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Concept development and testing of the UK's first hydrogen-hybrid train (HydroFLEX)

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Abstract In October 2018, Porterbrook and the University of Birmingham announced the HydroFLEX project, to demonstrate a hydrogen-hybrid modified train at Rail Live 2019. The concept of modifying a Class 319 Electric Multiple Unit was developed, with equipment including a fuel cell stack, traction battery, 24 V control system and hydrogen storage elements to be mounted inside one of the carriages. This was followed by procurement of a fuel cell stack, traction batteries, and control equipment, which was then installed inside the train, being fixed to the seat rails. One substantial change from the concept was the provision of considerably more hydrogen storage than the minimum necessary, providing the train with more potential to be further modified to allow for higher speed mainline testing. After the Rail Live exhibition where HydroFLEX was demonstrated, numerous modifications were performed to increase the reliability and power of the HydroFLEX train, primarily concerned with modifying the base train logic, with the aim of a successful mainline test. Supporting this effort was a multitude of documentation concerning safety, operations, and approvals to gain approvals from the relevant approval bodies. The project demonstrated the feasibility of using hydrogen fuel cells as an autonomous fuel for railway propulsion systems, which has the potential for full decarbonisation.

Keywords Hydrogen · Fuel cell · Hybrid · Systems engineering

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1 Introduction

The need for countries to take action on climate change was emphasised by the Paris Agreement of 2015 [1], which requires all parties to keep global temperature increase below 2 degrees centigrade, and to pursue an increase within 1.5 degrees centigrade, above pre-industrial levels. Climate change impacts, notably the increased frequency and severity of extreme weather events, can affect numerous aspects of human civilisation, and so mitigation is essential [2].

In order to achieve this, greenhouse gas emissions must be lowered, and the Great Britain's railway is making progress; Ref. [3] notes that Great Britain's rail emissions have been dropping in recent years, down to 36.6 g CO₂e per passenger km in 2018–2019. This compares favourably with new cars, which, according to [4], produce an average of 122.1 g of CO₂ per km. Given an average car occupancy rate on 1.6 passengers per car in 2018 [5], 76.3 g of CO₂ is emitted per car passenger km carbon emissions. However, despite these data suggesting that trains produce half the amount of carbon emissions of cars further improvement are required. A key driver of this is legislation and standards. This is the situation in the UK, a commitment to reduce greenhouse gas to net zero by 2050 was signed in 2019 [6].

Most of the UK's railway network relies on diesel-powered rolling stock, which has the substantial problem of producing emissions at the point of use, including nitrous oxides and particulates, even exceeding EU limits in some enclosed stations such as Birmingham New Street [7]. One alternative is to use electrified railways; however, these can prove expensive, with a typical figure in 2010 prices being £1 million per km per single line for mainline electrification [8].

Therefore, hydrogen propulsion has been presented as an alternative. Ref. [9] notes that the first hydrogen-powered train appeared in 2002, a small mining locomotive powered by a 17-kW fuel cell. A more recent development has been the trial fleet of hydrogen-powered regional trains in operation in Germany [10]. In Great Britain, however, there is a proliferation of restrictive loading gauges [11], and there have been no previous mainline hydrogen-powered train operations. However, the possibility of using hydrogen has been considered for some time [12].

To pioneer hydrogen trains in Britain, Porterbrook and the University of Birmingham announced the HydroFLEX train in October 2018 [13]. At the time of starting the project press releases from the manufacturers of the iLint, Europe's first hydrogen train stated that the train has a daily range of 1000 km [10]. This was taken to be an indication to the project partners that hydrogen fuel cell technology had reached the level of maturity required to be implemented on passenger trains and that an attempt should be made to do so in the UK.

The objective of this piece of research was to ascertain the suitability of hydrogen-hybrid trains on the British railway network through concept design, performance calculations, construction, and testing of a full-scale train. The approach taken was to retrofit an existing electric train with the new power system, instead of designing and constructing an entirely new vehicle.

2 Project systems engineering

The HydroFLEX project combined many different engineering disciplines to achieve a singular objective, to make an electric train self-powered by adding a hydrogen-hybrid power system.

Electrical engineering was applied to ensure that enough current was supplied at the correct voltage to the traction motors and auxiliary equipment to power the train. Mechanical engineering was required to ensure that all the new equipment could be secured to the train in a safe manner, in accordance with the relevant load cases, and that the existing train could accept the additional load. Chemical engineering was required in the original design of the fuel cell and to determine how much hydrogen was required to achieve the duty cycle.

