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Decision-Making Model of Urban Rail System for Operation Optimization and System Upgrading

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Abstract

Urban rail transport is an efficient and environmentally friendly transport solution. However, there are many challenges due to weak power supply and high capacity demand. To reduce energy consumption, minimize operational costs and increase transport capacity, there are many possible solutions to achieve these goals. It is needed to make a smart and cost-effective plan for efficiently using infrastructure as well as saving energy. This paper proposes a decision-making model to demonstrate the effectiveness of different technical solutions and quantify their costs and benefits on the energy and capacity aspects for comparison. Based on the model, two case studies on the Stockholm commuter trains and metro trains with several technical solutions as examples are analyzed. The model is supposed to provide a key reference for decision-makers to set up a smart and cost-effective management plan for efficiently using infrastructure as well as saving energy.

Keywords: urban rail transport, energy saving, capacity increasing, decision-making, operation optimization, system upgrading.

1 Introduction

The urban rail transport systems in Stockholm are the most important parts of public transport for both residents and travellers. They provide a cheap and time-efficient means of transport and help to ease congestion and pollution in urban areas. Even though rail transport is very energy-efficient and runs on green electricity, it still consumes a great amount of energy in operation. Meanwhile, the power supply systems of Stockholm's local rail transport are relatively old and weak, which lowers energy efficiency and limits the increase in transport capacity, so the power supply systems have become bottlenecks for the development of Stockholm's local rail transport. To reduce energy consumption, minimize operational costs and increase transport capacity, it is needed to set up a smart and cost-effective management plan for efficiently using infrastructure as well as saving energy.

For any urban transport system, there are many different technical solutions to save energy and/or increase capacity, but the costs and benefits vary a lot from case to case [1]. This work intends to build a business-case model to estimate the costs and benefits of different technical modifications to the train operation and system upgrading, and eventually assists the authority in making effective decisions on the system development and operational planning. With the implementation of modern trains, much detailed information during train operation can be recorded, e.g., speed, power, position, traction/braking effort, electric current, line voltage, pressure of air spring, indoor temperature, door opening, etc. All the information related to the operation can be used for data analysis and system modelling. The model is divided into two groups of sub-models: technical models to estimate the effectiveness of different technical solutions, and economical models to quantify the cost and benefits of different technical solutions to make fair comparisons among different solutions. In this way, the impact of the technical changes can be quantified as a key reference for decision-making.

The work builds a business-case model to estimate the costs, benefits and effectiveness of the proposed technical solutions. Firstly, the structures and relationships among different technical models and economic models are addressed. Secondly, based on the Stockholm urban rail transport system, two study cases are performed to quantify the costs, benefits and effectiveness of the several technical solutions: driving optimization, adjusting timetable, changing motor groups during cruising and upgrading the power supply with the energy storage system. Eventually, some suggestions for energy saving and capacity increase of the Stockholm urban rail transport systems are given, and future work for developing the decision-making model is outlined.

2 Models

For an urban transport system, which carries a great number of passengers and has frequent stops, in reality, there are many limitations to the train operations, e.g., train capacity, line capacity, timetable, track condition, power supply, comfort level, etc. In order to save energy and increase capacity, there are many different solutions to achieve these goals. However, since all different parts of the system are closely coupled together during operation, any small change to one system can have different degrees of impact on the overall performance. In order to assist the system operator in making a time-efficient and cost-effective decision, a business-case model for urban rail transport is built. The model consists of two groups of sub-models: technical models, and economical models.

2.1 Technical models

The fundamental group of models are technical models which are used to demonstrate different technical solutions and reflect their impacts on the system. At this moment, there are four technical models, which cover a wide scope of urban rail systems, as shown in Figure 1. They are the single train driving model, train indoor comfort model, switch heating model, and DC electric infrastructure model.

