Alternative powertrains for shunting locomotives – analysis of feasibility and limitations

Johannes PAGENKOPF[1], Marcel KONRAD[1], Mathias BÖHM[1], Victoria JÄGER[1], Holger DITTUS[1]

[1]German Aerospace Center (DLR), Institute of Vehicle Concepts, Berlin and Stuttgart, Germany
Corresponding Author: Johannes Pagenkopf (Johannes.pagenkopf@dlr.de)

Abstract

Zero-emission powertrain technologies for shunting locomotives are becoming increasingly relevant as potential replacement candidates to diesel operated powertrains. We investigate the feasibility of zero-emission technologies in light of generic operational shunter locomotive profiles and available limited space and mass of a widely in use MaK G 1206 four axle center-cab shunting locomotive. Two generic shunting locomotive operational cycle profiles were defined based on a survey among German shunting locomotive operators: a pure shunting profile and a mixed shunting and mainline service profile. Daily energy demand at DC link level in both scenarios is similar (1,469 and 1,368 kWh respectively), but average power is higher in the mixed mainline/shunting profile. Powertrain candidates were fuel cell hybrid, battery electric, overhead wire battery electric, BiMode overhead battery electric and hydrogen internal combustion engine. Key powertrain component dimensioning for both scenarios is done using a hybridization tool incorporating volumetric and efficiency specifications of state-of-the-art railway components. The fuel cell hydrogen and overhead wire battery electric drivetrains can fulfill the energy and power requirements for the defined operational profiles, whereas the hydrogen internal combustion engine powertrain has limitations due to installation space restrictions in terms of hydrogen storage tanks. Advancements in energy storage technologies might influence the applicability of alternative powertrain systems, not only of hydrogen-based but also of battery-based propulsion systems. Further research and demonstration projects on zero-tailpipe emission shunting locomotives are recommended.

Keywords: Shunting locomotive, alternative powertrains, fuel cell hydrogen, battery

1. Introduction

In shunting locomotives, the highly versatile diesel internal combustion engine (ICE) technology has been standard for decades. In recent years, efforts in industry and academia, primarily aiming at a reduction of fuel consumption and exhaust emissions, have led to a variety of hybridized diesel shunting locomotives both in testing environments and more recently also as 'off-the-shelve'-new built series locomotives. Now, there is increasingly an urgent need for action to cut back climate related greenhouse gas emissions in railway operation to net zero. In this context, it can be observed that zero-emission shunting locomotives are gradually entering the shunting locomotive arena, e.g. [1]. A variety of technology options are emerging, in particular hydrogen (both fuel cell and ICE) and (overhead wire) battery electric locomotives. Also, synthetic and bio-based hydrocarbons and (natural) gas-based fuels for ICE are being developed [2], [3]. Alternative powertrains for shunting locomotives have also in scientific literature been widely discussed, e.g. [3]. Studies have mainly focused each on one particular alternative powertrain technology, mainly on those with hybridized ICE [2]. Recently, scientific and sectoral interest has increasingly been directed to hydrogen powered fuel cells [4], [5]. In our study, we systematically compare a broad range of zero-emission electrified and hydrogen powertrain alternatives to conventional diesel shunting locomotives.

2. Aim and Methodology

The aim of our study is to analyze the applicability of various (near or complete) zero-emission tailpipe powertrain candidates for two characteristic shunting locomotive profiles. The investigated alternative powertrains include fuel cell hybrid (H2FCH), battery electric (BE), overhead wire battery electric (OBE), BiMode overhead battery electric (BiMode-OBE-H2FCH) and hydrogen internal combustion engine (H2ICE). The methodology is as follows: a) Definition of survey-based generic shunting locomotive operational profiles (speed, distance, gross train mass) and their composition to daily operational shunting locomotive scenarios; b) Simulation of power and energy demand at wheel level for a four-axle shunting locomotive; c) Dimensioning and layout of powertrain-specific converter and storage components on the locomotive for the scenarios based on a data set of alternative powertrain components, which have been developed or adapted recently for rolling stock applications; d) Assessment of overall technical feasibility and practicability of the investigated powertrain technologies for the defined operational cycles.

3. Generic driving profiles

We conducted a survey among 188 German railway undertakings (RU), which operate shunting locomotives and collected data with regard to towed masses of hauled wagons and mileage. 16 RU submitted data on mileage and towed mass. Data showed, that 94 % of daily shunting distances covered are below 80 km with a maximum of 2,000 tons towed mass. In mainline operation, which is also performed by some shunting locomotive operators, 95 % of trips are below 300 km daily at a maximum of 2,000 t towed mass (N=12 operators). Based on these data and further RU operating conditions being outcome of the survey such as velocities and operating times we defined four generic operational cycles (Figure 1) as a combination of velocity limits and towed mass representing typical shunting locomotive operations, all on flat level (no gradients).