In addition to the engineering disciplines involved, other factors such as logistics, management, and organisation were involved in the project. If each of these concerns was addressed individually, the result would be a haphazard project that would not be able to meet the aim. Instead, a different approach is needed.

Kossiakoff [13] describes systems engineering as being “focused on the system as a whole; it emphasizes its total

operation”. As such, a systems engineering lead approach was required to bridge the traditional engineering disciplines involved in retrofitting an existing train with a brand new hydrogen-hybrid powertrain and to operate it on passenger carrying demonstration services.

Systems engineering follows stages of development from conception and concept development through engineering development to a post-development stage. These stages are shown in Fig. 1, and this process was adopted in the development of HydroFLEX.

3 Concept development

Concept development began in October 2018 and finished in December that year.

The operational deficiency that the HydroFLEX concept design aimed to address was a lack of zero-harmful-emission options for powering self-propelled passenger trains in the UK. This would be addressed by producing a demonstrator hydrogen-hybrid passenger train using a surplus Class 319 Electric Multiple Unit (EMU).

At workshops held at the beginning of the concept development phase, the following metrics were determined from single train simulation of the intended route as the criteria for the functional specification, for an initial demonstration passenger service at Rail Live 2019 exhibition, albeit at reduced speed (see Table 1).

Extrapolating the data in Table 1, there is a minimum requirement for the hydrogen-hybrid system to provide 50.4 kWh of usable energy to meet an aim of running the train four times per day in passenger service.

To achieve this, at a high level, our hydrogen-hybrid system concept consisted of the following elements:

- Hydrogen storage in high-pressure gas cylinders
- A hydrogen fuel cell stack to convert hydrogen and oxygen into electricity
- A battery to store the output of the fuel cell in periods of low demand and release energy in periods of high demand
- A 24 V control system

At the inception of the project, it was not clear what approach to take with hydrogen storage. Removable and fixed options were available. However, after investigation it was decided that fixed cylinders on-board the train was the correct approach to take rather than utilising removable hydrogen storage elements due to the determined lack of feasibility for inserting and removing removable storage elements.

The need for a bespoke 24 V control system was identified early in the concept design phase as much equipment requires this as a control voltage and energy to start the

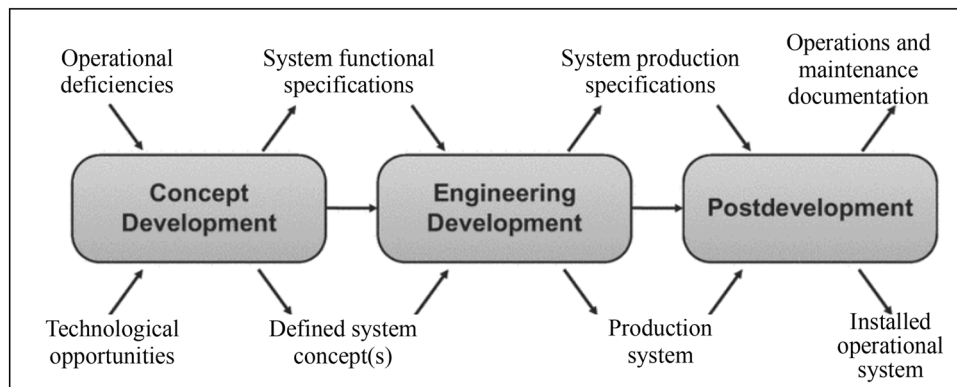


Fig. 1 Stages of system engineering, redrawn after [13]

Table 1 Criteria for successful operation at Rail Live 2019

Quantity	Value
Return run length	800 m
Return trips per day	4
Traction energy for 2 × 400 m	~6 kWh
Time for system on return journey	600 s
Aux power	40 kW
Aux energy for 1 return journey	6.6 kWh
Total energy required for return journey (Traction + Aux)	12.6 kWh

various equipment could be stored in readily available and inexpensive deep cycle leisure batteries.