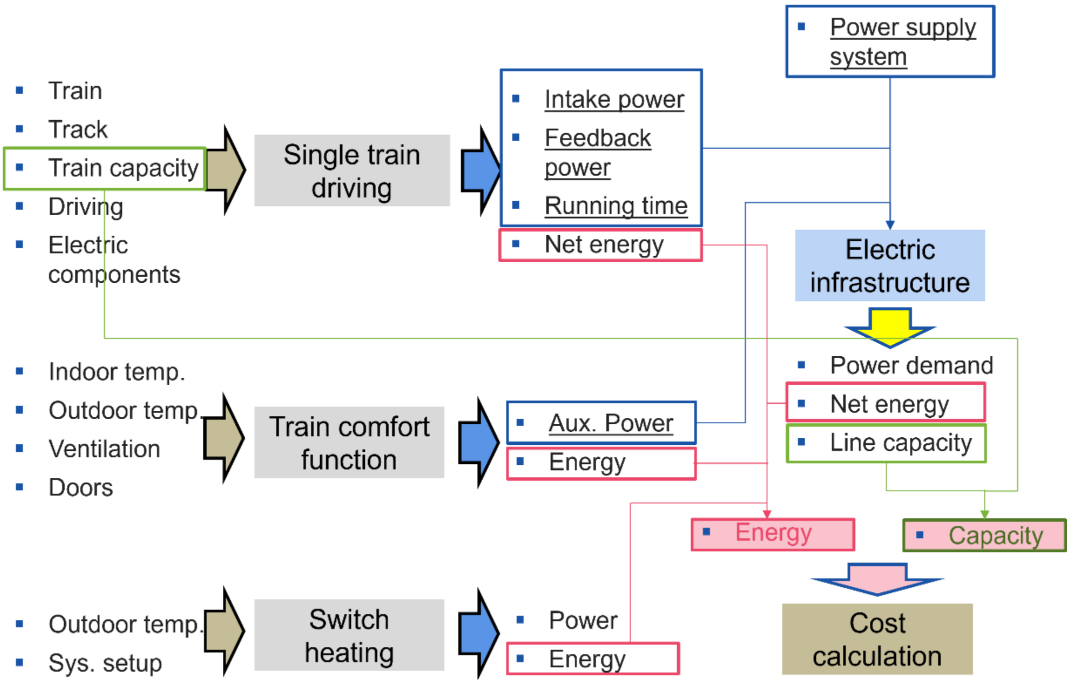

Figure 1: Technical models used to calculate energy, capacity and timetable.

The single train model calculates power, total energy consumption, running time and running speed with respect to train parameters, driving styles, track topography and electric components. Regarding the driving style, the traction and braking effort, speed limit, and timetable can be manageable in the model. For the train parameters, besides the basic train parameters, e.g., train weight, traction/braking curves, etc. [2]

The train indoor comfort model is used to reflect the power and energy consumption of heating, cooling and ventilation with respect to different temperature and ventilation settings, outdoor temperature, and frequency of door opening [3].

Since switches are critical components, in winter it is necessary to keep the switch points with the heating system. The switch heating model is built to estimate the power and energy consumption of the heating system to melt ice/snow in the switch area in winter conditions [4].

The electric infrastructure model is built to calculate power and energy demand according to different train operations. It is used to reflect the interaction between train(s) and power supply infrastructure. Using the output speed profile and power from the single train model, the energy loss and voltage drop at the electric infrastructure can be calculated.

Eventually, the total energy consumption from different parts can be summed up to calculate the total energy consumption. Correspondingly, the transport capacity can be calculated based on the capacity of the single train and the number of trains the infrastructure can support. In this way, the technical models can help to estimate the changes to total energy consumption and transport capacity with respect to different technical changes. Then the energy consumption and total capacity are used to calculate the costs and benefits of different technical solutions.

