Hydrogen Train Scenarios in Passenger and Freight Transport from Europe and North America: Simulation of Thermal Management

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Abstract. Hydrogen-powered trains present a sustainable alternative to diesel-powered trains for railway transport of passengers and freight. Hydrogen as an energy carrier is cost-intensive, which is why energy demand should be reduced in all relevant operational scenarios. Since thermal losses are one of the main reasons for efficiency reductions, the presented work investigated the research question: Can hydrogen-powered trains combined with targeted energy management strategies be simulated and potential energy efficiency gains be quantified for European and North American scenarios?

A digital railway vehicle simulation framework is developed, which models longitudinal dynamics and energy management. The framework is built with standardized functional mock-up interfaces (FMI) for component sub-models to enable a co-simulation with models from different entities. As input for the simulations, different passenger and freight transport scenarios from Europe and North America are used. Requirements for hydrogen-powered trains vary greatly for different use cases of passenger and freight transport, as well as the location with its surrounding climate. Recuperation of braking energy in freight transport is challenging and remains an opportunity for further enhancement. For passenger transport, metal hydride cooling systems can provide additional cooling capacity and reduce electrical energy demand for air conditioning.

Keywords: Hydrogen trains · Energy management · Passenger transport · Freight transport · Simulation framework

1 Introduction – Hydrogen Trains and their Characteristics

In recent years, hydrogen trains have been steadily developed and tested so that they are now a possible option for providing rail transport on track sections without catenary. Some hydrogen trains are developed as hybrid trains, which makes it possible for them to use the external power supply from catenary as well as the internal power supply from the hydrogen-based power train [1]. In Germany, three fleets of hydrogen trains

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are operational in regional passenger transport in 2025 with 7 to 27 vehicles [2]. Even for the smallest of these fleets around 1 million train km/year with a hydrogen demand of over 200 t/year are stated [3]. In North America, the first hydrogen passenger train started its service in September 2025 [4]. Components specific for hydrogen trains compared to other rail vehicles are fuel cells and hydrogen tanks. Most rail vehicles use 350 bar hydrogen storage compared to 700 bar storage, which is established for passenger cars [5]. For the optimization of hydrogen vehicles different components are under development to increase efficiency. The pressure difference between tank and fuel cell can be leveraged by an expansion engine to recover additional energy [6]. The pressure difference can also be used by metal hydride reactors to provide an additional cooling capacity which can be used for air conditioning in the cabin of hydrogen trains [7]. These systems are referred to as HyPAC (Hydrogen Powered Air Conditioning).

Overall, the energy management of hydrogen trains is challenging as it is necessary to satisfy the energy demands from the power train and auxiliaries under a wide range of operational conditions. Especially at very low or high ambient temperature the thermal management of rail vehicles must take into account high energy demand to cool or heat the cabin [8]. For a regional train the thermal power demand for heating can be up to 92 kW [9]. To evaluate all kinds of conditions, simulation models of rail vehicles are widely established. They are used to optimize speed profile and power control of the vehicles in a digital environment [10]. Especially, the trajectories of the vehicles can be optimized utilizing a direct method solver to find the minimum energy trajectory [11]. Simulations tools are also used to size hybrid traction systems, especially fuel cells and batteries, the key components in the energy management [12]. The sizing process for hydrogen trains is sensitive to input parameters such as the environmental conditions, which vary over the climate zone and the continent of operation. In Europe for example, a lot of tracks are equipped with catenary whereas in North America mostly catenary-free operation is performed by rail vehicles. The configuration of the train and propulsion system is also different if it is designed for passenger operation or for freight transport. Freight transport is mainly performed by locomotives which pull freight wagons. In North America they can reach a length of up to 3 km, whereas in Europe they are normally maximum 750 m long. Passenger transport is mainly performed with multiple units which have an integrated traction system and a large cabin for passengers.

The state-of-the-art analysis shows that optimization for hydrogen trains is focusing on reducing the energy demand in operation. Thermal management is a key component in this optimization process as HVAC systems require up to 30% of energy demand [13]. Nevertheless, the conditions for the operation of hydrogen trains vary greatly, so that the research question for this work is: Can hydrogen-powered trains combined with targeted energy management strategies be simulated and potential energy efficiency gains be quantified for European and North American scenarios?

