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Modular energy concept for last mile operation in single-wagon freight transport

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Abstract

The objective of this paper is to investigate the feasibility of integrating interchangeable power supply modules for self-propelled single wagons. For this purpose, 27 last mile operation are identified by collecting track data from sidings to the nearest marshalling yards, clustered in terms of length, elevation and speed. On this basis, the energy demands for each scenario is simulated to design a modular energy concept, with the focus to interchangeable modules in a flexible packaging concept. The investigations presented in the paper show that a modular energy storage concept for single-wagon transport is feasible to fulfil the diversity of requirements for the identified last mile operation scenarios. The developed concept is presented in a 1:25 demonstrator including a graphical user interface.

Keywords: single wagon, modular energy concept, battery and fuel-cell, railway transport.

1 Introduction

Major efforts have to be made in all sectors to reach the GHG reduction targets embedded in the European Green Deal. The transport sector was in 2018 responsible for 286.8 MTOE of final energy demand (30.5%) or 957.3 million t CO2-eq. (24.6%) in the European Union. Road transport was proportionally responsible for 71.8% of GHG emissions from the transport sector in the same year (38.4% trucks and buses). The share of GHG emissions in rail transport was 0.4% in the same year on a pro rata basis (excluding emissions from electricity), with an average share of rail freight transports modal split of 17.9% (in tkm) [1]. One contribution to the decarbonization target can be the modal shift to already electrified rail. However, rail freight - especially single-wagon transport - is currently not competitive with trucks since conventional methods such as shunting processes for train formation and last-mile transports to the siding are time- and cost-intensive. In addition, flexibility is not given due to the manual processes for train formation, which is why all processes must be planned with certain lead times [2]. Improved performance could be achieved through new vehicle concepts, making rail freight more attractive and flexible and reducing GHG emissions to net-zero in last-mile operations on non-electrified routes. There are already approaches to support rail freight's competitiveness such as projects by Russian Railways, EURO CAREX, Mercitalia Fast and other projects planned for time-sensitive goods [3] which are aimed to increase the overall operating speed of block trains.

Our approach is the electrification of single wagons, which can increase flexibility in single-wagon transport through self-propelled, autonomous operation. By enabling automatic train formation and siding connections through these wagons, shunting and mainline locomotives can be eliminated, resulting in time and cost savings.

The objective here is to investigate the feasibility of integrating interchangeable power supply modules for self-propelled single wagons. For this purpose, the range requirements for last mile operation are identified by collecting track data from sidings to the nearest marshalling yards, clustered in terms of length, elevation and speed. On this basis, the energy demands for each route are simulated to dimension the energy supply. The focus is on the definition of interchangeable modules in a flexible packaging concept, which includes the electrical components, such as energy storage, energy converters and power electronics. The developed concept is presented in a 1:25 demonstrator including a graphical user interface.

2 Methods

The first step in the design of the generic power supply modules was the definition of the operational boundary conditions of the single wagons. These include a maximum speed of 100 km/h and a general basic operation, which contains a 30-minute uncoupling at the marshalling yard, an unloading duration at the freight center of 60 min and a coupling duration after return to the marshalling yard of 30 min.

In a further step, operational scenarios relevant to Germany as a whole were identified for single-wagon transport. For this purpose, the last mile scenarios were defined as the shortest route between freight centers and the nearest marshalling yards in Germany. These scenarios were assumed to be representative because the freight hubs have high freight turnover rates, are located near transportation hubs and often have terminals for combined transport and include multiple companies (e.g., Amazon, DHL, etc.). The selected scenarios were analyzed, evaluated, and clustered with respect to their route length, topographical features, route maximum speeds, and energy requirements.

Based on the evaluation of the scenarios it was possible to proceed to the detailed elaboration of the modular energy supply concept. The modularity of the power supply enables flexible ranges for last mile operations or higher speeds for single wagons, depending on requirements. For this purpose, energy and traction components suitable for rail vehicles and available on the market for single wagons were selected with regard to the initial estimation of energy requirements. The space to accommodate the components was defined as the space available between the bogies.

Then, longitudinal dynamics simulation was used to calculate the feasible trajectory in all-out driving mode depending on the scenario and selected battery storage configuration. All calculations and simulations were performed using the models developed at the DLR institute of vehicle concepts cf. [4], [5]. Afterwards, the specific packaging in the available installation space and an arrangement of the selected components was carried out. The result of the modular energy concept for a single-wagon is shown in a 1:25 demonstrator.

The procedure and methodology used for the design of the generic power supply modules for the single-wagon concept is illustrated in Figure 1.

