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Integration of a hybrid hydrogen fuel cell-battery propulsion system into an modular rail vehicle

Electrification and Fuel Cells Development

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ABSTRACT

The FLIRT rail vehicle is a modular family of passenger trains manufactured by Stadler Rail. Since the first introduction to the market in 2004, more than 2'500 trainsets were sold. The common characteristics of this product family is its single decker, multiple unit articulated trainset design with low floor access to accommodate passengers with reduced mobility. Operational requirements vary greatly between different countries, railways and operators. The modularity of the FLIRT product family allows for this also by offering a broad range of propulsion systems, with the following key parameters:

Primary Energy source:
Overhead wire, Diesel Generator, Traction Battery, bi-mode, tri-mode

Overhead power supply:
15kV AC, 25kV AC, 1.5kV DC, 3kV DC

Continuous tractive power:
0.5 MW – 4 MW

Max velocity:
120 – 200 km/h

Max acceleration:
0.8 and 1.2 m/s2

In conjunction with a supply contract under negotiation, Stadler decided in 2019 to extend the available FLIRT propulsion systems by a hybrid hydrogen fuel cell – traction battery system. The decision to add hydrogen to the FLIRT portfolio resulted in a multitude of challenges.

This paper starts with general background on Stadler and the vehicle family. It then expands on the challenges encountered and the subsequent methods applied. A selection of implemented solutions is presented, as far as confidentiality allows. The overall system architecture, driven by the strategic decisions taken is laid out. The key sub-systems in the propulsion system are described, followed by relevant thoughts on design performance, fuel efficiency and homologation. The successful system integration is illustrated by the performance testing, concluding this paper.

1 INTRODUCTION

1.1 Origin of STADLER RAIL

Stadler started designing and building rail vehicles in 1942 in Switzerland, expanding to a global player with more than 15’000 employees today. The first decades of business were based on custom made locomotives and tractors with battery or overhead power supply, later also diesel-electrical. Customers initially included the local narrow gauge railroads as well as mines, factories and the Swiss military. The complexity of the delivered vehicles grew over time, as did the number of vehicles ordered. The main line operator BLS ordered 4 diesel-electrical tractors for their new-built tracks by end of the 70’s.

The unexpected passing away of the company’s founder and leader Ernst Stadler in 1981 lead to a new management team under Irma Stadler. This period was also marked by a concentration of rolling stock manufacturers in Switzerland, with a diminishing appetite for small series and custom made projects. Consequently, Stadler started to expand the business into the segment of passenger carriages and self-propelled railcars.

In 1989, Peter Spuhler acquired the company, which at this stage made an annual turnover of 4.5 M CHF with 18 employees.

1.2 Articulated Railcar - GTW

The continued success with new built and refurbished vehicles lead to the first contract with SBB in 1992. This was also the year a successor to the then retiring technical director was employed and the rather revolutionary development of the “Gelenktriebwagen” GTW – an articulated railcar concept - was kicked off. The initial GTW concept was an articulated multiple unit with two low floor passenger end-cars and a small central carbody containing the propulsion equipment, example is shown in Figure1.

The novel mix of low vehicle weight, spacious low floor passenger area in combination with a flexible choice of propulsion systems was convincing. Since the prototype was presented to the industry in 1995, more than 500 units have been delivered to customers by now. The GTW family is considered to be the foundation of STADLER’s current success as a train builder. The key to the GTW concept is the modular building blocks of this vehicle family, enabling a fast and cost effective customizing of the vehicle to best suit the clients’ respective operational needs. The thus developed flexibility in terms of gauge, number of cars, number of seats, maximum speed and propulsion technology (and even optional rack rail gears) proved to be a distinguishing factor for the comparably new supplier of rolling stock, in particular when small fleets were needed.

1.3 Regional Train - FLIRT

The need for modern regional trains was identified by SBB in 2000, with focus on improved acceleration, higher top speed and two level entry doors on each side of each carriage. Since this combination of requirements was beyond the potential technical scope of the GTW family, the development of Stadler’s second vehicle family the FLIRT (Fast Light Innovative Regional Train) was triggered. The first FLIRT was delivered in 2004, and the success of the vehicle family surpassed the GTW by far – more than 2’500 units were sold by now.