2 Methodical Approach - Simulation Framework for Rail Vehicles

To study the energy management in hydrogen trains a simulation framework called *pySimRail* is developed in Python. The framework uses parameter sets of environmental conditions, track profile and vehicle parameters as input to calculate the energy demand

of the vehicle. As environmental conditions, the ambient temperature, radiation and wind speed can be taken into account among other parameters. As track profile input, the different stations are listed with the intervals to the next station in terms of time and distance. In addition, the speed limit and gradient needs to be specified over the track distance. As vehicle parameters, the length, mass and Davis coefficients are listed in the input parameters set among other specifications of components such as efficiency or maximum power output.

Hydrogen tanks, fuel cells, batteries, traction motors and auxiliaries are sub-systems which are modelled in the simulation framework of a hydrogen train (see Fig. 1). The losses of these sub-systems are captured by using standard efficiency ratios for the components. The motor is represented by a steady-state equivalent-circuit model augmented with control logic that adjusts voltage and frequency to minimize losses. The model is used to calculate both motor operation for acceleration and alternator operation for regenerative braking. The battery model uses an equivalent-circuit model to estimate terminal voltage, ohmic losses, and to update state of charge. In addition, sub-systems like the hydrogen powered air-conditioning (HyPAC) can be included to study their effects on efficiency on vehicle level. The sub-models can be integrated as functional mock-up units (FMU) based on the functional mock-up interface (FMI) standard. This standardized interface allows a high flexibility in changing the implemented sub-models and enables co-simulation for component models from different parties. The code and equations of the model are not visible if it is packed as FMU, which makes it possible to share sub-models without disclosing intellectual property. In the simulation framework setup for this work, the models for battery, traction motor and traction motor inverter are developed by NRC as FMUs. Tank, fuel cell, HyPAC, auxiliaries, converters and other inverters are modelled by DLR. All sub-models are combined in the same simulation framework to perform the simulations.

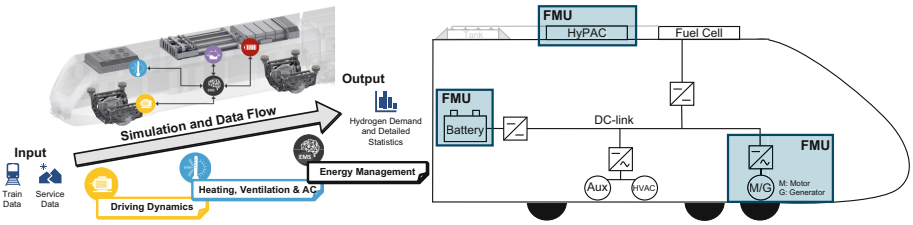


Fig. 1. Sub-models and simulation process of the rail vehicle simulation framework

The simulation process begins with loading the input parameter sets into the simulation framework. The simulation is then performed in three stages. The first stage simulates the driving dynamics. The vehicle trajectory is calculated by taking into account the track profile and the driving resistance based on the Davis coefficients. In the second stage the thermal power demand for HVAC is calculated based on the vehicle trajectory. In the simulation's third stage, energy demand for traction and HVAC is used to compute component-level energy demand and to run the energy management strategy. The energy management determines, based on vehicle state and operating conditions,

whether the battery or the fuel cell supplies the required power. Like in a finite state machine, the power output of the fuel cell is determined based on the current traction and auxiliary demand, as well as the state of charge of the battery. The battery then aims to meet the remaining demand or absorbs any excess power, thereby stabilizing the main DC-link voltage. All three stages of the simulation framework are combined to calculate the overall energy demand of a rail vehicle in a specific scenario.

As scenarios for this work, six track profiles from Europe and North America are defined in Table 1. The length of this scenarios varies from 165 km to 2,070 km. The meters climbed with positive elevation gain from start to final destination is only 118 m in track scenario 1 as it describes a scenario in Northern Germany where the landscape is flat. In comparison to this the scenarios from Spain and Canada show higher differences in elevation which must be considered when calculating energy demand.

Table 1. Track scenarios.