2.2 Economical model

The economical model is used to quantify the costs and benefits of different technical solutions for comparison, as shown in Figure 2. The outputs from the technical models, e.g., energy consumption and transport capacity, are the basic inputs for the economical model and are converted into monetary units. Meanwhile, any changes to train operation, system setup, and technical solutions need costs on implementation and have impacts on the long-term operation, which are also converted into monetary units. There are mainly five groups of inputs to the economical model: technical changes, cost list per change, cost list of operation and maintenance, economical information, and socio-economy information.

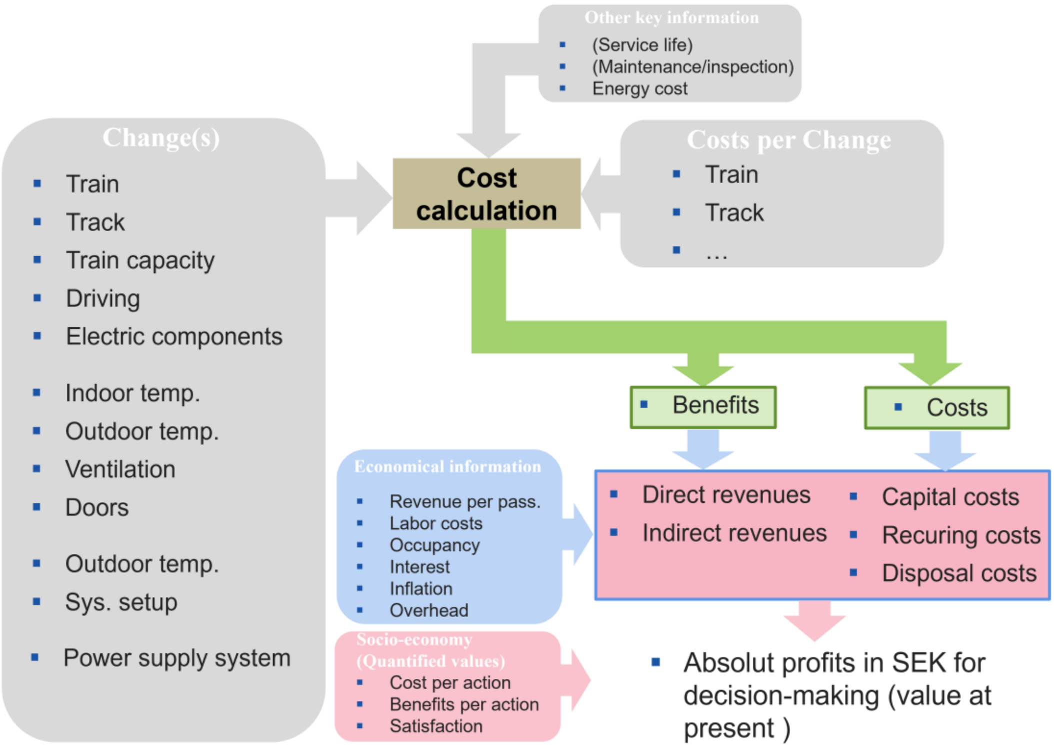

Figure 3: Economical model to calculate costs and benefits.

It mainly focuses on briefly calculating the life cycle cost of implementation of each technical solution. There are three kinds of costs included in the model [1]:

- Capital costs, which is a one-time investment, e.g., purchasing new equipment, construction, installation, etc.
- Recurring costs, which are the operational cost to keep system functionality, e.g., inspection, maintenance, repair, energy, administration, etc.

- Disposal costs, which is linked to asset disposal when service life is due, e.g., demolished batteries and used equipment.

With the help of the cost list per change, cost list of operation and maintenance, and economical information, (disposal costs as well), the costs and benefits associated with implementation of different technical solutions can be quantified in monetary value. If socio-economy information is available and quantified in monetary value, the part of cost and benefits can be also included.

After the costs and benefits of each technical solution are quantified into monetary value, it is possible to make comparisons among them. Based on the monetarized values of the suggested technical solutions, it can help to rank the priority of the solutions, as shown in Figure 3. Eventually, the ranking list can be used as a reference for the decision-maker to make a smart and cost-effective decision.