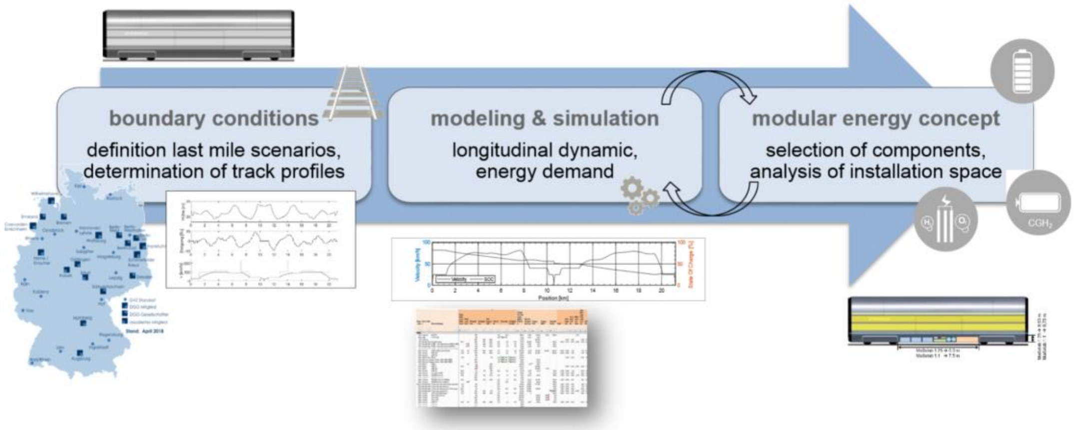

Figure 1: Methodology for the development of the modular energy concept.

3 Results

27 scenarios were identified throughout Germany in which the single wagon with generic energy supply concept can be used. The mapped route (left) and the route elevation profile, speed and pre-estimated required energy (right) are plotted for an example scenario analysis shown in Figure 2.

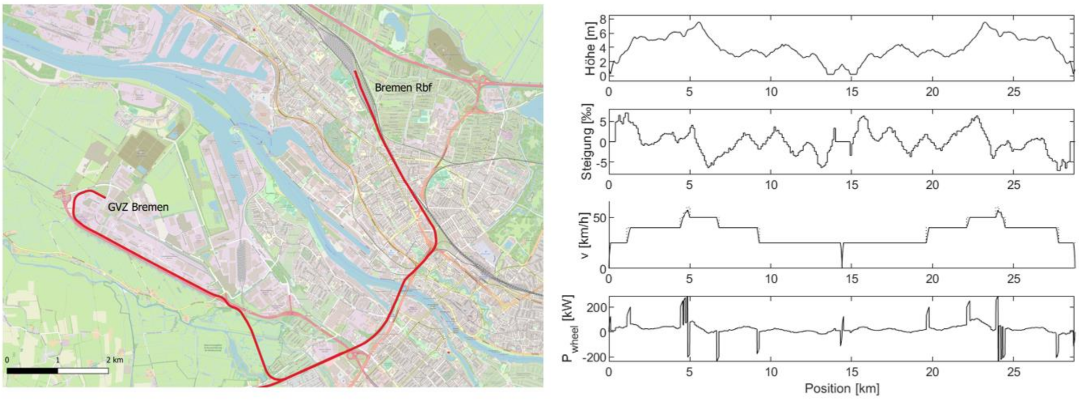

Figure 2: Exemplary scenario analysis.

Similar to the example shown in Figure 2, the considerations were carried out for all of the defined scenarios. Afterwards, the route-specific characteristics were statistically analyzed. 66.6% of the scenarios have a route cycle length of < 25 km. The arithmetic average is 20.4 km. It was found that the gradient has only a very small influence in the scenarios. The estimated energy requirements are < 39 kWh for 75% and < 6 kWh for 50% of the scenarios (Figure 3). The arithmetic average of the specific energy demand is 1.1 kWh/km.