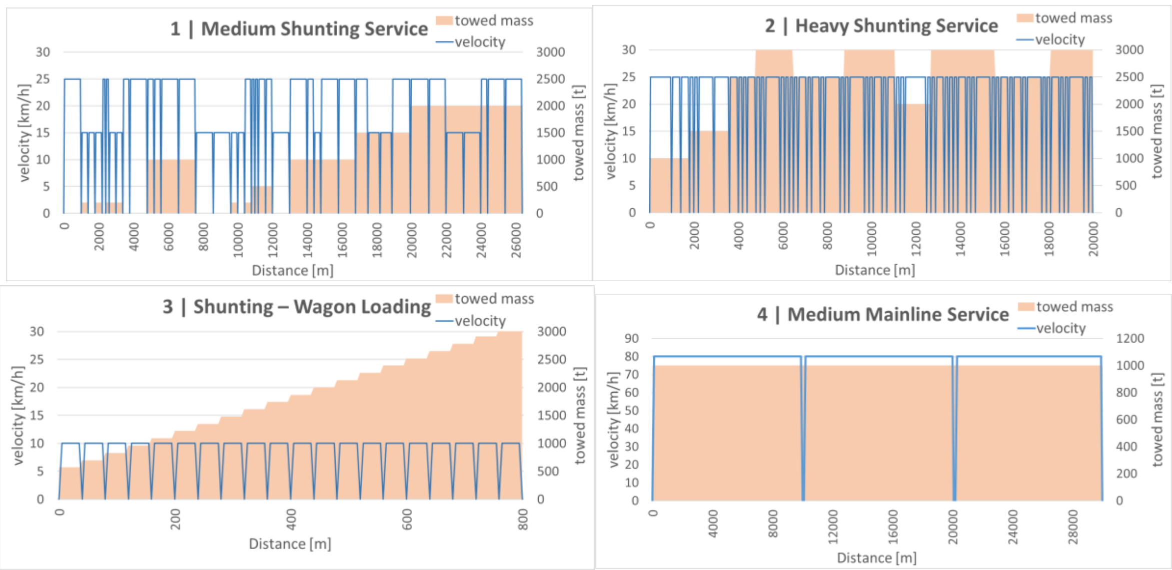


Figure 1: Generic operational shunting locomotive cycles

We then defined two operational scenarios: scenario S (only shunting) and scenario S+M (a mix of shunting and mainline operation) to assign the four operational cycles to them (Table 1). These cycles are used for simulating cumulative energy demand at DC link level. Each Scenario represents one operational day.

	Scenario S (shunting)	Scenario S+M (shunting+mainline)
Generic operational cycles		
1 – medium shunting service	1x	1x
2 – heavy shunting service	2x	-
3 – shunting – wagon loading	-	1x
4 – medium mainline service	-	3x
Trip time [h]	11.3	7.6
Total shunting service [km]	66.3	27.1
Total mainline service [km]		90
Total distance [km]	**66.3**	**117.1**

Table 1: Scenario set-up

4. Results – Dimensioning and layout

4.1 Simulation of power and energy demand

Locomotive mass and running resistance of the reference locomotive are based on the MaK G 1206. The four-axle, 14.7 m long, 87 t (operating mass) center-cab diesel shunting locomotive with hydrodynamic transmission is widely used in Germany. Maximum power at DC link was set to 1,540 kW with a maximum tractive force of 300 kN. With these locomotive data and the respective towed masses and velocities of the operational cycles, longitudinal simulation was performed using the DLR trajectory planner applying an all-out driving style. Simulation yielded a total energy demand at DC link level of 1,469 kWh in scenario S and 1,368 kWh in scenario S+M (Table 2 and Figure 2).