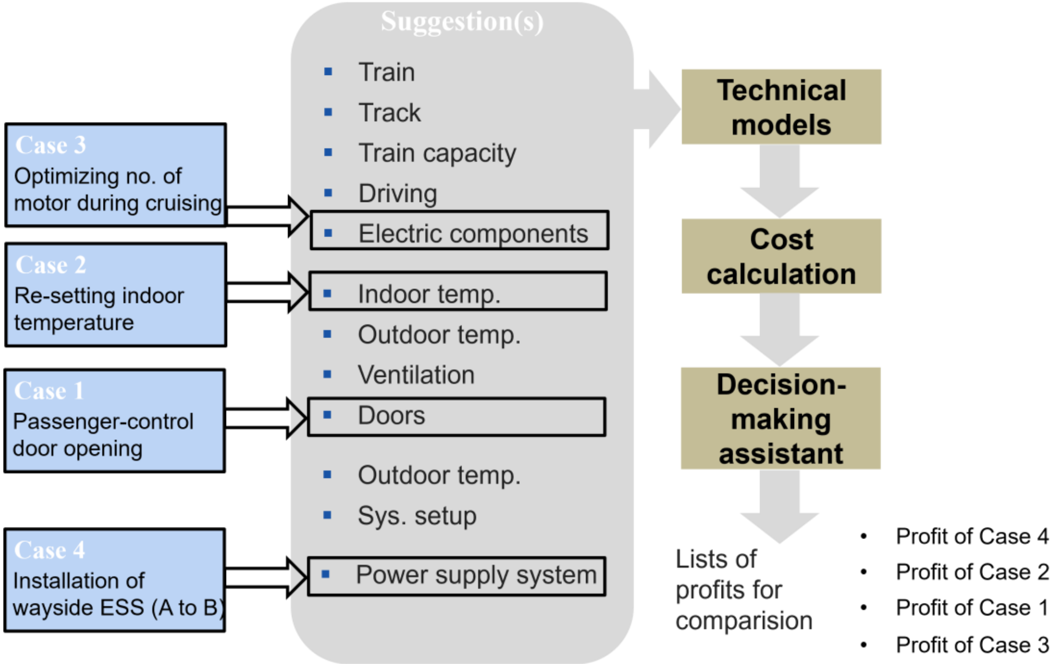

Figure 3: Decision-making assistance model.

3 Case study

3.1 Stockholm commuter train

For Stockholm's commuter train, as shown in Figure 4, there are many different measures to optimize the train operation and to upgrade the existing infrastructure. Although all the measures can contribute to energy saving and capacity increase, they need different costs for implementation and give different levels of benefits, especially when the service life of rail infrastructure and trains normally has a long time span. Based on the models mentioned in the work, the study takes the commuter trains as a case study to analyse the costs and benefits of three identified measures.

It is at the very beginning of the entire project, only three technical solutions are discussed now: optimization of train driving, optimization of traction motor groups during cruising, and optimized setpoint temperature.

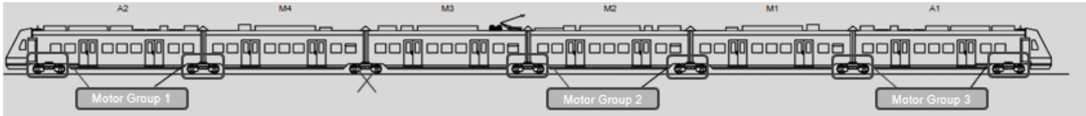

Figure 4: Stockholm's commuter train X60, which consists of six coaches.

The first technical solution is to drive the train in an energy-efficient way while keeping the total running time unchanged. A 5.2 km-long track section between Hemfosa station and Segersang station is selected. Since there are no technical changes to the system and it only requires the train driver to change the driving style, there are almost no costs in implementation (driver training costs are not considered). The timetable has not changed, so there is no change to the transport capacity. The only benefit we can expect is energy saving, which means saving the operational cost.

