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Holistic energy simulation and optimization tool for urban rail vehicles

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A B S T R A C T

A tool for holistic energy simulation and optimization of urban rail vehicles is presented. The modular vehicle model consists of easy to parameterize subsystems. All essential energy consuming subsystems (traction system and auxiliaries) can be considered via models of adequate detail level. Interaction between subsystems is simulated and driven by the operational conditions and internal controllers. Apart from energy signals the tool provides many other time signals, which contain valuable information for the vehicle manufacturer. Different workflow variants of the tool enable a case specific simulation or optimization. Furthermore a superordinated multi-objective mixed-integer optimization (MOMIO) can be applied to optimize the rail vehicle with respect to design parameters and operational conditions. Additionally a Brute-Force-Method (BFM) simulating all possible combinations enables to analyze the sensitivity of objectives (e.g. total energy) with respect to the selected design variables.

1. Introduction

Urban rail vehicles providing public transport services within metropolitan areas include tramways, light rail, metro, and regional or commuter rail vehicles [1]. These vehicles are operated in railway systems with relatively short distance between stations and are electrically powered [2]. Due to their electric drive train and large capacity they are considered as an ideal solution to reduce the impact of urban mobility [1]. However, urban rail is facing increasing pressure to analyze and minimize its energy consumption to reduce operational costs and environmental impact [2]. In that regard rail vehicle manufacturers have to improve the overall design of their vehicles and deliver appropriate warranties on energy consumption already in the bidding phase. However, a multitude of on-board electrical components affecting thermal comfort, possible train trajectories, and energy efficiency exist. Due to the inherent interaction of these components and the associated design variables it is difficult for experts to obtain a satisfying design result for a new train. The design must typically meet contradicting goals (low cost, high efficiency, high thermal comfort, etc.) in the presence of many constraints like travel schedule, comfort parameters, overall weight, etc.

The tool presented here aims at supporting the designer by providing the following features: The overall urban rail vehicle model is modular structured and consists of easy and robust to parameterize validated subsystems. Thereby all essential energy consuming subsystems can be considered via fast executable models of adequate detail level. The interaction between the individual subsystems is simulated in the time domain and driven by the operational and environmental conditions (e.g. passenger load, train speed/position/orientation, brake force, state of the indoor/outdoor air, radiation, etc.). Additionally, state of the art and sophisticated controllers (model predictive controllers) are incorporated in the simulation. Apart from power signals the tool provides a multitude of high resolution output signals. Different workflow variants of the tool enable a user-specific simulation and optimization. Furthermore, a superordinated multi-objective mixed-integer optimization (MOMIO) can be applied to optimize the system with respect to design parameters, and environmental or operational conditions. Additionally, a Brute-Force-Method (BFM) simulating all possible combinations enables to analyze the sensitivity of objectives (e.g. total energy) with respect to the chosen design variables, and environmental or operational conditions. Last but not least, the tool is embedded in a user-friendly graphical user interface (GUI) for robust parametrization and visualization. Note that most of these features have been covered by individual software tools but to the authors knowledge this is the first time that one tool covers all important aspects including a very general optimization.

The need for methods and tools to analyze, simulate and optimize the energy flows in urban rail was already emphasized by the authors in [2–5]. The authors in [6] present a review of hundred and twenty-five simulation tools for modeling and managing electric road vehicle

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energy requirements. Only two tools are reported that can cope with rail vehicles (trams). In [2] the authors use a holistic approach to produce a comprehensive set of key performance indicators (KPIs) for assessing and optimizing the energy consumption in urban rail systems. The authors conclude that energy saving measures will generally have to be evaluated at unit level before their implementation at system level. Given the difficulty and costs involved in testing measures at large scale, this process will normally need the use of simulation programs. Although the tool presented here so far focuses on the vehicle many of those KPIs can be computed by simulation, their sensitivity can be analyzed via the BFM, and optimized by the superordinated MOMIO.

In metropolises where urban rail is not developing further it may lose its position at the forefront of economic and sustainable solutions for urban mobility [7], since new individual electrical transportation modes are arising and improving by intensive research. In [8] a multi-sources e-scooter including energy management system (EMS) for Asian metropolises is presented. The authors of [9] use traffic preview information to optimize the speed trajectory of hybrid automotive vehicles. Such eco-driving techniques are also of great concern for rail vehicles, leading to significant energy savings. Therefore, the presented tool incorporates the validated train trajectory optimizer (TTO) developed in [10]. Fathabadi [11] proposes a fuel cell and super-capacitor hybrid power source to be utilized in hybrid electric automotive vehicles. Ahmadi et al. [12] develop an EMS for a hybrid (fuel-cell, battery, ultra-capacitor) electric automotive vehicle. Itani et al. [13] compare two hybrid energy storage systems (ESSs) (primary: Li-Ion battery, secondary: ultracapacitor/flywheel) for a hybrid electric car during start-up and regenerative braking. Such hybrid power sources with a suitable EMS are also increasingly investigated and used for urban rail to store recuperation energy, reduce power peaks, and enable catenary free operation [14,15]. Duan et al. [16] present a calibration method for an EMS of a hybrid electric car to optimize its control parameters with respect to multiple objectives. Also the superordinated MOMIO of this work can be utilized to optimize the parameters of subordinated controllers. The authors in [17] show a thorough analysis of braking energy dispatch in the urban traction power supply system. One investigated strategy was to raise the power of heaters during regenerative braking and reduce it while driving. The study in [18] presents an advanced EMS that couples traction and heating functions of an hybrid electric vehicle. In this work, the presented tool incorporates a mixed-integer predictive hierarchical HVAC controller which can be tuned to optimally use regenerative braking energy and obtain high passenger comfort.

