Bi-Mode Hydrogen Train Requirements Using Geospatial Line Assessment

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Abstract

In this paper we analyse use-cases of bi-mode multiple units with a fuel cell hydrogen power pack to identify vehicle requirements arising from infrastructure and operation. For this, we develop a methodology combining a geospatial assessment on available open data (i.e. Open Street Map and a digital elevation model) and a longitudinal dynamic simulation model of rail vehicles. Open data railway networks are suitable in this manner, but elaborate measures to account for data gaps and data inconsistencies are needed. Therefore, we deploy a routing and a smoothing algorithm for elevation profiles integrated in a geospatial model. The modelled data is fed into a simulation tool, which simulates force and speed trajectories at wheel. From the resulting trajectories we determine the necessary traction power at wheel, which has to be subsequently covered by a traction system. From the defined power demand, we derive indicative values for a fuel cell system and resultant net usable battery capacity. We deploy our model on a collection of railway services in Spain, Portugal and Germany currently operated with diesel multiple units. We consider 23 use-cases with varying vehicles and operational configuration. Determined power rates vary strongly and are especially sensible to operational issues such as very long or very short stopping times and to vehicle parameters such as vehicle mass. We determined net power at wheel capacities to be covered by fuel cell system between 82 kW and 674 kW. In relation we determined net usable battery capacities between 90 kWh and 274 kWh. Those demands cover demands for traction energy at wheel level, excluding auxiliary loads and efficiencies.

Keywords: Geodata, bi-mode fuel cell hydrogen multiple units, longitudinal dynamic simulation, FCH2Rail, fuel fell hydrogen power pack

1. Introduction

To reduce greenhouse gas emissions, new propulsion technologies for multiple units move into focus of current research. One of these technologies yet in development, are bi-mode hydrogen trains, i.e. multiple units which can operate from catenary as well as from a fuel cell and battery power pack. These bi-mode fuel cell hydrogen multiple units (bi-mode FCHMU). offer to be a substitute to the current operation with diesel-fueled internal combustion engine multiple units (DMU) on partly electrified railway lines. The power and autonomy requirements on such trains from an infrastructural and operational point of view can be quite heterogeneous and vary strongly across lines and countries. Currently, it is difficult to determine how the components (fuel cell, battery, hydrogen storage tanks, power electronics) and their block sizes (power, energy content) of a fuel cell hydrogen power pack (FCHPP) for a bi-mode hydrogen train should be dimensioned to meet the demands of various use-cases on partly electrified routes. Within the FCH JU-funded project FCH2RAIL [1] we develop an approach to systematically derive generic requirements for bi-mode FCH MU in general and specifically on the indicative requirements of their FCHPP components from the infrastructure and from operational profiles.