The second solution is to decrease the number of utilized motor groups during cruising. During the cruising phase, the speed remains constant, and the force generated by the motors matches the running resistance force. The X60 train is equipped with three sets of the motor group. According to the efficiency map of the traction chain of the X60 train, it is possible to increase overall efficiency levels and reduce energy waste by maintaining the same rotation speed with only two or even one motor group. For the case with a cruising distance of 4400 m, by switching off one and two motor groups, 0.9 kWh and 2.5 kWh of energy can be saved, respectively. This strategy does not require a change in timetables and driving style. The benefit is to save energy consumption and potentially extend the life span of the motor group.

3.2 Stockholm metro

The Stockholm metro is electrified with a third rail with a 750 V DC power supply. The C30 trains are in use, which are equipped with sensors and meters to collect very detailed information during operation. These data are used to build a single train model. For the metro system, the power is provided from the public grid to the middle voltage network through bulk substations and eventually to the third rail through rectifier substations, as shown in Figure 5. The movement of trains dynamically changes the power distribution along the route. The electric resistance of the infrastructure is simplified as the product of electric resistance per meter and the distance between the train and the substation.

Even the trains have functioned with regenerative braking, but unfortunately, the current substations do not allow to send power back to the grid, nor is the power supply system equipped with batteries. As a result, the extra energy is either used by other trains for accelerating or wasted as heat through onboard electric resistors.

In this case, the single train model is coupled with the electric infrastructure model, where a 1.77 km track section between two rectifier substations is used, as shown in Figure 6. It is assumed that two trains with the same technical parameters run from one substation to another, following the same driving style within a given interval.

Adjusting the timetable (here, the train interval) ensures that the first train applies regenerative braking simultaneously as the second train accelerates. Since only the timetable is changed, there is no additional cost. In the best case, the energy loss can be reduced by 20%, as shown in Figure 7. However, this strategy can not be as feasible as expected due to the constraints of timetable and traffic control, so the energy saving in reality is always lower. The transport capacity is heavily dependent on the timetable.

Another strategy is to upgrade substations into reversible ones or to install energy storage systems (ESS). The energy saving is determined by the power supply infrastructure, i.e., the upper limit of input and output power of ESSs, and reversible substations. Meanwhile, the line capacity can be increased a bit by upgrading the power supply. The total cost includes not only the capital investment in infrastructure upgrading but also the maintenance during the whole life span while in long-term operation, the energy saving and capacity increasing can be the win. The economic models are applied to evaluate the trade-off between the related costs and benefits, which will be further analysed in the future when more input information is available.

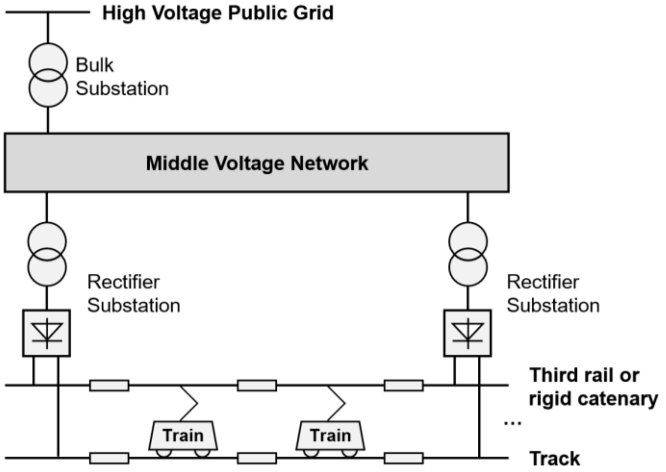

Figure 5: Illustration of the electric infrastructure of DC power supply.