It was decided at an early stage to abandon the idea of mounting equipment underneath the floor (as is common practice for British trains) [14]. This would require the design, manufacture, and installation of a bespoke under-frame raft, which would require a greater budget and more time than was available. Further, storing hydrogen fuel in large quantities underneath the floor presents safety issues due to the buoyancy and flammability of the hydrogen gas. It is also clear that additional measures would have to be taken to comply with EC79 [15], if hydrogen were stored beneath the carriage floor.

An alternative approach was selected, namely positioning the equipment inside one of the carriages of the Class 319 EMU, utilising the seat rails to mount the equipment securely to the floor. Along with the overall benefit of the large volume that is available, fitting the equipment within a carriage gives protection from the elements, from dust and water ingress and from impacts that could be expected if the equipment was located outside the vehicle. This configuration also allowed for easy access to the equipment for maintenance and upgrades, an important feature for a test train. Another advantage of this approach was visibility

of the equipment involved for demonstrations. One of the first concept renders is shown in Fig. 2.

Having decided to mount the power system within one of the carriages, the next task was to decide which carriage to fit the new equipment in. As such, it was important to understand the base configuration of the donor train.

The donated Class 319 train is made up of four carriages. In order these are titled as: driving trailer (A), pantograph motor open second (PMOS), trailer open second (lavatory), driving trailer (B) (see Fig. 3).

Each of the driving trailer carriages feature a driving cab on the outer end. Class 319s that previously operated on the Thameslink network feature collector shoes on the outer bogies of the driving trailers to collect 750 V DC electricity, although these have been removed from some units in service and were removed from the HydroFLEX donor unit before the project was commenced.

The PMOS carriage features a pantograph on the roof for collecting 25 kV AC electricity from overhead contact wires and each of the wheelsets of the carriage is powered by a traction motor. All other wheelsets on the train are



Fig. 2 Early concept render of HydroFLEX hydrogen-hybrid powertrain located within the PMOS carriage. Note that the specific equipment is not modelled yet as configurations were being trialled at this stage. The equipment from the nearest the viewpoint outwards is the battery, DC/DC converter, Ballard fuel cell and representative type 4 hydrogen tank

unpowered. All the space between the bogies is occupied with traction equipment.

The trailer open second (lavatory) carriage has auxiliary equipment including a motor alternator set and a compressor mounted between the bogies beneath the floor. All the space between the bogies is occupied by this equipment.

From the four available carriages, it was decided that the PMOS carriage was the most suitable for modification. The primary factor in this decision was that the traction equipment is located beneath the floor of the PMOS carriage. This would allow for the new powertrain to be electrically connected directly. If the powertrain was in any other carriage, it would necessitate the addition of a traction current return cable to the power equipment that would have to span the length of the carriages and be connected between carriages via a jumper connection.

4 Engineering development

4.1 Hydrogen-hybrid power system

Much of the engineering development was constrained by the limited time available. From the announcement of the project in October 2018, to Rail Live 2019, when the train was expected to be operated, there were just 9 months. In this time, equipment had to be procured, installed, tested, and finally operated. Therefore, the project team selected equipment which was readily available.

A Ballard FCVeloCity HD100, 100-kW fuel cell stack was selected and procured along with its coolant and air supply subsystems. This procurement also included a Danfoss DC-to-DC converter which could provide constant DC power to the train from both the fuel cell stack and battery. The fuel cell stack module was modified slightly in order to connect with this DC-to-DC converter.

It did not prove possible to order a single traction battery to meet our requirements; instead, two 42-kWh Denchi batteries was procured. Each battery consisted of 12 battery slices with an additional control slice, located in a cabinet with equivalent dimensions to a 21" server rack. While this did fit within the footprint of the vehicle, the centre of mass of this assembly was relatively high, and the base relatively narrow; it was therefore decided to install an external frame



Fig. 3 Class 319 EMU train formation

around the cabinets to comply with rail vehicle load cases specified in regulations such as GM/RT 2100.

The overall system for supplying power to the train is shown in Fig. 4. In this case, the DC-to-DC converter was connected across the batteries, providing a parallel connection to the traction system.

Following some investigation into the practicability of using removable type 1 tanks, it was determined that this was not a viable option. As such, a search was made for a workable alternative.