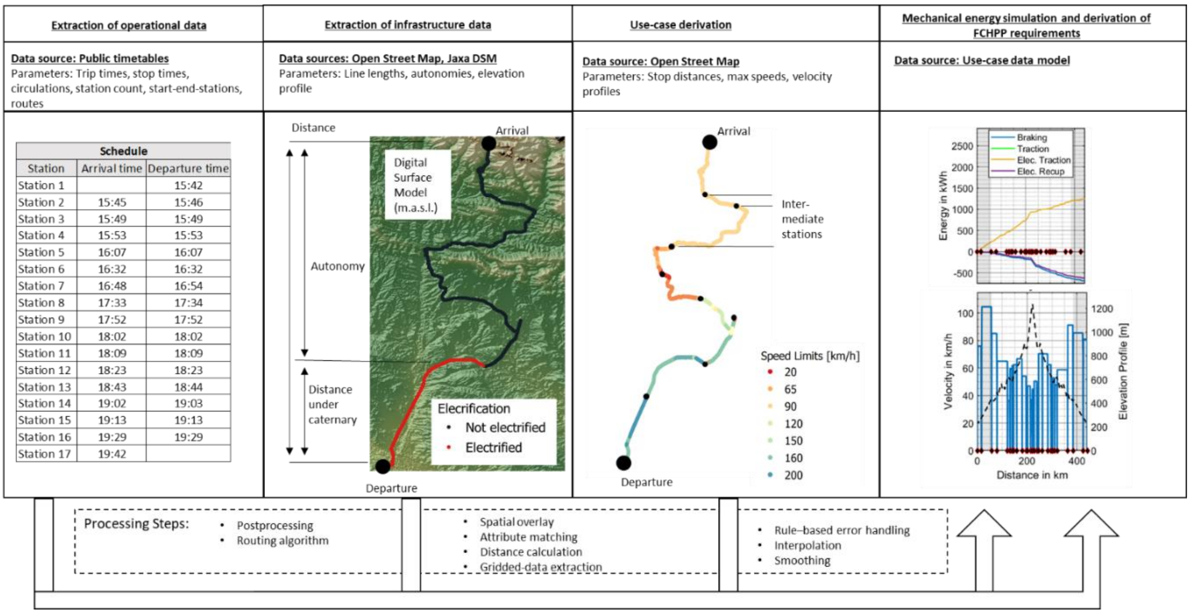
2. Aim and Methodology

The aim of our study is to assess technical requirements for the operation of bi-mode FCH MU which arise from infrastructural and operational parameters. We develop a workflow to derive these requirements from public data sources using geospatial operations. We derive typical use-cases (train type, operational profile, infrastructural profile, etc.) for bi-mode trains and simulate traction energy demands with respect to daily mileages and autonomies, that is, cumulated mileage not under catenary. We further analyze the processed data sets to characterize the DMU train-kilometer in the considered area and to derive required battery capacity, fuel-cell power and on-board hydrogen storage capacity for each of the considered use-cases. We perform this analysis for a set of regional railway passenger services in Spain, Portugal and Germany operated with DMU today.

We approach this issue in two main steps. First, we perform a geospatial data analysis and deploy a data model to derive use-cases from public data. Second, we simulate the traction power at wheel level and derive FCHPP-requirements necessary to serve the considered railway use-cases. This study is part of a series of publications within work package 1 of the FCH2Rail project, namely deliverable 1.3 [2] AND deliverable 1.1 [3]

3. Geospatial assessment

From public timetables, we extracted trips for each railway service considered. A routing algorithm was used to determine the actual railway tracks on which the services operate. We then extracted elevation profiles from a gridded digital surface model (DSM) and draw infrastructural and operational attributes from Open Street Map data (OSM) by using various spatial overlay methods and processing tools. Figure 1 displays the workflow for an exemplary railway service.



Schedule		
Station	Arrival time	Departure time
Station 1		15:42
Station 2	15:45	15:46
Station 3	15:49	15:49
Station 4	15:53	15:53
Station 5	16:07	16:07
Station 6	16:32	16:32
Station 7	16:48	16:54
Station 8	17:33	17:34
Station 9	17:52	17:52
Station 10	18:02	18:02
Station 11	18:09	18:09
Station 12	18:23	18:23
Station 13	18:43	18:44
Station 14	19:02	19:03
Station 15	19:13	19:13
Station 16	19:29	19:29
Station 17	19:42	

Figure 1: Exemplary workflow to derive and analyse a bi-mode FCH MU use-case.

The main attributes to be extracted from the various data sources per use-case are trip length, track electrification, slopes (i.e. elevation profile), trips per day, travel times, stop times, and speed limitations. Vehicle types and their characteristics such as resistance curves, traction curves, mass, etc. where provided by infrastructure managers and railway undertakings contributing to the FCH2Rail project.

4. Derivation of driving profiles from open data

First, we identified all passenger rail services in the study area currently operated by DMU. For these services the timetables were extracted and transferred into a table format including station names and locations. To identify the actual railway tracks used by those services we deployed a Dijkstra routing algorithm [4] over a noded OSM-based routing network. For this we acquired vector-based rail networks from the OSM data model (keys:railway; unfit tracks such as industrial or tram tracks were filtered out). The network was noded using the pg-routing tool framework for PostgreSQL. The stations in the gathered timetables were matched with OSM-stations and connected to the nodes of the routing network. For this we used a chained distance-query using stepwise matching distances from 0.00001 arcseconds to 0.0075 arcseconds. As Dijkstra is a shortest path-algorithm, we avoided deviations from the actual routes by routing between each station along a service. OSM attributes such as electrification information, maxspeeds, tunnels and bridges were than reapplied to the acquired routes by a spatial overlay. The elevation profiles were derived from JAXA ALOS DSM with a 0.1 to 0.1 grid size (approx. 30 x 30 meters) [5]. To compensate data inaccuracies in the DSM as well as infrastructure (i.e. tunnels, bridges, etc.) we applied a set of geostatistical countermeasures to derive a smooth elevation profile. Figure 2 shows an unprocessed profile (lower box, grey line) as well as a smoothed variant used for simulation (brown line).