The design envelope the engineers had to comply to are briefly summarized with:

- improve traction performance
- reduce interior noise level
- flexible range of number of cars per train
- spacious design of the interior layout

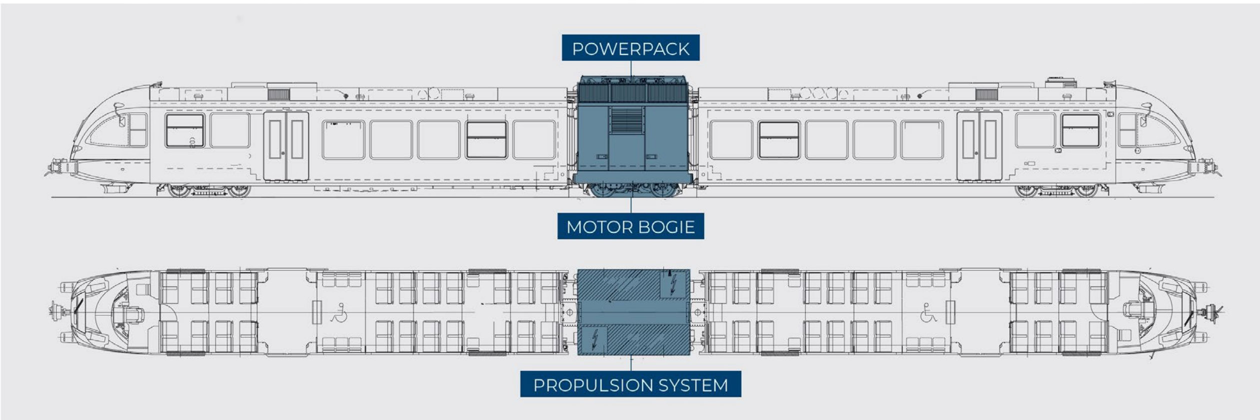

Figure 1. GTW Gelenktriebwagen – Articulated Railcar

- double leaf doors and extendable platforms
- step-free passage between cars
- big multifunctional compartment which can be reconfigured by the operators

The rail industry is the second oldest industry, after the shipbuilding industry. The regulatory frame-work is continuously evolving, incorporating learnings from accidents and expanding with the emergence of new technologies. Since the introduction of the GTW, the revision of the regulations for crashworthiness on the European mainline rail network resulted in significant weight increase of the GTW. By 2010 the seat per weight of the GTW surpassed the one of a comparable FLIRT, bringing the GTW success story to an end.

Same as the GTW’s, all FLIRT’s have an electric traction system, with dedicated traction motors for each driven axle. New are the motor bogies at either end of the train, in close vicinity to the two traction converters. This results in four driven axles per train rather than the previously two driven axles, significantly improving acceleration and tractive performance. An additional benefit is the redundancy in the propulsion system, and the subsequent increase in availability of the vehicles.

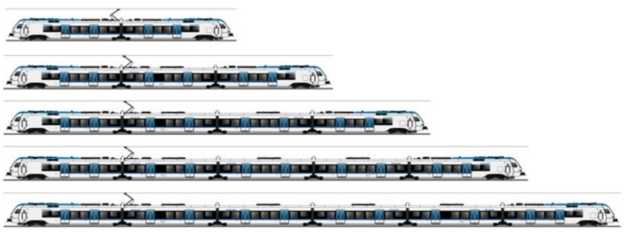

Figure 2. size modularity: 2-6 car FLIRT

By 2019, a wide range of different primary energy sources have been ordered and incorporated into the truly modular FLIRT family. Starting with 15 kV AC overhead (OH) power supply, the scope expanded not only to the various overhead supply voltages and diesel-generators, but by then included hybrid, bi- and trimodal configurations as well as the first pure battery powered FLIRT. A comprehensive overview of the range of parameters the FLIRT can be configured to is shown in Table 1, a range of different train sizes is shown in figure 2.

Table 1. modular FLIRT vehicle family in 2019

Modular Parameter	range / choice		
# of passenger cars	2	-	12
Length	46	-	237 m
Seats	116	-	767
Platform height	550 mm	-	800 mm
# of driven axles	4	-	8
Max. tractive power	0.7 MW	-	5.2 MW
Max. velocity	120 km/h	-	200 km/h
Max. acceleration	0.8 m/s^2	-	1.3 m/s^2
Track gauge	1,067 mm (3’ 6”) 1,435 mm (4’ 8+1⁄2”) 1,520 mm (4’ 11+27⁄32”) 1,524 mm (5’) 1,668 mm (5’ 5+21⁄32”)		
Primary energy source	overhead OH power diesel generator traction battery hybrid diesel-battery bi-mode OH / diesel tri-mode diesel / OH / battery		
OH power supply	15 kV AC 25 kV AC 1.5 kV DC 3 kV DC		

1.4 DECARBONIZATION

By 2019, with the global trend towards decarbonization being anchored in society and politics, dedicated public funding and subsidies was made available for a wide range of sectors, including rail transport.

