sccer mobility
Swiss Competence Center for Energy Research
Efficient Technologies and Systems for Mobility

Supported by:
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Innosuisse – Swiss Innovation Agency

# Predictive Energy Management for «SwissTrolley plus»

«SwissTrolley plus» is a collaboration project between the industry partners Carosserie HESS AG and VBZ, and the research institutions Bern University of Applied Sciences (BFH) and ETH Zurich. The research project deals with a trolley bus prototype, featuring a novel traction system with a battery serving as a buffer for electrical energy. This buffer on the one hand allows for the recuperation of braking energy, thereby improving system efficiency. On the other hand, it makes grid-free operation of the bus possible for prolonged distances, enabling the extension of existing bus routes without the need for expensive infrastructure. Additionally, overhead wires on heavily frequented crossings could be removed and maintenance costs for the grid operator thereby drastically lowered. ETH's project contribution is the development of the intelligent energy management software .

Andreas Ritter, anritter@idsc.mavt.ethz.ch
Fabio Widmer, fawidmer@idsc.mavt.ethz.ch
Cary Müller, mullerc@student.ethz.ch
Prof. Dr. Christopher Onder, onder@idsc.mavt.ethz.ch
ETH Zürich, Institute for Dynamic Systems and Control (IDSC)

## Introduction and Motivation

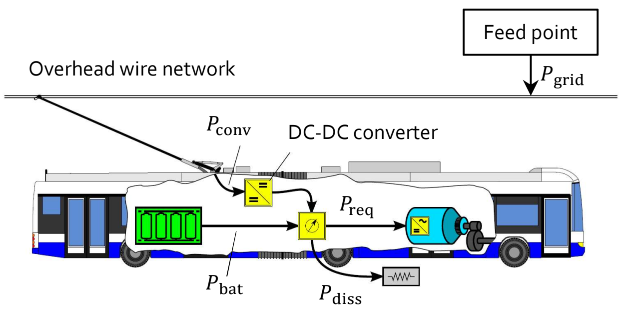


Fig. 1: Powertrain of the «SwissTrolley plus»

The prototype's novel drivetrain architecture (see fig. 1) introduces a degree of freedom in fulfilling the current power request $P_{req}$. This so-called power split can be used by an intelligent energy management system (EMS) to optimize overall system efficiency, i.e., to minimize the energy fed into the grid ($P_{grid}$ in fig. 1). This is equivalent to minimizing the losses in the electrical path. These are predominantly arising in the grid, the DC-DC converter, and in the battery. As the battery efficiency is typically higher than the efficiency of the grid and the converter, an optimal energy management will predominantly use the battery to deal with short-term power variations, while using the grid to constantly recharge the battery, thus avoiding high grid power peaks. In addition, the EMS must always keep the battery state of energy (SOE) high enough to allow grid-free operation, but low enough to allow the battery to absorb all the recuperated braking energy.

## Learning and Predicting

The software on the bus is constantly learning about its environment by incrementally building the so-called road map. It does so by adding nodes and edges to construct a directed graph (see fig. 2) [1]. The nodes of this graph can store and combine data from multiple trips. The value of the signals can be retrieved for predicting upcoming driving conditions, most importantly the altitude and velocity profile. The learning process is unsupervised and has been implemented and tested on the prototype.

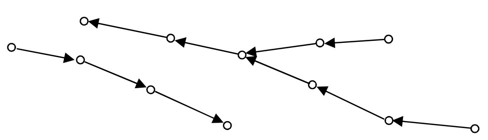

Fig. 2: Schematic depiction of the directed graph representing the road map. The nodes (circles) are connected by edges (arrows).

## Energy Management Strategies

Multiple EMS have been developed so far. Fig. 3 to 5 show a performance comparison of the different EMS, which are presented in the following. The optimal non-causal offline solution serves as a benchmark.

- The "Backup-EMS" is a heuristic strategy that is implemented by HESS on the central control unit of the bus. It serves as a fallback solution for the more sophisticated strategies.
- The "adaptive equivalent consumption minimization strategy" (A-ECMS) is a simple, non-predictive online-controller based on optimal control theory, adapted from [2].
- The model predictive control (MPC) approach uses the (imperfect) predictions from the road map on a receding horizon to generate a reference SOE trajectory, which is then tracked by an ECMS-based online controller.