The search for hydrogen storage led to discussions with representatives of Swagelok, a supplier of EC79 rated hydrogen piping and valves, revealed that a suitable supplier of type 3 hydrogen storage tanks, Luxfer, operated in the UK. 4 × Luxfer W205N tanks were procured, with a total storage capacity of 20 kg of hydrogen. These were suitable for permanent attachment to the floor of the carriage. These tanks are commonly used in hydrogen-powered buses, and the project team benefited from this prior development to support this use case. While the total hydrogen capacity was substantially greater than what the concept required for a single journey, it was quickly realised that additional duties during testing would be required. These additional duties consisted of static testing, idling time, and multiple-day operation between refuelling opportunities. The provision of greater range than initially required also allowed for long distance testing following the initial low-speed testing around the Long Marston site.

Static testing occurred both prior to the introduction to service of the train and on a regular basis during the lifespan of the train, such as every morning before going into demonstration and testing service and after a prolonged period of inactivity to confirm continued function of the system.

Idling time occurred between specific demonstration and testing duties that occurred on the same day. Whilst the power produced by the hydrogen fuel cell during these idling periods would not necessarily be wasted as it could be stored as energy in the batteries or used to keep auxiliary loads such as the motor alternator and the compressor running.

Multiple-day operation between refuelling opportunities did happen on several occasions. This happened due to both operational planning and as an unplanned reaction to other trains being stabled on the siding where the refueller was located.

By engaging with Luxfer it was confirmed that it would be possible for the tanks to be supplied within the tight deadlines of the project and that an assembly of four tanks could be supplied in a frame that met the GM/RT 2100 standards [16] for equipment to be mounted to rail vehicles. The solution would also include the refuelling and defueling nozzles, pressure gauges, high-pressure

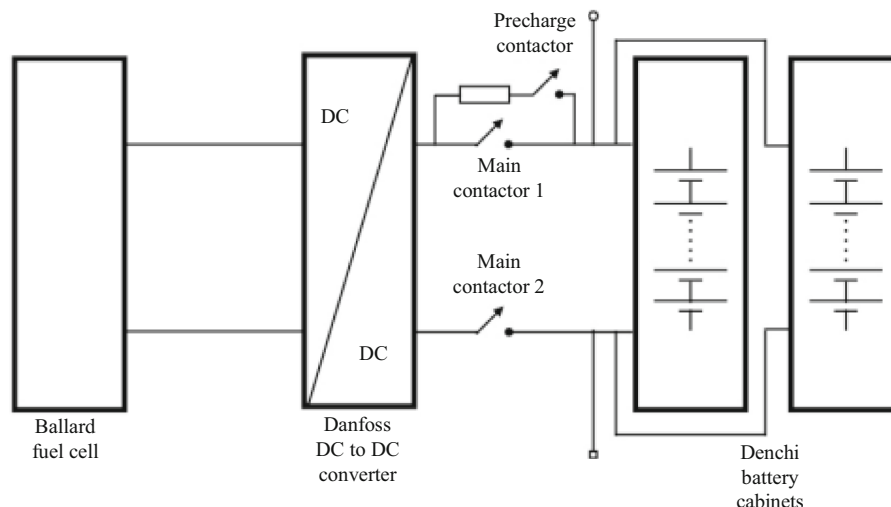


Fig. 4 Block diagram of the overall power system of HydroFLEX

pipework, pressure reducer and systems integration, and engineering support.

4.2 Control equipment

In order to start the hydrogen-hybrid power system components and operate them correctly when traction or auxiliary power is demanded, control equipment was necessary. The control system is also required to shut down these components when required (including in emergencies) and provide voltage, current, and temperature protection for the traction batteries.

The control modules of traction batteries required a 48 V supply. This was supplied by two DC-to-DC converters using the 110 V DC train supply. The two converters produce 24 V each and are connected in series to produce the required voltage. Each battery was started using software running on a laptop supplied by Denchi. This software also showed the operator the individual cell voltages and any alarms (including overvoltage, undervoltage, overcurrent, over-temperature, and under-temperature). These alarms automatically trigger a shutdown of the relevant battery if required. When the fuel cell stack was connected, various traction battery outputs and charge paths were enabled to allow the traction battery voltages to balance.

The laptop control was supported by an auxiliary control battery box containing 6×12 V batteries, arranged as three series pairs of batteries connected in parallel producing the required 24 V supply. The batteries were charged from the three-phase train supply and could supply the 24 V System for over an hour, which is much longer than is necessary to complete the start-up process and thus establish the three-phase train supply.