Overhead power is an established and technically straightforward option to decarbonize rail transport. The carbon footprint is directly linked to the source of electrical power fed into the overhead wire system. This approach, however, does not solve everything everywhere. The CAPEX- and maintenance-intensive OH system tends not to support sustainable business cases for tracks with a low frequency of usage. Shorter non-electrified distances can be covered by battery trains, recharging when operating under OH power. For non-electrified distances beyond the operational range of a battery vehicle however (ballpark figure >100 km), liquid fuels were the long established alternative to installing an OH system, predominantly diesel of fossil origin. Decarbonization of this segment of rail transport presents the biggest technical challenge.

The market trend towards renewable propulsion and zero emission solutions for non-electrified tracks was picking up pace at this time. Further-more, the clients' desire to preserve the operational flexibility of "traditional diesel powered" trainsets was recognized, which can be translated to a maximum of one refueling (or recharging) activity per 24, typically at night. This again limits the applicability of battery vehicles to partly electrified tracks, where recharging during operation is an elegant solution.

The solution is to either decarbonize the liquid fuels by substituting fossil- with bio- or syn- fuels. Or to use alternative fuels like hydrogen or ammonia. The hydrogen approach had gained some traction also in the rail industry by 2019, the first hydrogen fueled vehicles had been developed and tested.

At this stage, the FLIRT already included the traction battery solution [2] [3]. Adding hydrogen to the mix was seen as a viable next development step, should the market express interest thusly.

2 FLIRT H2

2.1 Project start

The greater LA area is renowned for the bad local air quality. A high population density with over 18 million people in the metropolitan area, industrial activity, a mountainous terrain that traps pollution, and a warm climate that helps form ozone and other pollutants all together contribute to this adverse, and at times harmful environment. Los Angeles smog consists mainly of carbon oxides, nitrogen oxides, and hydrocarbons, originating from exhaust fumes and industrial emissions.

San Bernardino is a city in the greater LA area, 97 miles east of Los Angeles at the foot of a mountain range. Temperatures reach more than 45°C in summer. Arrow is a passenger rail link to neighboring Redlands that opened in 2022. Trains begin at the San Bernardino Transit Center and make an additional stop at Tippecanoe Avenue before continuing into Redlands [1]. Three FLIRT DMUs (Diesel Multiple Units) were purchased by the San Bernardino County Transportation Authority (SBCTA) to provide the commuter service on the Arrow corridor.

Following extensive studies with the MSU (Michigan State University), SBCTA was granted public funding by the state of California to purchase an additional hydrogen fueled train. Once delivered, this would be the first hydrogen fueled passenger train in the US.

In conjunction with a supply contract under negotiation, Stadler decided in 2019 to extend the available FLIRT propulsion systems by a hybrid hydrogen fuel cell – traction battery system.

The delivery contract between the San Bernardino County Transport Authority (SBCTA) and Stadler for a two-car FLIRT HEMU (Hydrogen Electrical Multiple Unit) with hydrogen-battery hybrid drive was signed at the end of 2019 as result. The start of commercial operations for the first vehicle is planned to be in 2025.

2.2 Project requirements

The thorough digestion of all technical requirements is a key step for every project, even more so when the degree of novelty is high. This project is a little bit different in that technical requirements were not only specified by the client, but also by the internal corporate organization. This was to ensure a targeted product development for the FLIRT family, that suits future clients' needs in different markets as well. The most relevant requirements from both entities are highlighted below.

Client requirements

- Zero on-track emission of harmful substances
- Very high max. ambient temperature of 49°C
- Full day of operations without refueling
- Enable vehicle for refueling in 15 minutes
- DMU's can be retrofitted to HEMU's
- Design compliant to Buy America Act

Stadler requirements

- Safety first
- high vehicle availability, low fuel consumption, Swiss quality
- scalable H_2 FC propulsion system in terms of available power
- scalable H_2 storage solution in terms of usable inventory
- develop a solution compliant to both European and US rail market, wherever feasible

2.3 Challenges

Stadler as a rail vehicle manufacturer has two area of expertise:

- **Core technology** development and manufacturing, like bogies and car bodies
- **Integration of all systems** into a safe, reliable and conform rail vehicle

The corporate decision to add hydrogen to the FLIRT propulsion portfolio directly resulted in a multitude of integration challenges, in three topical areas:

- “new” basic technologies to be integrated in vehicle system,
- key suppliers with limited experience in rail industry‘s high reliability and durability requirements
- distinct lack of H_2-specific laws, regulations and standards in rail industry and rail authorities

Since the beginning of the project, disruptions of the global supply chain and havoc caused by the COVID-19 pandemic, followed by the Ukraine and middle east conflicts have required flexibility and adaptability as the project moved forward.

