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Energy Saving Potential of a Battery-Assisted Fleet of Trolley Buses ⋆

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Abstract: This article investigates the opportunities of integrating battery-assisted trolley buses into a given trolley bus network in public transportation. In this new generation of vehicles, the diesel-powered auxiliary unit is replaced with a high-performance traction battery. On the one hand, the new vehicles can be operated without the overhead wire, while on the other hand the battery capacity improves the overall system efficiency. The energy saving potential is identified via simulation of a realistic trolley bus line including the optimization of the energy management strategy. The problem is formulated as a convex optimal control problem. The results show that up to 20% of energy can be saved, compared to the case with conventional trolley buses only.

Keywords: Trolley bus, convex optimization, energy efficiency, public transportation.

1. INTRODUCTION

One of the main problems of todays transportation vehicles in terms of energy efficiency and pollutant emissions is the lack of environmentally friendly energy storage systems with high energy density. Although the storage capacity of commercially available electric batteries has been reduplicated every ten years within the last decades, the specific energy of automotive batteries is still very low compared to the specific energy of liquid fuels, e.g. hydrogen or fossil fuels. The lower heating values of gasoline and diesel fuel are in the region of $12\,\mathrm{kWh/kg}$, whereas state-of-the-art lithium batteries for automotive applications achieve only a specific energy of $150\,\mathrm{Wh/kg}$. Even when a low average tank-to-wheel efficiency of $10\,\%$ and a high battery-to-wheel efficiency of $100\,\%$ are assumed, the specific energy of the combustion engine based systems is approximately 10 times higher compared to an electric powertrain.

Traditional trolley bus systems provide locally emission-free transportation while avoiding the energy storage problem. As a downside, standard trolley buses require an overhead contact wire network that is expensive to build and maintain and not easily expandable.

The idea behind the battery-assisted trolley bus is to recover the flexibility of driving outside of the overhead wire network for short distances without carrying a large and heavy energy storage system. In particular, the emergency engine-generator unit of a conventional trolley bus is replaced by a traction battery of approximately the same size and weight. With this design choice the new generation of vehicles can regenerate and store braking energy for future use independently of the grid's absorption capacity.

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Opposed to that, the engine-generator unit of a standard trolley bus is only "dead weight" during normal operation.

Trolley bus grids are operated on $680\,\mathrm{V}$ DC. Due to the electric resistance of the contact wires, the grid is divided into electrically decoupled grid sectors of approximately 1.5 kilometer length. Each sector is powered separately by a specific feeding point. Energy transfer from one grid sector to another is not possible. Moreover, the feeding points cannot absorb energy. This limitation implies that energy can only be transferred if it is consumed within the same grid sector at the same time. Considering a bus fleet of traditional trolley buses, the regenerated braking energy can therefore not be absorbed completely and hence must be dissipated in the braking resistors of the buses. Using sufficiently sized batteries to store this "free" energy, the limitation of the grid becomes irrelevant.

In the new battery-assisted trolley buses, the possibility to provide or absorb energy to or from the DC-link represents an additional degree of freedom. Therefore, the battery-assisted buses require an energy management during operation to control the battery power and the battery state-of-charge. An important observation is the fact that the energy management strategy has a significant influence on the energy efficiency of the vehicle and on the overall system. In order to obtain comparable results, the disturbing influence of a possibly sub-optimal energy management should be excluded. Even though the global optimal solution is non-causal and can therefore not be implemented on the real vehicle, it serves as a means to evaluate the best possible energy saving potential. The obtained results provide insights that are useful in the design phase and a benchmark for causal controllers to be implemented on the real vehicles. As a consequence, heuristic methods or methods derived from Pontryagin's minimum principle, as described in Geering (2007), are not applicable. Optimality is only guaranteed by more

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sophisticated numerical solvers that are based on optimal control theory, such as dynamic programming described by Bellman (1957) and Bertsekas (2005), and convex programming proposed by Boyd and Vandenberghe (2009). Since dynamic programming suffers the so-called "curse of dimensionality", it is not applicable to large problems such as the given potential study. Convex programming requires the problem to be formulated in terms of convex constraints. The optimization is then usually conducted via dedicated numerical solvers that are extremely fast and reliable. The problem presented in this study can be written in convex form with reasonable approximation and is thus solved using convex programming.

The potential study is organized as follows. In section 2, the problem is described. In section 3, the mathematical models of the grid and the vehicles are presented. In section 4, the problem is depicted as a convex program. In section 5, we present and discuss the results, and in section 6, we state our conclusions.