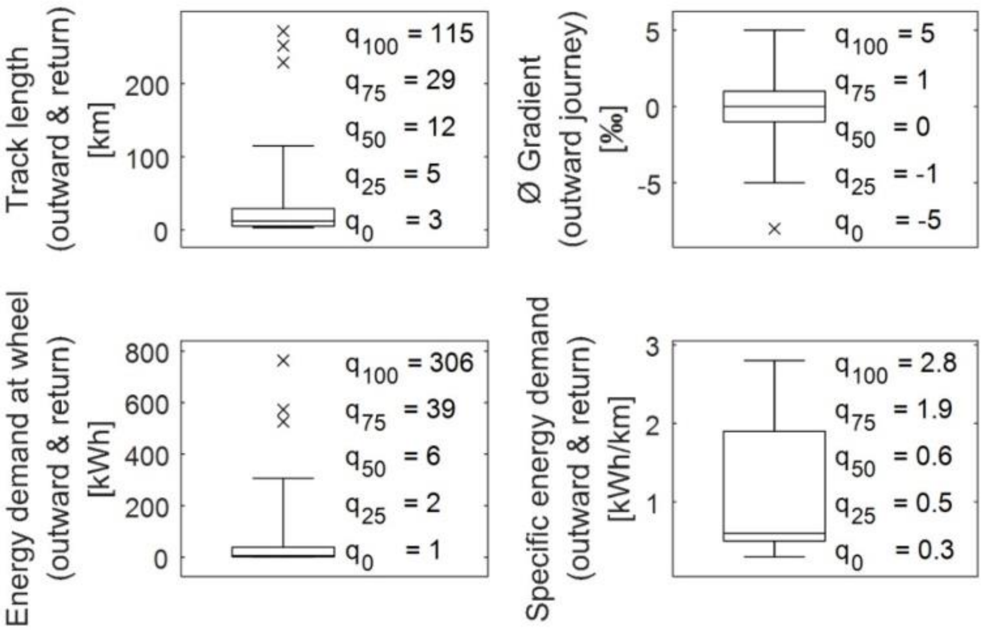

Figure 3: Statistical analysis of all scenarios.

Modular energy concept

Based on the scenario-specific requirements for the energy supply system and the estimated energy demands, the generic modular energy supply concept was developed and its suitability was investigated.

The Modular Energy and Power System (MEPS) was initially predefined in three versions (Light, Basic, Extended). They contain one, two or three battery branches, respectively, and are designed as pure battery electric multiple units. The corresponding depth of discharge of the scenarios for different MEPS designs is shown in Figure 4. In addition to the batteries, all MEPS versions include a battery thermal management system (BTMS) and a power electronics box (PEB).

A maximum of four energy storage units could be accommodated in the available installation space. However, since not all scenarios could be covered with four battery branches while maintaining a tolerable depth of discharge, an additional 4th MEPS variant (Edge) was defined. This includes three energy storage units as well as an additional fuel cell module, which includes a 90 kW fuel cell system and hydrogen tanks (7.2 kg hydrogen in total).

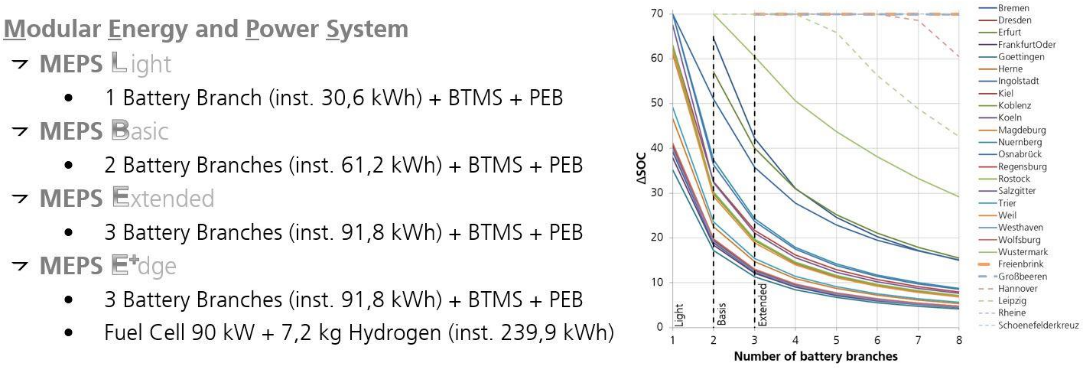

Figure 4: MEPS specifications and depths of discharge per scenario.

1:25 Demonstrator

A 3-D CAD model was created to visualize the developed concept of the single-wagon with the generic modular energy supply. The components of the MEPS are housed between the bogies of the double-deck single wagon (Figure 5).

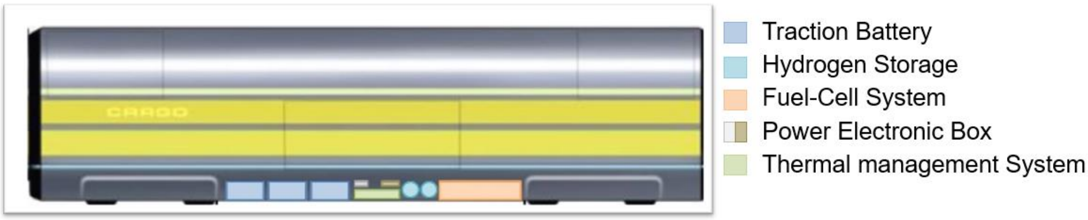

Figure 5: Concept of the single-wagon.