2.4 Development Methodology

2.4.1 Project approach

The project started with the core team taking inventory of the steps not covered by the standard project execution processes. The most pressing and complex ones promised to be interlinked and had to be tackled in parallel and iterative fashion:

- **Build-up internal knowledge:** sufficient to make strategic technical decision early on in the project, select and specify best suited technology & supplier, define and optimize interfaces
- **Strategic technical decisions:** liquid / cryogenic hydrogen (LH2) vs compressed hydrogen (CH2), pressure level of CH2 storage, tank type for Hydrogen Storage System (HSS)
- **Select suitable suppliers:** products suitable for both EU and US market, compliant with Buy-America-Act (BAA) requirements
- **Specify new components:** Interfaces mechanical, electrical and controls; performance BoL & EoL, rail- and national standards
- **Layout engineering:** finding the sweet spot between the core objectives: –safety –volume –weight –maintainability –cost
- **System integration**: overall project delivery: -design –assembly –commissioning –testing

In addition to vehicle development itself, the project entailed other challenges because of its duration, multinational coordination across multiple time zones, technical and regulatory complexity, the first-ever U.S. approval of H_2 as a source of energy in rail transport, and supplier development compliant with the Buy America Act.

Stadler met them with special attention to the technical and cultural orientation of the project team, the implementation of additional reviews, and all internal offices and additional project phases as shown in Figure 3.

As early as possible in the concept phase, the selection of strategic suppliers for the powertrain was begun. The additional drive concept validation phase saw both regular coordination with the customer and the approval process with U.S. agencies and experts. Delaying public presentations until InnoTrans 2022 helped keep the focus on development progress and meeting planned deadlines.

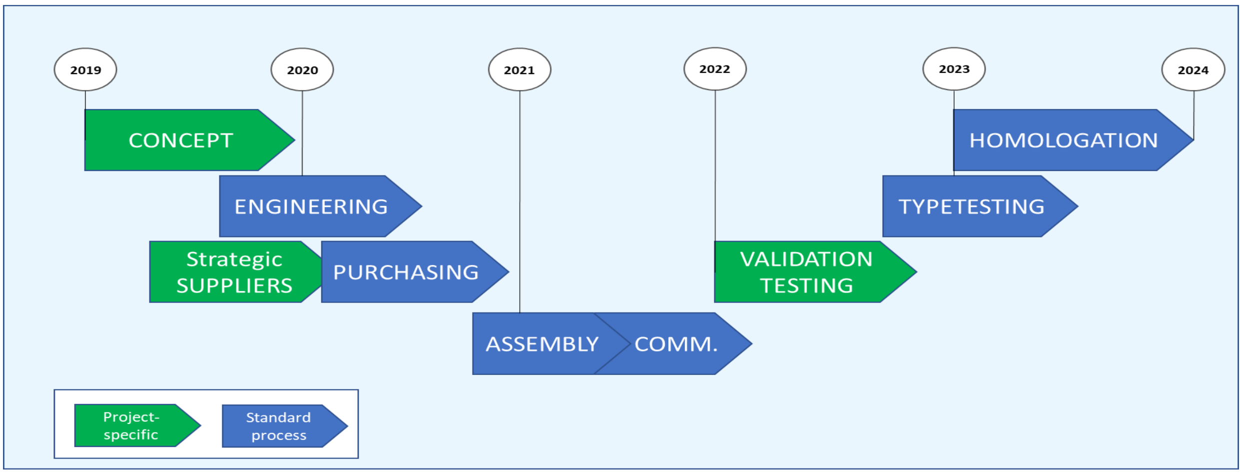

Figure 3. adapted project execution

2.4.2 Concept development

The concept phase was aimed at combining detailed, customer-specific requirements from SBCTA with internal vehicle family requirements. The product requirements define a modular, scalable vehicle concept of a two- to four-car FLIRT with a wide range of mission profiles. In addition to typical parameters such as weight, volume, power, maintainability, and service life costs, safety was critical in concept selection.

