on a consistent basis. Complementing this, the Business Model Canvas (BMC) is applied as a qualitative tool to capture stakeholder incentives, distribution of responsibilities, potential barriers, and expected outcomes. This ensures that promising technical measures are supported by viable organizational and business cases.

The methodology is structured around a five-step decision flow that guides measures from initial consideration to long-term implementation:

- **D1 – Identification and prioritisation:** A broad longlist of potential measures is generated through stakeholder workshops and preliminary data analysis. Measures are prioritised according to perceived impact, feasibility, and data availability.
- **D2 – Pre-study:** Selected measures undergo a theoretical assessment including model selection, data availability checks, and initial estimation of technical effects and cost–benefit potential.
- **D3 – Test design:** Promising measures proceed to detailed pilot-test planning, including definition of key performance indicators, data-collection protocols, risk assessment and resource planning.
- **D4 – Implementation decision:** A business case is prepared combining calculation results, pilot-test, economic analysis and stakeholder considerations. Decision-makers determine whether full implementation is justified.
- **D5 – Continuation and scaling:** Implemented measures that are monitored over time to verify performance and guide decisions on expansion, adaptation, or discontinuation.

In summary, the D3-Rail methodology integrates sensor-data analysis, specialized engineering models, economic evaluation, and structured decision-making into a single framework. By bridging the gap between theoretical analysis and practice, it provides a scalable and repeatable approach for improving energy efficiency in urban rail systems.

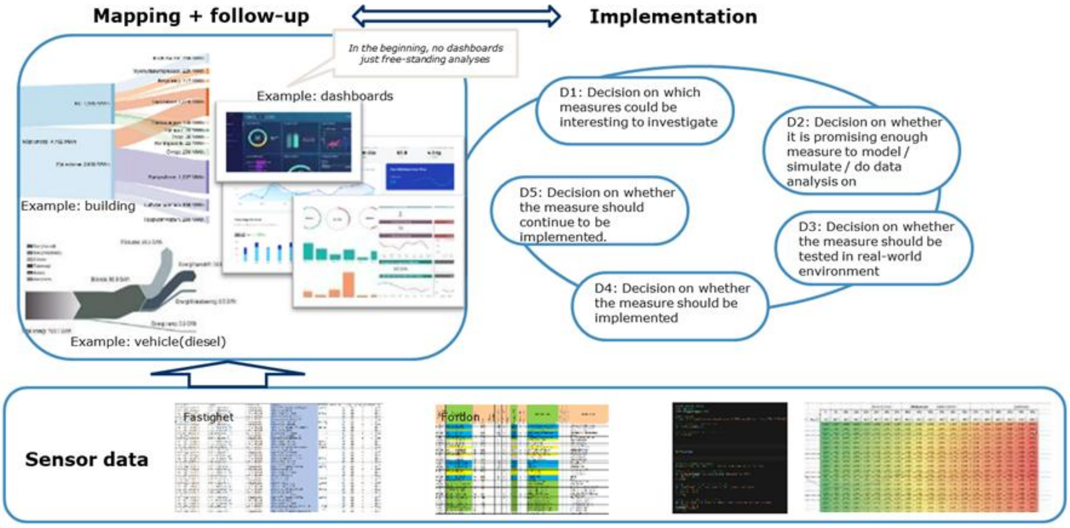

Figure 1: Overview of the method. The sensor data from vehicles and infrastructure is gathered, analyzed, and used to support implementation and evaluation.

3 Case Study

This case study applies the D3-Rail methodology to Stockholm's commuter rail system with a focus on the X60 fleet, illustrating how sensor data, multi-system modelling, and structured decision steps translate into implementable energy-efficiency measures.

In a cold-climate setting like Stockholm, auxiliary heating loads are heavy while frequency stops require high traction demand, making energy performance a strategic priority. The X60 fleets can supply high-resolution train status (e.g., door state, HVAC modes, etc.) and analogue measurement (e.g., traction power, speed, voltage, current, temperatures) via the NEXALA R2M platform. These streams, together with the manufacturer's documentation and detailed track/route profiles from the infrastructure manager, enable calibration and scenario analysis based on real operation.