	Scenario S	Scenario S+M
Duration (h)	11.2	7.6
Distance (km)	66.3	116.9
Average velocity (km/h)	5.9	15.1
Energy demand at DC link (kWh)	1,469	1,368

Table 2: Scenario energy demand DC Link

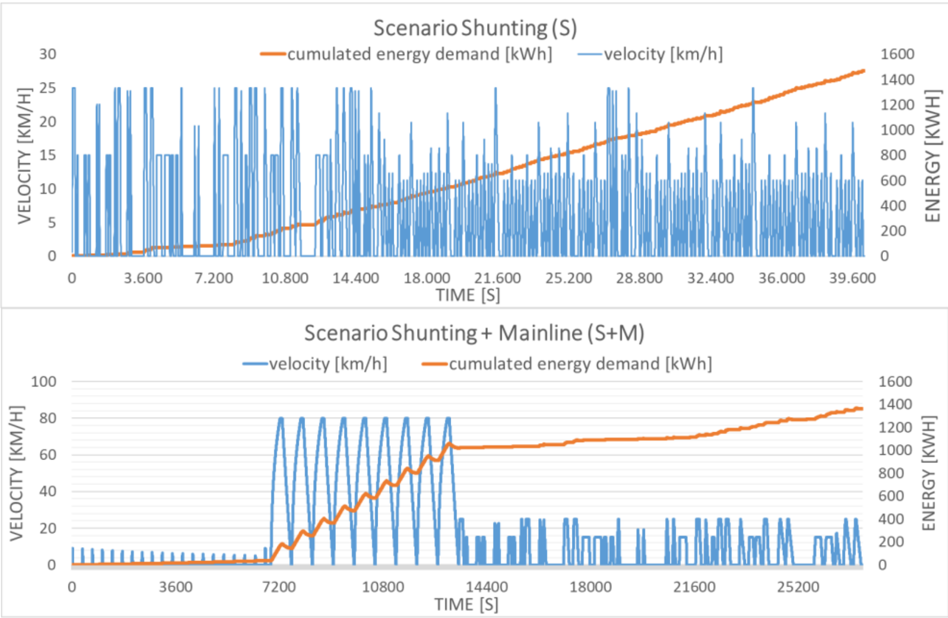


Figure 2: Scenario S (top) and scenario S+M (below); cumulated energy demand at DC link, velocity

4.2 Powertrain dimensioning and layouts

<u>*Powertrain systems:*</u> Powertrain candidates are fuel cell hybrid (H2FCH), battery electric (BE), overhead battery electric (OBE), BiMode overhead battery electric (BiMode-OBE-H2FCH) and hydrogen internal combustion engine (H2ICE).

<u>*Installation space:*</u> We consider the space along the section in front of the central driver's cab and the space between the bogies under the locomotive frame as feasible for the integration of key powertrain components. Other areas will be excluded because their current use for components such as the air compressor and the locomotive control system. Besides space, also mass and axle load limits need to be considered. We found that limits in available space are more an issue than weight limitations.

<u>*Dimensioning:*</u> Dimensioning was done on high-level component level. Included are energy converters (fuel cell, motor converter, DCDC converter), 16.7 Hz transformer, energy storage units (battery, hydrogen tank) and cooling units for batteries, fuel cells and converters. Hydrogen tank capacity and battery capacity (in case of the

battery electric locomotive) are designed for a full day operation. Dimensioning of power level (battery, fuel cell, power converters) and amount of energy stored on-board follows the minimum energy and power requirements respecting max. DoD, C-rates and average efficiency rates. The key components are arranged using characteristic volumetric (and gravimetric) energy and power densities of state-of-the-art railway components (Table 3). Not pictured are traction motors and drives / motor gears, since we assume, that they are installed in the bogies not altering the general space conditions of the locomotive as a whole.