The basis for the vehicle layout was first the rough drive concept and the vehicle architecture. All plausible integration variants for the five new primary systems – hydrogen storage, fuel cells, traction batteries, DC/DC converter, and cooling systems – were considered and the relevant key technical data defined. The first step generated 36 layouts for a two-car train and 69 for a four-car train. These layouts were compared and evaluated in a multi-criteria analysis.

Many of the variants failed to provide enough space for hydrogen tanks or had insufficient traction battery capacity and were therefore discarded. Some variants had poor cost-benefit ratios or exceeded weight limits. After this sorting, 13 variants remained for the two-car FLIRT H2 and 4 for the four-car version.

After further comparison of the remaining variants with respect to safety, complexity, and modularity, Stadler chose a vehicle concept with energy storage (H_2 tanks) and energy generation (fuel cells) in a power pack analogous to the diesel multiple unit (DMU) and the FLIRT family’s proven hybrid drive concept. The traction batteries and their cooling system were positioned on the end car roofs to ensure a clear spatial separation between them and the area with hydrogen containing systems, thus maximizing fire safety.

Three discrete power pack lengths allow the number of hydrogen tanks or fuel cells to be scaled to power requirements and vehicle size according to customer requirements.

The proposed concept also fulfilled one of the requirements: simple conversion from a diesel multiple unit (DMU) to a hydrogen multiple unit (HEMU). Future implementation would limit its focus to replacing the current diesel unit power pack with an H_2 power pack and installing the traction batteries on the end car roofs.

2.5 Solutions

2.5.1 Vehicle Architecture

Figure 4 shows the basic layout of the propulsion system. The power pack encompasses all hydrogen-related systems, the fuel tanks, the fuel line system, the fuel cells, and all necessary auxiliary systems. The remaining cars can thus be implemented independently of the drive concept selected. The power pack is designed to provide passengers a wide, well-lit passage from one car to the next.

The power pack is designed so that there is a machine compartment for the fuel cells and a tank compartment for the fuel tanks arranged symmetrically on the two sides of the passenger walkway. This provides a complete energy supply system for each rail vehicle side. The fuel cells are stacked, and each fuel tank is mounted vertically.

The arrangement of the fuel tank in a tank compartment and the fuel cells in a machine compartment allows the fuel tanks and the fuel cells to be separated structurally and sealed gas-tight from the passenger area, preventing fuel from entering. This concept also produces effective acoustic insulation from the machine compartment, contributing to travel com-fort.

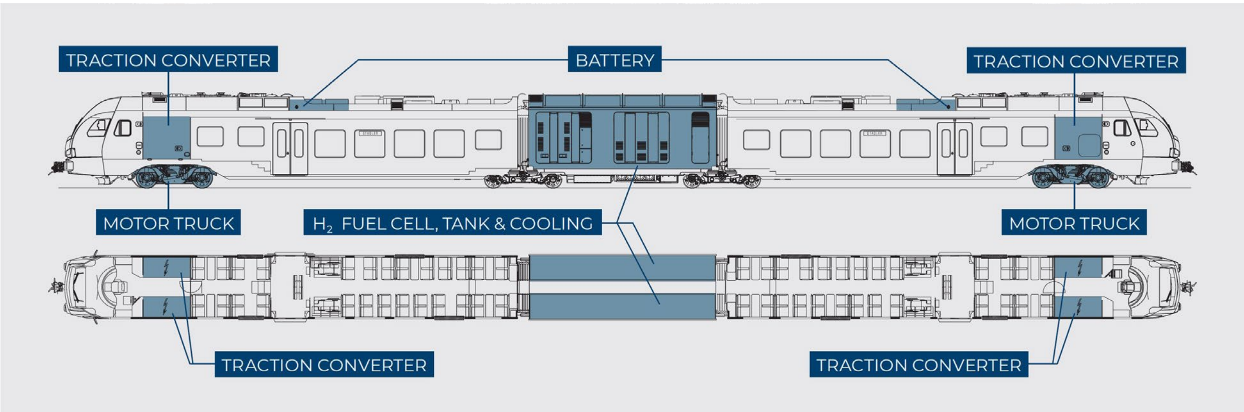

Figure 4. layout of propulsion system

The tank compartment is located directly next to the machine compartment, so fuel lines are very short, resulting in an extremely simple design that is resistant to fatigue failure.

2.5.2 Modularity of propulsion system

The basic concept provides for a variable number of fuel cells and fuel tanks. Depending on the power required for the mission profile, up to eight fuel cells can be installed in the power pack. The length of the power pack is used to adjust the number of H_2 tanks and thus the vehicle's energy storage capacity. This flexibility has been taken into account in the detailed drive section design for SBCTA.