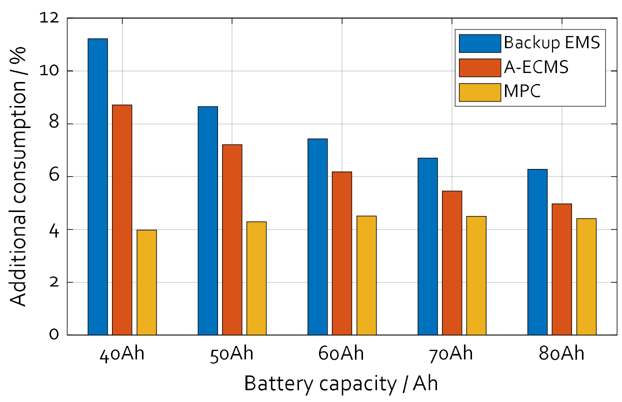


Fig. 3: Simulated additional energy consumption (with respect to the optimal solution) using the different EMS. The differences are more significant with smaller battery sizes, as in this case the energy management task gets more challenging and predictive information is thus more valuable.

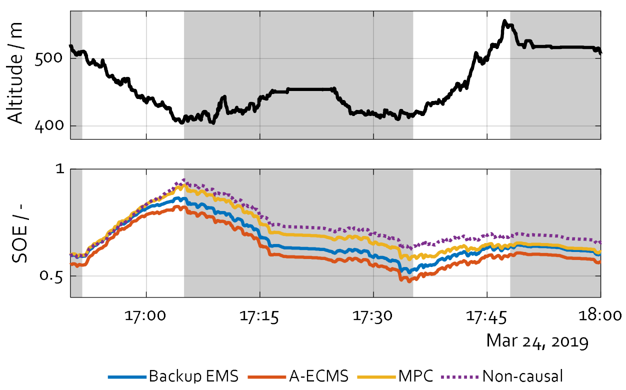


Fig. 4: Resulting SOE trajectories using different EMS and the non-causal solution. The sections shaded in grey correspond to grid-free operation.

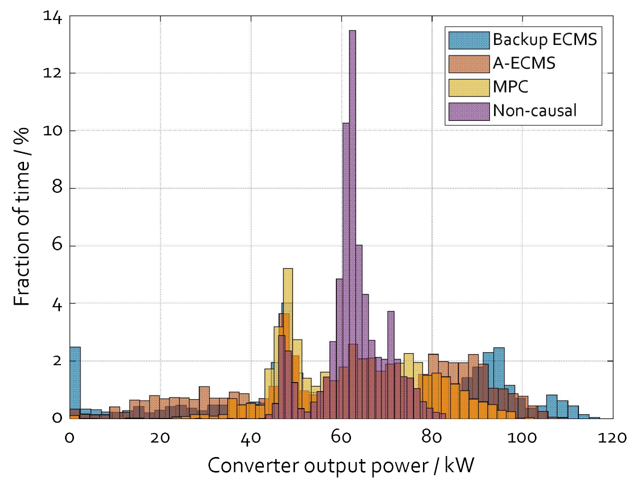


Fig. 5: Converter output power histograms. The more sophisticated the EMS, the more constant the grid load and thus the lower the ohmic losses in the grid.

## Expected Impact

A 15 % reduction in energy consumption, compared to state-of-the-art trolley buses, could be shown in a field study [3]. The savings are mainly due to the increased amount of recuperated braking energy. The already implemented A-ECMS controller can reduce the energy fed into the overhead grid by an additional 1-2 %. Simulation studies show the great potential of a predictive EMS, especially with the use of smaller batteries: In this case, a predictive EMS can reduce the overall energy consumption by an additional 5 % (see fig. 3). Similar results are expected on bus routes with more pronounced altitude profiles. The developed MPC algorithms have been validated in software-in-the-loop tests and are now being implemented on the bus.

## References

[1] A. Ritter, F. Widmer, J. Wei Niam, P. Elbert, and C. H. Onder, "Probabilistic Predictions of Spatio-Temporal Data in Vehicular Applications," unpublished.

[2] C. Musardo, G. Rizzoni, Y. Guezennec, B. Staccia, "A-ECMS: An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management," *European Journal of Control*, vol. 11, pp. 509-524, 2005

[3] A. Ritter, A. Santis, M. Widmer et. al., "SwissTrolley plus," Swiss Federal Office of Energy (SFOE), Final Project Report, unpublished.

## Partners

ETH Eidgenössische Technische Hochschule Zürich, Swiss Federal Institute of Technology Zurich
IDSC Institute for Dynamic Systems and Control
Bern University of Applied Sciences
HESS
VBZ Züri Linie
Schweizerische Eidgenossenschaft, Confédération suisse, Confederazione Svizzera, Confederaziun svizra
Bundesamt für Energie BFE, Swiss Federal Office of Energy SFOE