The great benefit of an electric drive train beside its inherent efficiency is recuperative braking. Itani et al. [19] compare two braking methods for an automotive electric vehicle. Lv et al. [20] and Qiu and Wang [21] investigate regenerative braking of electric automotive vehicles on efficiency and driving range improvement. Due to higher mass, connection to an electric grid, and many on-board electric auxiliaries the possible benefit of regenerative braking is higher in a train than for plug-in electric automotive vehicles.

ESSs and optimal EMS are also of great concern for renewable energy sources applications (efficiency improvement and voltage stabilization). Important application examples of such concepts are ESS and EMS for wind farms using super-capacitors or flywheels for energy storage. Integration of a super-capacitor ESS into an alternative wind farm including fault detection is discussed in [22–24]. In [25] a hybrid flow-battery super capacitor ESS is studied, which is coupled in a wind turbine generator to smooth wind power including an EMS. A stand-alone hybrid power generation system of a wind turbine is presented in [26], where an EMS acts as a supervisory controller for micro-turbine, solar array, and battery storage. In [27] a flywheel based ESS for a wind farm is presented. However, flywheels present a number of drawbacks that hinder their extensive use in railway applications [4] (i.e. high weight, losses due to internal friction produced by vehicle movements, negative effects on driving dynamics, and especially safety issues).

A thorough analysis of the energy flows and possible measures to improve efficiency in urban rail systems and different railway networks is given in [3,5], respectively. In [4] the authors focus on a comprehensive overview of the currently available strategies and technologies for recovery and management of braking energy in urban rail, covering timetable optimization, on-board and way-side ESSs and reversible substations. In this work a battery model which specifically addresses the pulse power charging/discharging possibility of traction batteries was developed and included to the holistic energy simulation and optimization tool. Although the presented tool focuses on the systems of the vehicle the interaction with reversible sub-stations/way-side ESSs can be simulated given the time and distance dependent receptivity and efficiency as environmental influences.

In [28] the optimal sizing of ESSs to save regenerative braking energy in a metro line is based on the predicted maximum instantaneous regenerative energy. Although the tool of this work focuses on the rail vehicle, it can help to minimize transmission losses by determining the optimal positions of way-side ESSs along the line. In case of multiple power sources an EMS is required to optimize operation. The authors in [29] focus on the performance evaluation of meta-heuristics to deal with power management of a dual ESS for electric vehicles. Both, Fernandez et al. [14] and Zhang et al. [15] test a hybrid tram composed by a fuel cell and different on-board ESSs for catenary free operation. An EMS is proposed to optimize power consumption. Also the holistic tool of this work comprises an EMS optimizing the power flow to the supply grid (receptivity and efficiency), on-board ESS, auxiliaries, and brake resistor and can be used to test catenary free operation.

The authors in [30] develop an electric train energy consumption modeling framework considering instantaneous regenerative braking efficiency. However, the model does not consider internal engine data. This work not only considers the operating point dependent power losses of the traction components given by validated static lookup tables, but also allows to optimize the possible reuse of regenerative braking energy. Furthermore, the built in TTO enables energy-efficient driving and can be used to optimize a dedicated speed profile. Frilli et al. [31] develop a model for the interactions between the motion of a high-speed train and the electrical line in case of regenerative braking. A constant power consumption of the train's auxiliary systems was assumed. However, for urban rail power consumption of the auxiliaries can rise up to about 35 % of the total energy entering the rolling stock [32,33]. In this work power consumption for the components of the traction system but also for the main auxiliary systems is obtained as time signal.

The remainder of this paper is structured as follows: In Section 2 the system component models are stated. In Section 3 the incorporated controllers and optimization methods are explained. In Section 4 the workflow variants and the graphical user interface (GUI) of the holistic tool are presented. Section 5 gives a glimpse to the multitude of possible simulations and optimizations. Section 6 gives a discussion. Section 7 gives a conclusion.

2. System component models

2.1. System overview DC operated rail vehicle

Fig. 1 shows a schematic illustration of a fully equipped rail vehicle operating on a DC net. Subsystems, environmental influences, and the main interdependencies are depicted as blocks and arrows, respectively. The presented holistic energy simulation and optimization tool for train trips considers all these blocks and arrows via dynamic models, characteristic diagrams, controllers, and simulation-based optimization methods. Note that the overall state vector $\boldsymbol{x}$ of the vehicle model is composed of the individual staked state vectors $\boldsymbol{x}_i$ of the submodels.