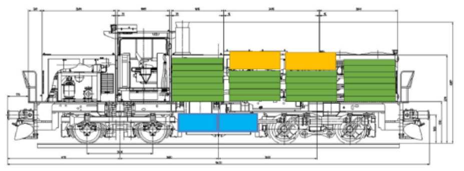
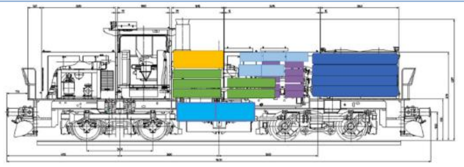
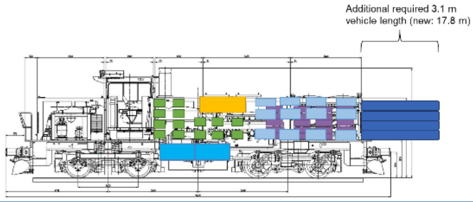
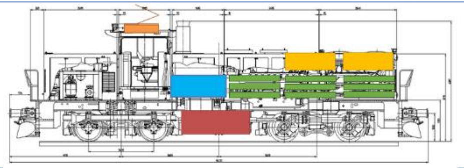
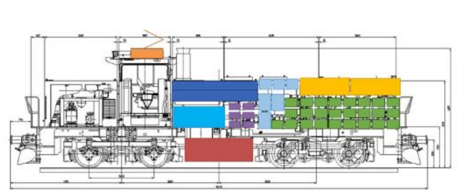
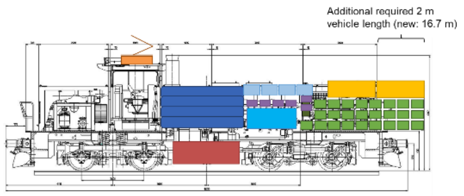
Powertrain concepts and dimensioning of main components	Arrangement (simplified)
Battery electric (BE) - scenario S ➢ HE battery capacity: 1,766 kWh	
Fuel cell hybrid (H2FCH) - scenario S ➢ Fuel cell: 600 kW ➢ HP battery capacity: 146 kWh ➢ H_2 capacity: 109 kg H_2	
Fuel cell hybrid (H2FCH) - scenario S+M ➢ Fuel cell: 1,170 kW ➢ HP battery capacity: 204 kWh ➢ H_2 capacity: 109 kg H_2 (35 MPa CGH_2) *Comment: installation space not sufficient for the scenario*	
Overhead battery electric (OBE) - scenario S+M ➢ HE battery capacity: 662 kWh *66 % of cycle's mainline track equipped with overhead wires*	
BiMode overhead battery electric (BiMode-OBE-H2FCH) - scenario S+M ➢ Fuel cell: 360 kW ➢ HP battery capacity: 375 kWh ➢ H_2 capacity: 54 kg H_2 (35 MPa CGH_2) *66 % of cycle's mainline track equipped with overhead wires*	
BiMode overhead battery electric (BiMode-OBE-H2FCH) - scenario S ➢ Fuel cell: 360 kW ➢ HP battery capacity: 375 kWh ➢ H_2 capacity: 108 kg H_2 (35 MPa CGH_2) *Comment: installation space not sufficient for the scenario (overhead wire cannot be utilized, but 15 kV-equipment requires installation space)*	
Legend Battery; Battery Cooling Unit; Fuel Cell; Fuel Cell Cooling Unit; DC/DC-Converter; Hydrogen storage tanks; Line/Motor & DCDC Converter, incl. Cooling; Transformer; Pantograph and HV-equipment	

Table 3: Dimensioning and layout of key components (background figure: Vossloh Locomotives)
HE: High energy, HP: High Power

The analysis shows, that from the perspective of installation space for the two generic scenarios in the reference locomotive (1) in scenario S, the powertrain candidates BE and H2FCH are feasible, (2) in scenario S+M, OBE and BiMode-OBE-H2FCH are feasible, whereas H2FCH is not, mainly because of high fuel cell power and H_2 storage amount requirements, demanding much installation space. Therefore, additional measures to free up additional installation space are needed for example by using of the side gangways on the locomotive or energy storage tenders. The layout and arrangement of components on the locomotive introduced above, the MaK G 1206, however, does not consider the type of installed power conversion on other existing vehicles. In practice, a retrofit of a hydrodynamic locomotive to electric transmission is closely linked to a couple of specific technical and implementation challenges which are not subject of this paper. Instead, our focus in this paper concerns general installation space issues.

For the H2ICE, we assume a replacement of the diesel engine by a hydrogen ICE (same dimensions as diesel engine). The hydrodynamic transmission and other powertrain components remain unmodified. Since that limits the available space of hydrogen tanks to the mounting position of the diesel storage tanks - which is, both for 35 MPa and 70 MPa CGH_2, not sufficient to fulfil the range requirements for both scenarios (S and S+M). Thus, we propose to install further hydrogen tanks both on the locomotive's left and right gangways allowing for a clear line of sight to the central buffer coupling (Table 4).