The number of fuel tanks and fuel cells in a power pack can be varied independently of one another.

This allows each vehicle to be adapted individually and modularly to future customer requirements to achieve the optimum balance of power (number of fuel cells) and energy storage capacity (number of fuel tanks).

The final parameters for the first FLIRT H2 to be built for operation by SBCTA are summarized in table 2.

Table 2. key parameters FLIRT H2

Length	51.5 m
max. **axle load**	20 t
# of Seats	116
# of Standing places	120
max. **speed**	127 km/h (79 mph)
Range	> 460 km (> 286 miles)
Sustained power	550 kW
max. **power**	700 kW
Traction	160 kN
# of Fuelcells FC	6
Working pressure FC	8 barg
max. **working pressure H_2 tanks**	350 barg

2.5.3 Fuel Cell System - FCS

The performance modelling of the vehicle's operation resulted in the integration of six fuel cell systems (FCS) in the power pack. This number allows operations of the fuel cells at a high efficiency part load point and gives ample redundancy within the overall vehicle, ensuring maximum availability.

In the machine compartments (on each side of the aisle through the powerpack - see also figure 4), the fuel cell systems are installed on top of each other in a vertical stack. Interfaces and maintenance-intensive components such as air filters, hydrogen sensors and deionization filters are easily accessible from the outside.

The fuel cells are installed on extendable platforms mounted on the holding de- vices with telescopic pull-out. This ensures that all components in these complex systems are easy to access and maintain.

The output voltage of the fuel cell has a wide range of approximately 250 – 480 V DC. Therefore a DC/DC converter does adapt the voltage level to the DC Link of the main traction converter.

2.5.4 Hydrogen Storage System - HSS

Storage of hydrogen as a liquid (LH2) storage was investigated. H_2 at cryogenic temperatures of around -253 °C has a significantly higher volumetric energy density. The disadvantage, the continuous boil-off and loss of inventory from the relatively small storage vessels outweighed this advantage. The decision was taken to store hydrogen as a compressed gas (CH2) on board the train.

The pressure level for CH2 were investigated in a next step. Two common pressure levels are used in industrial and mobility applications, 350 bar and 700 bar. The higher pressure level comes with almost 70% higher volumetric energy density. The associated cost of the storage system experiences a significant step change from 350 bar to 700 bar, however. This cost adder not only impacts on the initially installed equipment but also on the necessary spare parts over the decades of life time of a rail vehicle. The decision for a 350 bar CH2 system was taken.

The last fundamental decision had to be taken on the type of storage tanks to be used. There is four different types of storage vessel on the market for CH2, Type 1 - 4. Details like materials used, dimensions and interfaces differ between suppliers and applications, one of the commonalities is their cylindrical shape.

Type 1 is a fully metallic vessel, with working pressures in the order of 200 bar. Type 2 are metallic vessels with an additional outer reinforcement of glass fiber or carbon fiber and are rated for higher pressure of up to 1000 bar. They are often used in stationary applications. Type 3 are predominantly carbon fiber structural vessels, with a metallic liner reducing the leakage rate. They come in 350 bar or 700 bar rating and are common in mobility and transport applications. Type 4 are non-metallic composite storage vessels with a carbon fiber structure and non-metallic liner like Polyethylene. They are the lightest version of CH2 storage vessels and are mostly used in transport and mobile applications.

Type 4 was chosen for this project, since removing the metallic liner reduces the risk of an explosive rupture should a tank ever be exposed to a fire. Another advantage is the comparably low weight of those type of tanks. The disadvantage is the higher cost compared to the other types of tanks.

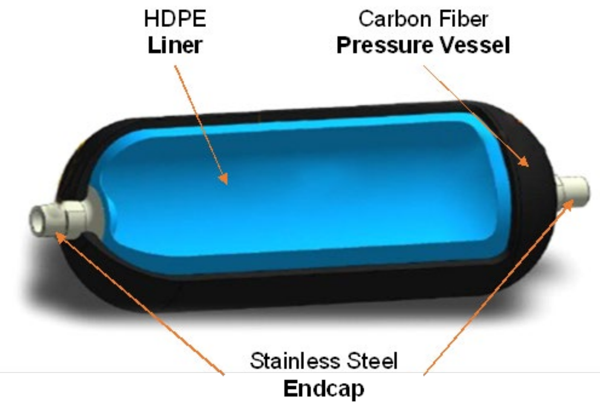

Figure 5. Type 4 tank schematic

Several hydrogen tanks are combined to form a storage module, and several of these storage modules are connected to form a fuel tank system. Two independent tank systems are installed for reasons of redundancy, one on either side of the powerpack.