4 Conclusions and Contributions

The investigations show that a modular energy storage concept for single-wagon transport is feasible to fulfil the diversity of requirements for the identified last mile operation scenarios. The results can be used as a basis for further investigations in the field of automated last mile transport on rail and thus contribute to increasing the flexibility and acceptance of the entire rail freight transport as well as to reducing GHG emissions through the decarbonization of last mile transport.

Specific application scenarios were identified and evaluated for which an autonomously driving single wagon with its own energy supply is applicable. A statistical analysis of these scenarios determined the range of requirements for the single-wagon operation. In combination with the longitudinal simulation and energetic evaluation of these scenarios, the systematics of a modular energy concept was developed. Based on this systematics, the interchangeable modules as well as their suitability in a flexible packaging concept for use in the single wagon could be investigated and defined.

In the MEPS Light configuration, 18 of the 27 considered scenarios could be operated, representing 67%. With the MEPS Basic option, 78% of the scenarios can be fulfilled. 92.5% of the scenarios are possible to operate by the MEPS Extended variant. Two scenarios (7.5%) are longer than 100 km and require the MEPS Edge variant with the additional fuel cell module.

To demonstrate the modular energy concept of the single wagon, an interactive demonstrator was set up on a scale of 1:25 (Figure 6, top). A drawer-system between the bogies enables the selection of the different energy storage configurations. In addition, a user interface was programmed in Python to visualize the different scenarios as well as the corresponding trajectories and energy requirements depending on the chosen energy storage configuration (Figure 6, bottom).

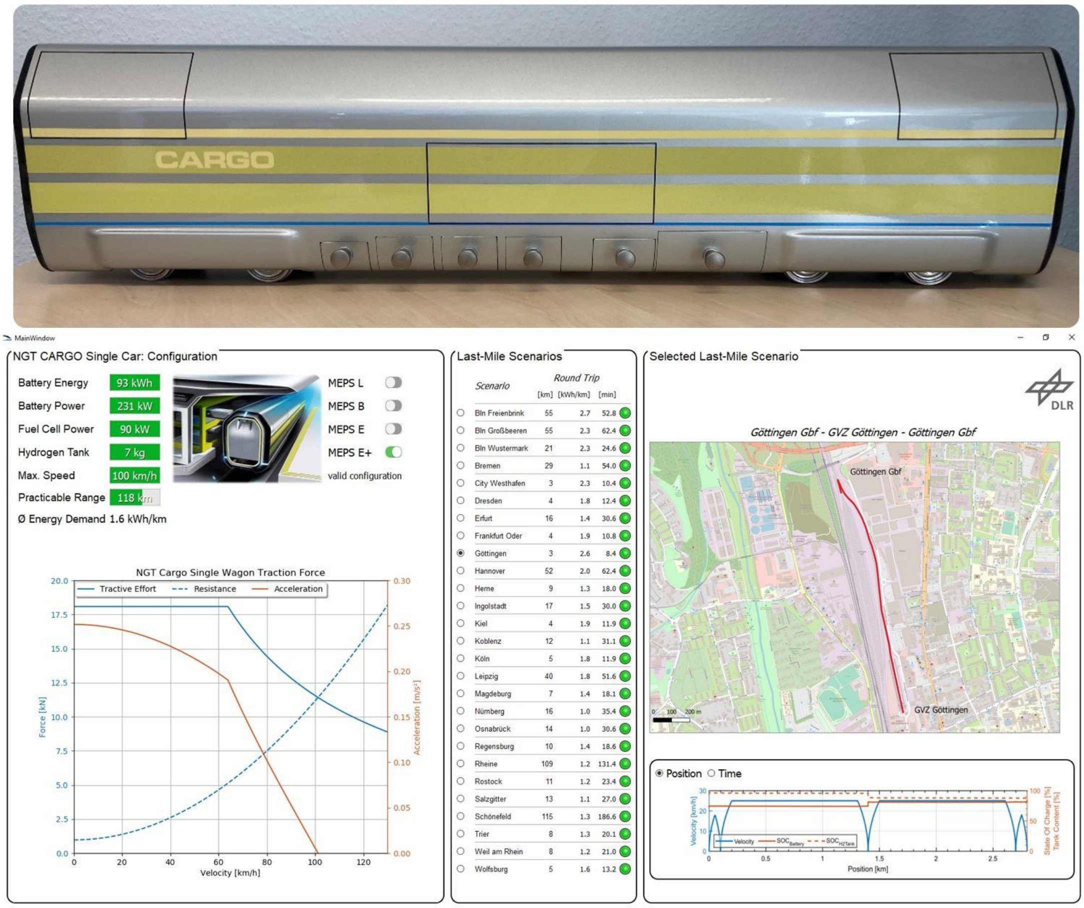

Figure 6: 1:25 Demonstrator (top) and graphical-user-interface (bottom) of the single-wagon modular energy concept

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