2. PROBLEM DESCRIPTION

The goal of this study is to identify and evaluate the maximum possible energy saving that can be achieved using battery-assisted trolley buses. Therefore, all possible bus fleet configurations consisting of all possible combinations of conventional and battery-assisted trolley buses are considered. Thereby the total number of buses serving the bus line is kept constant. The objective of each simulation is to find the global minimum of the total energy consumption of the bus fleet. The obtained solutions will be compared and discussed, subsequently.

The simulations in this study are based on the trolley bus line 46 of Zurich, Switzerland. As illustrated in Fig. 1, the electric grid is divided into five decoupled grid sectors with approximately equal length of 1.5 km. The grid sectors are arbitrarily chosen. The run from Zurich HB (main station) to the terminal station Rütihof and back to Zurich HB

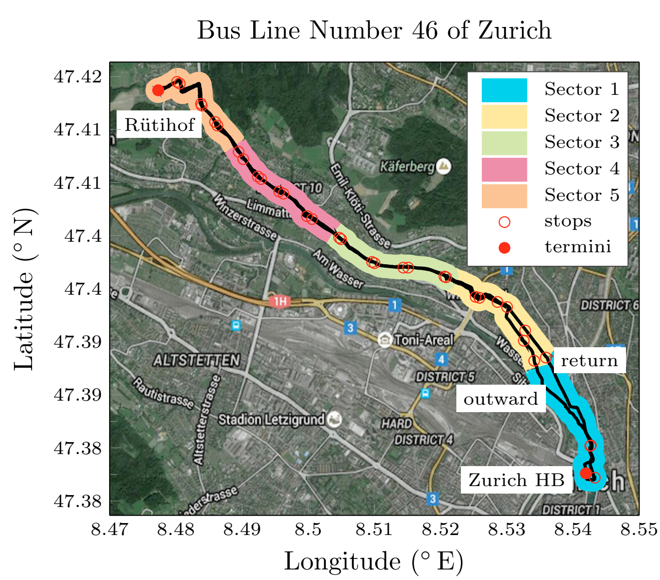

Fig. 1. Outward run and return run of bus line 46 in Zurich, Switzerland. The red dots denote the bus stops. The colors indicate the different grid sectors. The map is taken from Google.

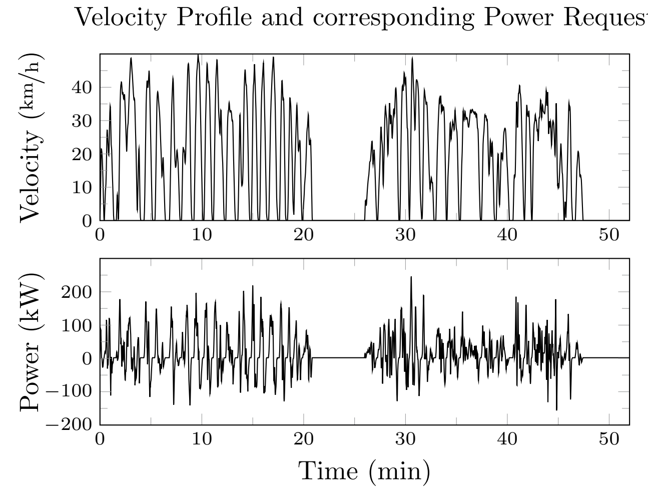

Fig. 2. Logged velocity profile and power request calculated according to section 3.7.

has a total length of 14.7 kilometers. The position and velocity data is obtained with a GPS logger while traveling with a regular trolley bus of the chosen bus line during a non-busy period. In accordance with the corresponding timetable, the simulation consists of seven trolley buses that are running simultaneously on the bus line. The bus stops and termini are obtained from a regular road map of Zurich's public transportation provider VBZ. The altitude profile is neglected by assuming that the buses are running on a flat road.

The logged velocity profile is shown in Fig. 2. Each bus departs with a time interval of alternately seven or eight minutes to the preceding bus and follows the exact same velocity profile. As the simulation depicts a typical situation during the day, all buses start at the same time at different locations on the bus line, where the initial locations are determined by the time intervals.

3. MODELING

The optimization problem comprises the model of the grid and the models of the buses, respectively, which describe the energy flows and losses in the system. For vehicles with pure electric propulsion systems the corresponding equations describing the energy conservation and energy losses can be formulated as a set of convex constraints.

The general method to solve such time-based optimization problems with convex programming is to formulate the power balances for each point in time (point in discrete time vector) separately and then collect and augment them with global constraints, as first introduced by Tate and Boyd (1998). For each point in time, the energy balances as well as the system dynamics and the system's limits are represented by a set of convex constraints, where the time dependency is usually neglected and the equations are formulated as functions of the disturbances. This approach keeps the problem description in a clear form similar to other optimization techniques such as dynamic programming or Pontryagin's minimum principle.

The velocity profiles of the buses are assumed to be perfectly known in advance. Consequently, they are not subject to the optimization, but are included in the constraints