The bundling of individual tanks to storage modules makes the initial installation and future removal for maintenance easy and safe. To further simplify installation and maintenance, the storage module can be shifted in the power pack.

The power pack has a refilling system for each tank system on each side. This arrangement allows both tank systems to be filled simultaneously, greatly reducing the time required. Vehicle direction is thus also independent of the position of the fueling station, enhancing flexibility in fueling station infrastructure planning.

2.5.5 Electrical Storage System - ESS

The electrical storage system (ESS) traction battery system consists of traction battery units and BTMS (Battery Thermal Management System) units that ensure optimal operating temperatures for the batteries. The selection and sizing was based on the vehicle parameters and the performance requirements as available volume, weight, route performance (cycles), environment, life cycle cost and safety considerations.

Redundancy and subsequent vehicle availability drove the final layout of the ESS as well. A set of traction batteries and dedicated BTMS was installed on the roof of each end car, as an integral of this car's propulsion system. With two independent propulsion systems installed in the train, it is possible to operate the train with only one system.

2.5.6 Vehicle performance

An important design requirement was to match the performance of the diesel electrical FLIRTs, which the client recently had begun to operate, with the hydrogen fueled vehicle. This was achieved despite the differences in vehicle length and weight, and of course the entirely different characteristics of the propulsion system. The tractive effort curve in figure 6 shows the design performance envelope, which was later confirmed by testing.

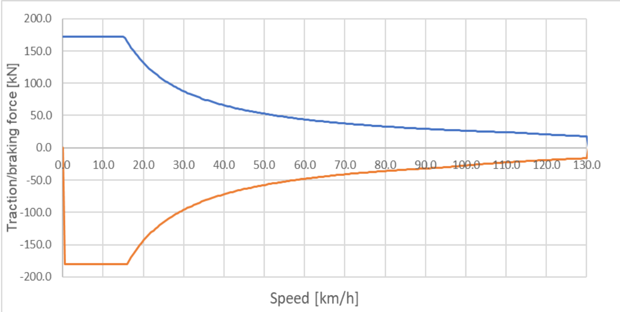

Figure 6. tractive effort curve

2.5.7 Fuel efficiency [4]

Energy costs are a significant contribution to the life cycle cost (LCC) of rail vehicles. Consequently, optimization of the hydrogen fuel consumption was started in an early phase of the project development. In vehicles with a hybrid propulsion system consisting of an energy storage system and an energy generation system, an important degree of freedom is the power distribution between the two energy systems.

The optimal power distribution is thus greatly dependent on specific characteristics of the energy generation system and the energy storage system. Unlike internal combustion engines, fuel cells used as an energy generation system show the highest energy efficiency in the low to moderate load range. Additionally operating points with very low and very high loads have the largest detrimental effect on fuel cell service life. The most efficient fuel cell operation is under constant load.

Ideally, battery storage systems will operate in a tight range to avoid premature ageing. And, unlike fuel cells, battery storage offers high dynamics when operating points are changed.

A predictive algorithm was developed for optimum power distribution selection and tested in a simulation. In addition to general vehicle data and current system condition data, this algorithm requires pre-dictions about the route ahead. Such predictions can be provided by a database using GNSS (Global Navigation Satellite System). This predictive loop is conducted several times per route, compensating for imprecision in prediction.

The simulation compared the predictive algorithm and a non-predictive function in order to quantify algorithm quality. The non-predictive function has only historical data available – power requirements for the distance already covered. The comparison showed hydrogen consumption of up to 10 % less for the predictive algorithm and improved conditions regarding component ageing. Both functions (predictive and non-predictive) have been validated and optimized during vehicle testing.

2.5.8 Homologation

A detailed path towards safety compliance and vehicle homologation had to be defined and agreed, in the absence of hydrogen specific rail standards. A safety approach was applied, with a detailed hazard identification workscope and subsequent hazard mitigation whenever required. A wide range of physical tests and simulations were specified and conducted to validate the safety compliance.

This scope covered the hydrogen containing components and systems, the substantial traction battery system as well as the protective structural components including the actual car body.

The ESS underwent shock and vibration testing, housing impact test and short circuit tests. Outgassing simulations demonstrated that no harmful substance will enter the passenger compartment.