Track scenario	1	2	3	4	5	6
Country	Germany	Spain	Spain	Canada	Canada	Canada
Type	Pass.	Pass.	Pass.	Pass.	Pass.	Freight
Length in km	165	1,343	442	2,070	1,492	1,127
Stations	33	49	27	7	33	3
Meters climbed	118	4,842	1,578	5,472	1,959	1,720

In addition to the track scenarios, vehicles parameter sets are defined in Table 2. Vehicle parameter set 1 is used for the simulation of passenger use cases in combination with track scenarios 1 to 5. Vehicle parameter set 2 is used for the simulation of Canadian freight transport in track scenario 6.

Table 2. Generic hydrogen rail vehicle parameter sets.

Vehicle parameter set	1	2
Type	Passenger	Freight
Vehicle length	42 m	3,000 m
Vehicle mass	95 t	24,000 t
Number of cars	2	164
Passenger seats	120	–
Max. speed	140 km/h	40 km/h
Hydrogen capacity	200 kg	10,000 kg
Battery capacity	300 kWh	5,244 kWh
Max. fuel cell power	400 kW	7,200 kW

The passenger transport vehicle set describes hydrogen electric multiple units (HEMU) with 2 cars in the vehicle. The freight transport vehicle parameter set 2 describes a freight train with 6 locomotives, 6 tenders and 152 freight cars. The vehicle length, mass as well as the power levels of the components are higher for this scenario as the energy demand rises with the overall vehicle mass. The presented track scenarios are simulated with the *pySimRail* simulation framework in combination with the respective vehicle parameter sets. The scenarios are simulated at summer conditions at 30 °C and at winter conditions at −20 °C. For all conditions a reference simulation is performed to calculate the overall energy and hydrogen demand. In addition, an option with optimized thermal management is simulated. For summer conditions, it takes into account the exemplary usage of HyPAC to cool the cabin in the vehicle. However, this model is not optimized for the focused cabin and therefore, the cooling power reduction cannot be assessed quantitatively, as the metal hydride mass is at least five times lower than expected for this application. The usage of this model demonstrates how this simulation frameworks allows to implement various energy improvement strategies. For winter conditions, the optimized option considers the fuel cell waste heat to heat the cabin. The comparison of these scenarios will be presented in the results of the following Sect. 3.

3 Results and Discussion - Energy Demand of Hydrogen Trains in Europe and North America

The scenarios introduced in Sect. 2 are simulated to determine the energy demand accordingly. The hydrogen demand is presented in Fig. 2 for the track scenarios 1, 2 and 3. For the reference passenger transport cases the hydrogen demand is between 13.56 kg/100 km and 15.03 kg/100 km in the base case of the blue bars, which corresponds to the order of magnitude stated by the FCH2RAIL project [14].

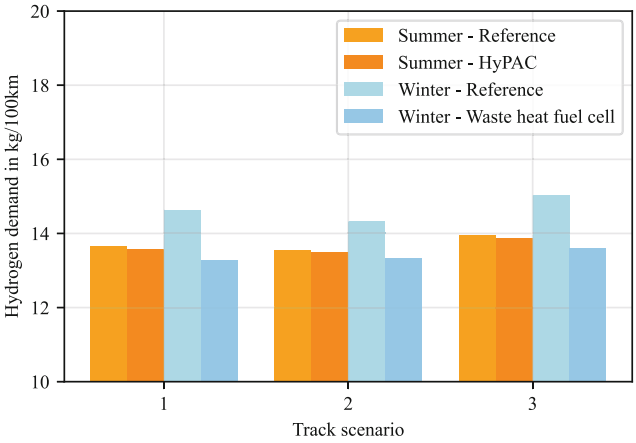


Fig. 2. Hydrogen demand for track scenarios from Table 1 in reference case and optimized case with HyPAC and utilization of waste heat from the fuel cell

The hydrogen demand varies over the three presented track scenarios as the gradients and mean velocities are different. The overall hydrogen demand for these cases is between 22.6 kg and 192.3 kg and is mainly depending on the length of the scenario. For the freight case from Table 1, the overall energy demand sums up to around 10,000 kg of hydrogen. The presented case represents an extreme energy demanding edge case because of the high vehicle weight, length and the gradient on the track as it was parametrized as a fully loaded train driving from the mountains to the coast. This results in an average hydrogen demand of 873.0 kg/100 km.