The fuel cell stack was controlled by software running on a laptop supplied by the University of Birmingham. Once the traction batteries were switched on, a switch could be operated in this software to start the other components. The software closed contactors between the DC-to-DC converter, traction batteries, and fuel cell stack and then started the fuel cell, enabled, and controlled the DC-to-DC converter to achieve the required power. The fuel cell software running on the University of Birmingham laptop communicated with the control modules in the traction batteries via CAN bus messages sent by the latter. In addition, the fuel cell had its own control system for its air, fuel, and coolant subsystems.

4.3 Installation

The company dg8 was responsible for designing the arrangements for mounting the new equipment to the train, and for ensuring these arrangements were compliant with rail vehicle legislation. They designed the rafts for the fuel cell and its various subsystems (including DC-to-DC converter), the external battery frames, and the 24 V control system box reinforcement.

The final design layout of equipment is shown as a CAD image in Fig. 5. This is largely representative of the layout that was implemented. The only detail difference between this CAD image and the true layout is the slightly smaller size of the true hydrogen storage.

This equipment was installed between March and May 2019, primarily using the door openings. These openings proved wide enough for all rafts to be moved in and installed without difficulty.

4.4 Rail Live

Following functional testing, the engineering development achieved its objective of supplying a working train for use at Rail Live 2019, where numerous low-speed demonstration runs were performed with the public on-board. All were successful.

5 Post-development

Although the HydroFLEX train had been intended to debut at Rail Live 2019 as a demonstrator, it was felt that sufficient potential existed in the design to carry out additional testing, including on the UK mainline railway. This was part-funded by Innovate UK FOAK 3 funding, from the UK's Department for Transport.

5.1 Power

The first issue to be solved beyond Rail Live was that of power. In operation, the traction batteries proved more vulnerable to peaks in load than had been anticipated. This was due to the traction load fluctuating more rapidly than the design load of the battery, which was intended for steady charging and discharging rates when used as an uninterrupted power supply system. While it was in theory possible to operate the train in notch 2 (the Class 319's power controller has four power notches, notch 4 being the most powerful and notch 1 being the least) this state would often cause one or both of the traction batteries' protective systems to cut out the battery for battery protection.

To attempt to mitigate the vulnerability of the batteries to the power transients demanded by the Class 319 traction system the slice modules were returned to the manufacturer for modifications to the control hardware and software. The modifications included changes that allowed for charging and discharging at a higher rate than before the modification. The conservative thresholds that the battery protection system was originally set at were originally imposed due to the control software being intended for use in uninterrupted

power supplies. As such, the harsh changes in demanded load created by the HydroFLEX train were routinely tripping the protections at their original setpoints.

Further, the train control was modified, with new train control logic equipment being implemented (see Fig. 6). This allowed engineers in the PMOS to control the train logic, rather than it being automatically controlled from the Class 319 power controller. When notch 2 was selected on the controller, for example, this would illuminate a button on the logic equipment, allowing engineers to prevent the train from drawing more power if the fuel cell stack and traction batteries were not ready. This equipment also



Fig. 6 Train control logic equipment, showing the exterior (above), and interior wiring (below)

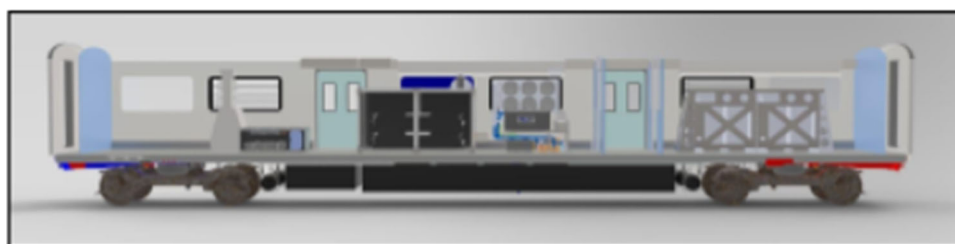


Fig. 5 CAD image of the design of the inside of the PMOS carriage. From the left to right the visible components are the 24 V control box, hydrogen tanks, fuel cell stack and DC-DC raft, and the protective structural frame for the traction batteries