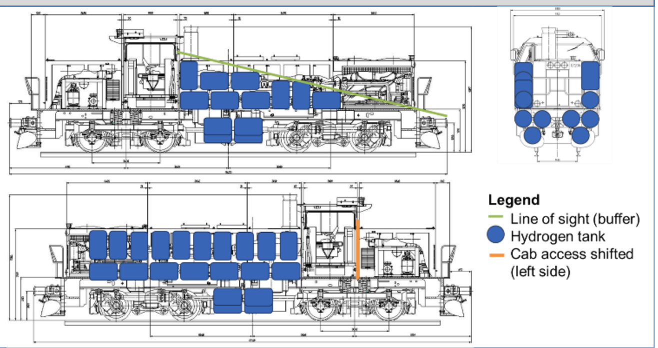
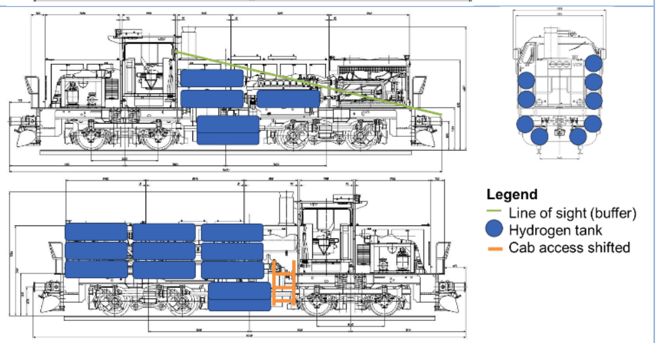
<table>
<tr><th>Powertrain concept and dimensioning of main components</th><th>Arrangement (simplified)</th></tr>
<tr><td>Hydrogen internal combustion engine (H2ICE) – scenario S/S+M
➢ H_2 ICE: 1,500 kW
➢ H_2 capacity: 162 kg H_2 (35 MPa CGH_2)</td><td>
</td></tr>
<tr><td>Hydrogen internal combustion engine (H2ICE) – scenario S/S+M
➢ H_2 ICE: 1,500 kW
➢ H_2 capacity: 272 kg H_2 (70 MPa CGH_2)</td><td>
</td></tr>
</table>

Table 4: Dimensioning and layout of the hydrogen storages of the H2ICE (background figure: Vossloh Locomotives)

In any case, the powertrain technology choice must be aligned with the locomotive's operational profile. Figure 3 matches the analyzed powertrain technologies with the operational profiles and scenarios. The rating matrix ranges from '*full applicability*' (five boxes filled green) to '*minimal applicability*' (one box filled green) and represents a rough orientation framework. The conventional diesel engine drive is included as a benchmark. Of course, Figure 3 shows an assessment image for components available on the market todaa. A step change in applicability of the alternative powertrains might be in reach, once volumetric and gravimetric energy and power densities increase considerably as compared to current state-of-the-art railway-adapted battery, fuel cell and hydrogen storage systems.

Figure 3: Technology fit of powertrain candidates for shunting locomotives operational cycles

5. Conclusion

Our results show that the range of all investigated powertrain options are clearly below the range of incumbent diesel locomotives due to the very high energy density of diesel fuel and the limited available space on the representative locomotive considered here (MaK G 1206). A substantial percentage of shunting locomotives in Germany is operated both in shunting in yards and on mainline tracks and therefore a 15 kV overhead electric powertrain with additional battery or fuel cell hybrid powerpack for shunting operations can be an option in case of a high share of operation under overhead catenary. Our results and the methodology are intended to serve as a decision support for manufacturers and operators of shunting locomotives by providing generalized technology recommendations in terms of zero-emissions technologies.

Acknowledgment

The project was funded by German NOW GmbH which coordinates German federal funding schemes and the electrification technology strategy on behalf of the German Federal Ministry for Digital and Transport.

References

[1] Railvolution, “Paribus Purchases Type DM 20-EBB Locomotives”. https://www.railvolution.net/news/paribus-purchases-type-dm-20-ebb-locomotives, 2021.

[2] Walton, S., “Alternative fuels locomotive in full commercial service”, https://www.railfreight.com/railfreight/2021/02/24/alternative-fuels-loco-in-full-commercial-service/?gdpr=accept, 24.02.2021.

[3] MTU, “E-Fuels powering a climate-neutral future”, https://www.mtu-solutions.com/eu/en/stories/technology/e-fuels-powering-a-climate-neutral-future.html, 14.12.2020.

[4] Falendysh, A.; Kharlamov, P.; Kletska, O.; Volodarets, N., “Calculation of the Parameters of Hybrid Shunting Locomotive“, in Transportation Research Procedia, Volume 14, 2016, pp. 665-671.

[5] Barbosa, F., “Fuel Cell Rail Technology Review: A Tool for an Autonomous Rail Electrifying Strategy“, Proceedings of the 2019 Joint Rail Conference. 2019 Joint Rail Conference. Snowbird, Utah, USA. April 9–12, 2019. V001T07A001. ASME. https://doi.org/10.1115/JRC2019-1223, 2019.

[6] Roland Berger, “Study on the use of fuel cell and hydrogen in the railway environment“, Study for Shift2Rail and FCHJU, doi:10.2881/495604, 2019.