5. Use-case derivation

The acquired and derived attributes were combined into fitting arrays within a Python environment [6] and transferred into a simulation-friendly data structure. Figure 2 shows an exemplary driving profile for a railway service in the study area.

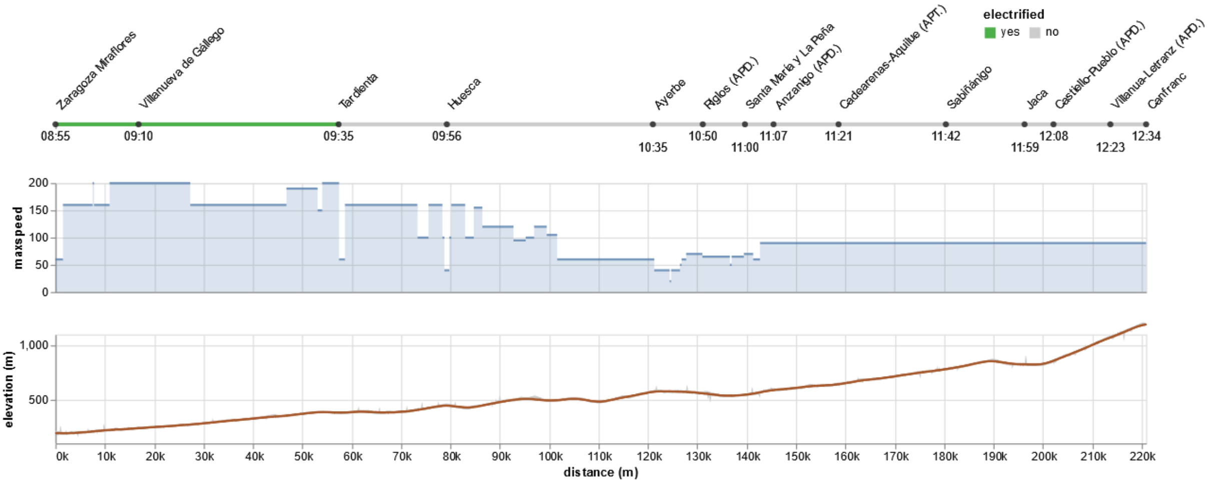


Figure 2: Exemplary driving profile derived from open data

max speeds, electrification and station positions were derived from the earlier acquired vector data. For this we dissolved line-segments with matching attributes where the start and end vertices intersect. To consider possible circulations, we derived the maximal possible circulation of a train over a business day from the timetables, representing the worst-case circulation to define maximum autonomy over a business day. Based on the use-cases derived, we generated simulation input files for longitudinal dynamic simulations.

6. Derivation of FCHPP-requirements

The herein introduced method shall allow for an indicative requirements derivation, which could potentially be used as a guidance in the decision process of dimensioning the propulsion system. In this study, this method is exemplary deployed for a basic definition of a FCHPP. Prior in-depth knowledge specifically of the energy storage system (ESS), fuel cell (FC) as well as the drivetrain efficiencies is deliberately excluded. Furthermore, specific auxiliary demands, as cabin air conditioning or battery and fuel cell cooling are excluded in this study as well, as it would need in-depth knowledge of the underlying powertrain and environmental influences, which exceeds the scope of this study. Instead characteristic values in terms of cumulated traction energy and time-based power demand at the wheels have to be evaluated to define indicative requirements for a feasible fuel cell hybrid powertrain layout.

The necessary power demand profile is obtained with the Trajectory Planner Tool (TPT). This algorithm, developed by DLR, represents a longitudinal dynamic simulation of rail vehicles. Input variables are the previous defined line profile, consisting of timetable and track profile data, as well as vehicle variables, such as, mass, traction power and acceleration. The TPT calculates the speed profile, which is exclusively composed of acceleration, deceleration and cruising phases. [7] Two velocity profiles are calculated. A profile with maximum possible speed and a profile with a reduced velocity. The applicable search criterion for the *Reduced- Velocity-Profile* is to minimize average speed without violating the timetable. If a timetable compliant solution cannot be achieved with this approach, the maximum speed profile, further referred to as the *All-Out-Profile*, is applied as a fallback solution. The different profiles are shown in Figure 3.