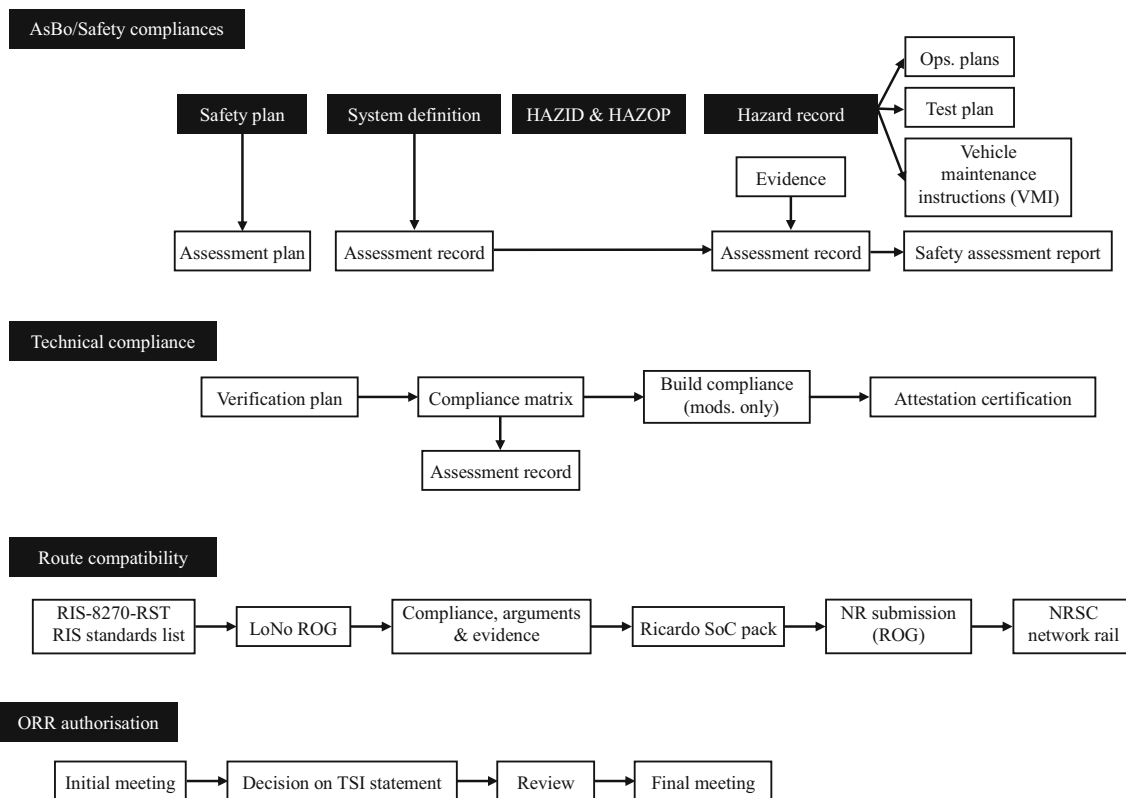


Fig. 7 Overall schematic of the approvals process, showing the four categories of the process

allowed engineers to monitor other traction system activity such as the Wheel Slide Protection (WSP) system activity.

An additional mode of operation, beyond what had originally been envisaged, was also implemented. In normal operation, the Class 319 EMU engages a field divert at notch 4. This is because as the speed of the train rises, the back-EMF produced by the traction motors also increases, leading to a limitation in power. To allow for higher speed operation on the UK mainline railway with the limited power available from the fuel cell and traction batteries, the train control was further modified, with the field divert being activated when notch 3 was selected.

5.2 Mainline documentation, test and approvals

It was necessary to seek formal authorisation to take the train onto the mainline via an approvals process.

To standardise procedures, an engineering operations manual was collated. This was just one of many documents necessary for approvals purposes. An overview of the approvals process is shown in Fig. 7.

The following are the key elements of the assessment body (AsBo)/safety compliances.

- Safety plan. A safety plan was produced by Porterbrook covering evacuation, procedures, dispatch procedures,

control of passengers, etc. This concerns public safety while using the HydroFLEX train.

- System definition. This document defines the system such that safety issues with our system could be identified and mitigated.
- HAZID & HAZOP. This consists of two phases:
 - HAZID or Hazard Identification. This is defined as “A systematic review of the possible causes and consequences of hazardous events” and is largely concerned with the effects of hazardous events [18]
 - HAZOP or Hazard & Operability. HAZOP is a systems level review, to identify any further hazards that may occur either when the system is operating as intended or any likely deviations from expected operations [19].
- Hazard record. This is a centralised repository for all hazards identified, which was used as a reference for the operations plant, test plans, and the vehicle maintenance instructions (VMI).