The orange bars in Fig. 2 compare the summer reference case with the summer HyPAC case. The difference between the bars is the potential reduction in energy demand if HyPAC systems are used as part of the thermal management. For the three passenger cases this leads to a reduction in energy demand by 0.4% to 0.6% for the overall vehicle. An energy reduction potential is shown, but these values do not correlate with expected values of such a vehicle, as the HyPAC's metal hydride mass is at least five times lower than expected for the cooling demand in this passenger carriage. The blue bars compare the winter reference case with a winter case where the waste heat from the fuel cell is used to heat the cabin. The energy demand is reduced by 6.8% to 9.2% by the utilization of the fuel cell waste heat.

For the freight case, the potential for a reduction of energy demand is lower. The energy demand for HVAC is lower and the demand for traction is higher compared to the passenger transport scenarios. As HyPAC systems and waste heat utilization reduce HVAC energy demand, passenger transport cases represent the main intended application for these technologies. For freight trains the share of recuperated energy from braking is low currently, but a re-sizing of batteries for regenerative braking could be part of future work for optimized energy management in hydrogen freight trains.

For a more detailed analysis of the energy demand the split in energy of scenario 1 is presented in Fig. 3. The provided energy is visible on the left of the figure by hydrogen, battery discharge and recuperation. Energy is provided to the DC-link of the vehicle and distributed from there into the energy demand of different parts.

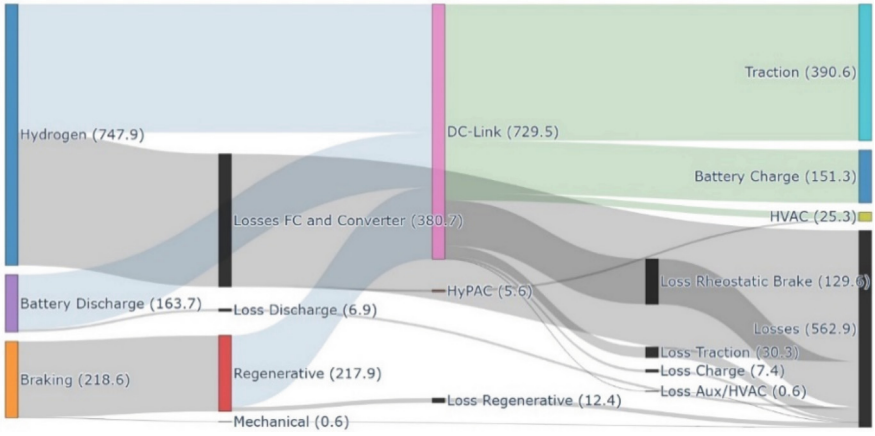


Fig. 3. Energy split in the hydrogen train in kWh in scenario 1 as Sankey diagram

The overall energy demand consists of the losses in the different components, the charging of the battery, the traction and HVAC. All losses are marked in black in the Sankey diagram. Over the scenario the losses sum up to 562.9 kWh. Most of these losses occur in the fuel cell system and the corresponding converter with 380.7 kWh.

HVAC energy demand sums up to 25.3 kWh in scenario 1. The HyPAC system can provide 5.6 kWh out of the HVAC energy demand. This leads to a reduction of HVAC energy demand from the DC-link of 22%. Therefore, HyPAC systems represent an innovative technology as part of a thermal management strategy to reduce energy demand in hydrogen trains for passenger transport.

4 Conclusion

Hydrogen train scenarios from Europe and North America are simulated in this work and the corresponding energy demand is calculated. For the simulation the *pySimRail* simulation framework is used, which is able to implement sub-models for individual components from several parties. The simulation results show that the hydrogen demand for passenger use-cases is significantly lower than for freight use-cases. For passenger use-cases, a hydrogen demand between 22.6 kg and 192.3 kg was calculated. An optimized thermal management strategy based on metal hydride cooling systems (HyPAC) can reduce electrical energy demand for HVAC in hydrogen trains. However, a detailed study how much this technology can reduce the energy demand with a custom design needs to be assessed. For freight trains this technology leads to less improvements as the energy demand for cooling is lower. Overall, freight trains represent a demanding scenario for decarbonization as the vehicle weight and length are high. For the simulated case in this work an overall hydrogen demand of up to 10,000 kg were calculated for a track length of around 1,100 km. New hybridization strategies between fuel cell and battery show potential to reduce this energy demand by taking advantage of regenerative braking also in freight trains. The investigation of better leveraging braking energy for higher efficiency as well as thermal management strategies for high ambient temperatures represent future work based on the presented results.

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