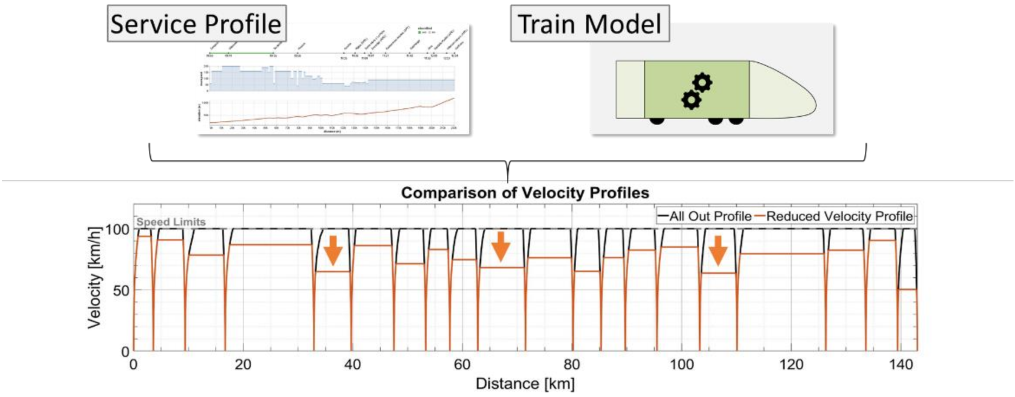


Figure 3: Comparison *"All-Out-Profile"* and *"Reduced Velocity-Profile"*

As a result of the speed trajectory and the train-specific characteristics, the power profiles are generated at wheel level. For the preliminary dimensioning of the ESS and FC, the *"All-Out-Profile"* is used. Due to its maximum allowed velocity profile, it imposes the highest demand the powertrain has to comply with. It is assumed that the fuel cell covers the average traction demand. The remaining threshold to comply with the maximum power demand has to be covered by the ESS. To derive the resulting necessary battery capacity, a literature value for moderate C-Rates for railway applications is chosen [8]. Figure 4 shows the exemplary approach of the power profile analysis of one use-case.

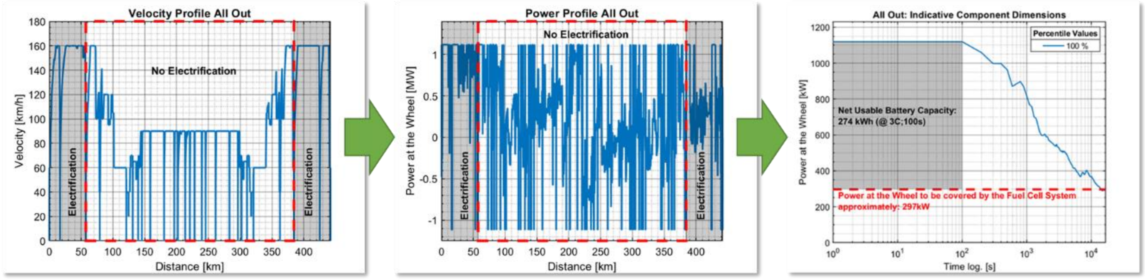


Figure 4: TPT generated Velocity and Power Profile (left) and the 100th percentile of power demand at the wheel used for component sizing. (right)

The complete demand profile, as seen on the left side of Figure 4, is averaged over a range of suitable moving time windows. As this study focuses on the investigation of bi-mode FCHMU, only the non-electrified sections of the use-case are consulted. If non-contiguous non-electrified sections occur, the most demanding section was chosen as reference for the component dimensioning. Furthermore, from the resulting time averaged power values the 100th percentile is extracted for the FC and ESS pre-dimensioning, as it represents the most demanding load spectrum during operation. At this point, it has to be noted, that the determined battery and fuel cell size resembles the necessary power requirements which are needed exclusively at the wheels. In order to take the advantages of recuperation into account, additional knowledge about the efficiencies of the traction drive would have to be considered. Otherwise, a misleading energy balance results at the wheel through the exclusion of the respective losses.

Derived FCHPP requirements are displayed in Figure 5. The influence of the overall stop times in relation to the total travel times are directly linked to the average power demand, hence the resulting FC size. This is due to the fact that no load is applied during stand still times. By excluding further auxiliary loads, there is consequently zero load demanded, hence the average power demand decreases. Considering the battery capacity, the stop -/ travel time ratio is also an indirect driver for the battery capacity fluctuation. The varying battery sizes are directly linked to the maximum traction effort the train model can apply. The method adjusts the necessary capacity to the threshold between the maximum traction effort and deliverable fuel cell power. The dominant influence of the time ratio can be seen further in the average velocity plot. The Spanish and German network have similar average velocities, though the estimated FC sizes increase significantly. Additionally, the very high fuel cell power of 674 kW can be assigned to the highest average velocity and lowest time ratio value in this study overall. Finally, the findings can be validated with the specific energy demand. On average, the estimated component sizes of the Spanish use-cases are larger than in the considered German use-cases, even though the specific energy demand, as displayed in the last plot, is lesser in comparison to the German use-cases. This can indicate, that in the German railway network trains operate potentially closer at their designed powertrain limit, whereby in the Spanish railway network trains experience lower demands compared to the installed power. Though, further research is required for a qualitative evaluation. Nevertheless, it could illustrate the benefits of this data driven method, as it allows an initial assessment of the applicability for specific powertrain topologies, such as the one outlined in this study.