The project followed the D3-Rail five-step flow, as shown in Figure 1. In D1, stakeholder workshops create and prioritise a longlist which considers auxiliary, traction/operations, and infrastructure measures. D2 establishes data requirements and quantifies theoretical potential with calibrated models. D3 prepares pilots with KPIs and available data. D4 assembles techno-economic results and Business Model Canvas to support decision-making. D5 defines monitoring for continuation and scaling. A set of measures has been studied by following the D3-Rail five-step flow, and the results of the studies are summarized as follows:

1. **Setpoint temperature optimisation.** A thermodynamic model (IDA ICE) for the X60 shows that lowering the winter cabin setpoint from 20 °C to 18 °C reduces annual heating energy by 16.5% while slightly improving comfort through more uniform vertical temperature distribution [1]. This is a low-barrier, "software-based" measure, that does not require significant modification.
2. **Energy-saving parking mode**. For overnight stabling, reducing the setpoint to ~15 °C with ventilation shut-down can reduce energy consumption. The implementation of the **energy**-saving parking mode can help to reach up to 34% of energy saving during parking [1]. This measure moved forward to test planning under D3.
3. **Door-opening strategy**. Using timetable-based door events, analysis indicated that about 11,000 kWh of annual heating savings per train can be achieved by curbing unnecessary openings during off-peak **hours**; The frequent openings during peaks also allow air exchange and CO_2 control to minimize the energy loss from ventilation [1]. It has been partly implemented during train operation in winter.
4. **Driving-strategy optimisation.** Single-train simulations on a representative 5.2 km segment showed that smooth acceleration, early coasting, and constant braking reduced net **traction** energy by up to 44% versus an aggressive baseline [2]. It is relatively easy to implement in train operations.
5. **Timetable adjustments**. Allowing +10% extension of running time achieved traction energy reduction, which justifies that small slack increases can unlock large savings, **especially** off-peak hours. About 22 s extension in the referenced case can lead to 45% reduction in net traction energy [2]. This measure does not require large modifications to the hardware and can be implemented.
6. **Planned motor control.** Power from motors is only demanded during acceleration and braking. Theoretically, it is possible to intentionally deactivate some motors during cruise to shift active motors to more efficient load points. In

the studied case between two stations, this can save up to 4.1 kWh per train, modest but possible to achieve via software logic [2]. But it requires big changes to the control logics of traction chain.

7. **Switch-heating optimisation.** Modelling of heat losses around railway switches shows substantial inefficiency in continuous resistive heating; a ground-source heat-pump concept can help to reduce roughly two-thirds of electricity (COP=3) to lower running costs and improve resilience [3]. But large-scale modification and civil work are needed.
8. **Combination of different measures.** The analysed measures can be coupled together to maximize the energy saving. The implementation can be planned based on their effectiveness and difficulties.

Across domains, D3-Rail coupled technical results with life-cycle cost evaluation [4] and a Business Model Canvas [5], clarifying stakeholder incentives and barriers. In the short-term, "software/operation" measures, e.g., setpoint temperature optimisation, driving-strategy optimisation, door-opening strategy, and timetable adjustment, offer high Return on Investment with low risk and minimal hardware dependency. In parallel, strategic upgrades, e.g., switch-heating optimisation and planned motor control, present compelling long-term opportunities with capital investment.

Overall, the Stockholm application demonstrates that substantial, multi-domain savings can be achieved. A sensor-based, data-driven, five-step process is effective for turning theoretical studies into implementation by prioritising quick wins while preparing for transformative infrastructure improvements.

4 Conclusions

This work presents D3-Rail, a structured, data-driven methodology that links high-resolution sensor data, multi-domain simulation, and business modelling to deliver decision-ready energy-efficiency measures for urban rail. The proposed five-step flow creates traceability from idea to implementation, ensuring that technical evidence, possibility to implement and follow-up plan are evaluated.

Applied to Stockholm's X60 commuter rail, the approach identified substantial and actionable savings across auxiliary functions, traction/operations, and infrastructure domains. The study with "software/operation" measures offers high Return on Investment with low risk and minimal hardware modifications. Crucially, the method integrates cost analysis and the Business Model Canvas so that the technical potential is translated into investable business cases aligned with stakeholder incentives and implementation capacity. Overall, D3-Rail demonstrates a practical pathway from theoretical study to action, enabling targeted, cost-effective, and scalable energy improvements in urban rail systems.

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