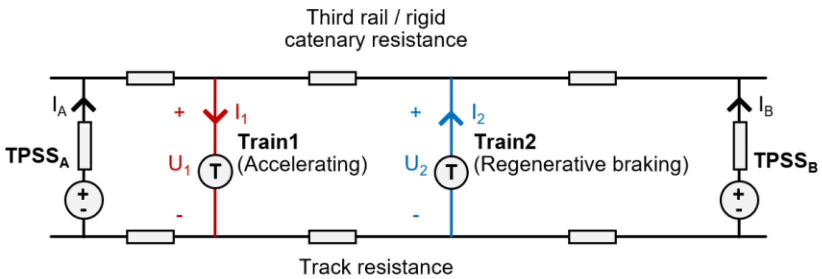

Figure 6: Electric diagram of the DC network with two C30 trains running.

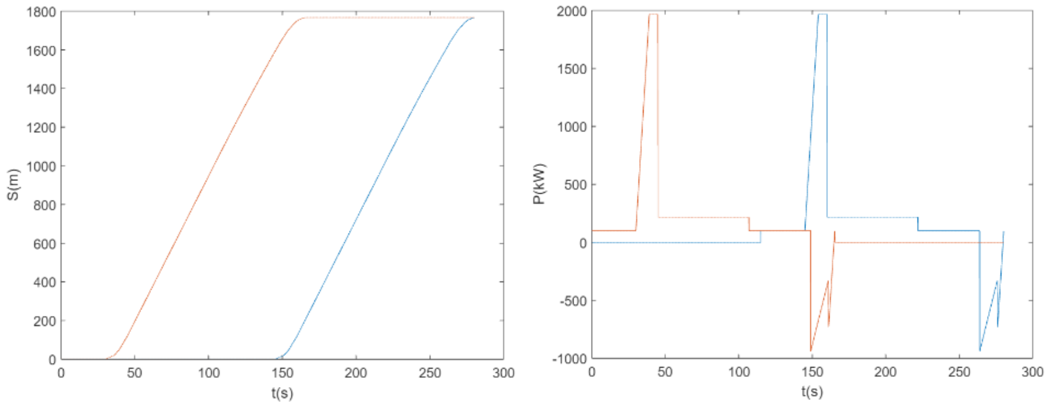

Figure 7: Location-time curve and power-time curve of the trains in the analysis.

4 Conclusions and Contributions

In this paper, a decision-making model is built aiming at evaluating the costs and benefits of different technical modifications to urban rail transport on the energy and capacity aspects. The technical models presented include train energy calculation, indoor comfort, switch heating, and electric infrastructure. Additionally, the economical model provides a framework for quantifying the costs and benefits associated with each solution, taking into account factors such as capital investment, recurring operational costs, and long-term maintenance.

Through two case studies on the Stockholm commuter train X60 and metro train C30, several technical solutions, e.g., optimized train driving, controlling traction motor groups during cruising, adjusting timetabling and installation of energy storage systems, are analysed, which showcase their impacts on train operation, capacity, and energy saving. For the next step, their detailed cost and benefits of implementation will be collected and compared when more cost elements are available as input to the model. The technical models will be validated against measurement data and the cost model will be checked against previous project reports.

Overall, our research provides insights into the challenges and opportunities of the urban rail transport systems in energy efficiency and capacity increase. With the help of the further developed business-case model, transport authorities and train operators can use the model to set up cost-efficient and effective decisions to optimize operations and upgrade the system to reduce energy consumption and increase capacity, which can contribute to building a sustainable and eco-friendly city for everyone to live in.

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References

[1] E. Andersson, M. Berg, S. Stichel, et al. "Rail systems and rail vehicles", text books, 2018. Stockholm: KTH Railway Group. ISBN 978-91-7595-922-1.

[2] Y. Pang, "Optimization of traction energy of Stockholm commuter trains", 2023. TRITA-SCI-GRU 2023:302

[3] J. Liden, "Optimization of comfort-related energy of Stockholm commuter trains", master thesis, 2023. TRITA-ITM-EX 2023:402

[4] S. Sumathi, "Modelling of heat transfer of railway switch heating", 2023. TRITA-ITM-EX 2023:565