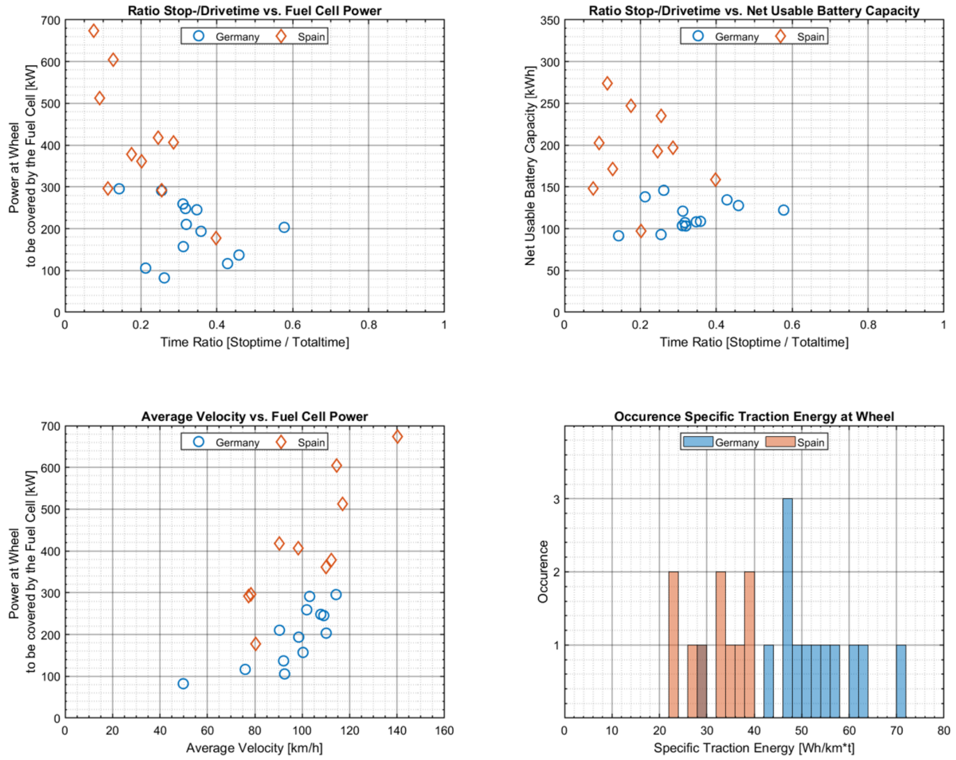


Figure 5: Power at wheel to be covered by fuel cell system and net usable battery capacity.

7. Conclusion

We determined requirements on fuel cell power and battery capacities on wheel level, based on operational attributes and infrastructure derived from (geo)data. Our data driven method helps to identify railway services where the operation of bi-mode trains is reasonable and to predict necessary power demands. The results can be used as KPI`s for comparison with competing technologies such as DMU, line electrification or battery electric multiple units. As our method relies on open data sources, it is reproducible and transferable to other regions, countries and vehicles. Additionally, the pooling and automation of the various aspects of the data analysis and simulation enables the rapid investigation of entire route networks.

However, this line-based analysis and attached component dimensioning process has its limitations. To be named is a missing energy management, with which a reduced average fuel cell power demand could be achieved. Additionally, the missing consideration of auxiliaries could lead to a benefit in the reduction of stand still times, as the secondary loads to play a vital role in the overall energy balance. Therefore, based on our results we developed a hybridization tool framework for dimensioning of FCHPP components, specifically fuel cell, traction battery and hydrogen tank in a more sophisticated way. This is part of subsequent studies within the FCH2Rail project.

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Map data copyrighted OpenStreetMap contributors and available from: https://www.openstreetmap.org.

The data set used in this paper is uploaded to the open repository Zenodo and referenced with the following two DOIs: 10.5281/zenodo.6359030 & 10.5281/zenodo.6355894.

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