The HSS and FCS subassemblies have been shock and vibration tested combined with tightness tests. The individual HSS components were tested and qualified against today's automotive standards. In addition, the behavior of the tank valve in case of high shear force has been tested and the noise level of a gas release to atmosphere was measured.

Simulation and validation for the car body structure in defined crash situations has been performed, demonstrating a safe environment for the HSS equipment.

2.6 World record

In December 2021, the battery-powered FLIRT Akku, set a Guinness World Record for the longest journey with a battery multiple unit in pure battery mode, without recharging. The distance covered was 224 km, on the public railnetwork in Northern Germany.

Inspired by this in-house example, the benefits of an endurance test under very specific ambient

Figure 7. during Testing on TTC test track

and operational conditions were evaluated for the FLIRT H2. Being able to calibrate and further improve the advanced performance models was seen as extremely valuable.

From mid-2023 to middle of 2024 extensive type testing on the test-facility TTC in Colorado / US was scheduled for the FLIRT H2. As shown in Figure 7, the facility is located in sight of the rocky mountain range and has a test loop length of 21.7 km.

The opportunity was too good to miss, the attempt to set a new record for a hydrogen fueled rail vehicle was started on March 21st 2024 under the close scrutiny of the Guinness experts and judges.

129 laps and 46 hours later, including 16 stops for crew changes, a new official Guinness World Record was established with 2'803 km. [5]

For this record attempt, the train configuration remained as it will be used in commercial operation, no changes to the train's hard- or software were done. An average speed of about 60 km/h was targeted and achieved for the record run, which is representative for a regional commuter train. The record attempt was stopped with sufficient fuel still in the tanks to return to the fuel station under own power.

The range under the given conditions was predicted with an error of less than 0.5% by the in-house performance modelling tool. In essence a best-case scenario in terms of ambient and operational conditions for optimum vehicle range was defined and validated by this record run. In Parallel, the robustness of the overall vehicle in an endurance test surpassing the typical driving time and distance of an operational target scenario by far, was proven. In particular, the stability of the multitude of cooling systems for FCS, and ESS over an extended time of operation was confirmed.

A benchmark in the rail industry for the range of a hydrogen fueled rail vehicle was set, one of the most common question raised in any conversation about this vehicle.

Overall, the achievable range is aligned with the objective to extend the operational range of a battery powered vehicle by one order of magnitude by addition of a hydrogen range extender system.

3 CONCLUSIONS

This paper gives an overview on how a hydrogen fuel cell propulsion system is added to the building blocks of a modular rail vehicle family. The first vehicle built will be used in commercial operation in California and will be the first hydrogen fueled passenger train operating in the US.

The major challenges in the vehicle development are highlighted, and the relevant decisions are motivated.

The vehicle has worked safely during two years of intensive validation and type testing. The performance of the new propulsion system is in line with the required and expected parameters. Commercial operations will start once the last steps of type testing are concluded.

A significant buildup of technical know-how within our organization took place, together with the learnings on how to execute a somehow "different" project successfully.

4 ACKNOWLEDGMENTS

We deeply appreciate the team's unwavering dedication and synchronized efforts during this challenging project. The exceptional perseverance has led to our remarkable success.

We are grateful for the assistance of the staff of the marketing Division of Stadler, for providing and editing the graphics and photographs.

The responsibility for the content and any remaining errors remains exclusively with the authors.

5 ACRONYMS, ABBREVIATIONS

AC: Alternating Current

BAA: Buy America Act

BoL: Beginning of Life

BLS: Bern Lötschberg Simplon Bahn

BTMS: Battery Thermal Management System

CAPEX: Capital Expenditure

CH2: Compressed Hydrogen

DC: Direct Current

DMU: Diesel Multiple Unit

EMU: Electrical Multiple Unit

EoL: End of Life

ESS: Electrical Storage System

EU: European Union

FC: Fuel Cell

FCS: Fuel Cell System

FLIRT: Fast Light Innovative Regional Train

GNSS: Global Navigation Satellite System

GTW: articulated multiple unit (Gelenktriebwagen)

H_2: Hydrogen

HEMU: Hydrogen Multiple Unit

HSS: Hydrogen Storage System

LCC: Life Cycle Cost

LH2: Liquid Hydrogen (Cryogenic)

MSU: Michigan State University

OH: Overhead

OHP: Overhead Power

OPEX: Operation Expenditure

SBB: Swiss Federal Railway

SBCTA: San Bernardino County Transport Authority

SoC: State of Charge

TTC: Transportation Technology Centre

US: United States of America

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