The technical compliance consisted of verifying that the new equipment (noted as “mods.” or modifications in Fig. 7) was compliant with the relevant technical standards (including GM/RT 2100)[17] to be permitted to run on the mainline railway.

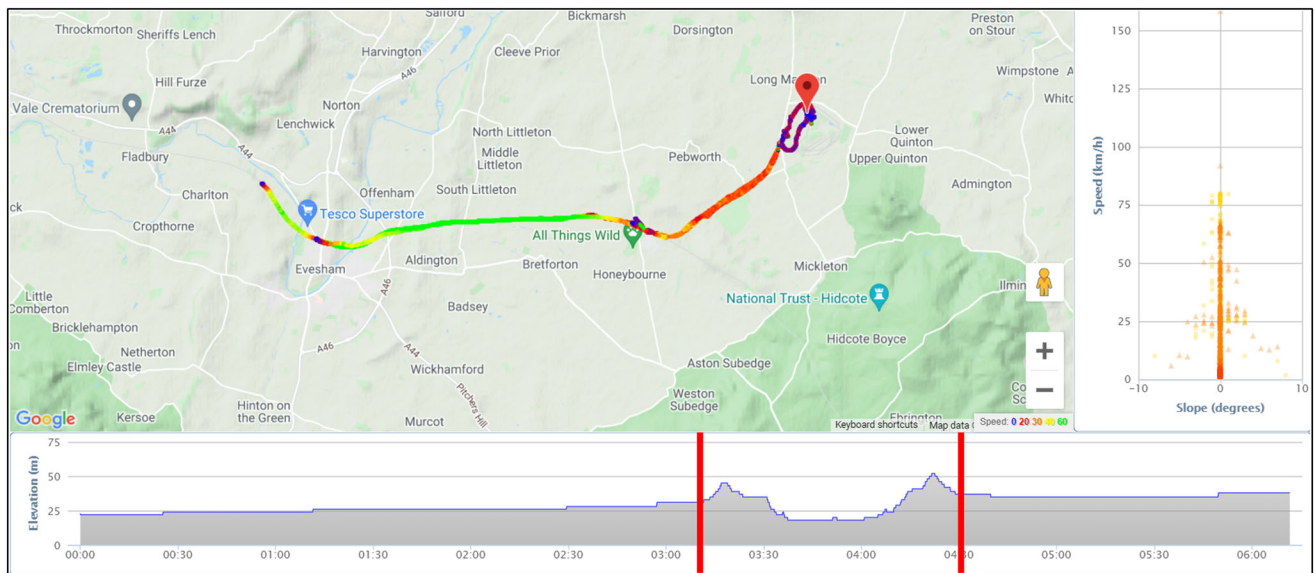


Fig. 8 GPS data for a mainline test run to Evesham. The colour coding of the GPS track shows the speed, and the plot on the right shows speed readings; although one reading indicates 91.5 km/h, this is spurious and was not corroborated by any other sensor. Altitude data are shown in the lower plot against time from system start-up in hours and minutes. The thick red lines added to the elevation plot bracket the time when the train was in operation

Route compatibility is essential; while it may be theoretically possible for the train to operate on the rail network in Great Britain, in practice it is necessary to ensure there are no barriers to it operating on a particular route. This began with a search of the rail industry standards (RIS), followed by a Letter of No Objection (LoNo) from Rail Operations Group (ROG), who are licensed to operate trains on the mainland UK network. Ricardo, as the AsBo, provided a Statement of Compliance (SoC), and following the submission to Network Rail, a Network Rail Safety Certificate (NRSC) was awarded.

The Office of Rail & Road (ORR) took some interest in the project, and a review was carried out; however, it was not considered to be necessary to issue a Technical Standards for Interoperability (TSI) statement.

Numerous tests had to be carried out to support the approvals effort, including

- Electro-magnetic compatibility (EMC) testing. This was carried July 2020, using both lineside and on-board equipment to monitor electromagnetic emissions from the train.
- Annual exam of the equipment on board the train.
- Fitness to run (FTR) exams. These were carried out every day before a mainline test, with sign off by a competent inspector required before operations

5.3 Mainline running

Following the approvals and testing process, HydroFLEX was approved for mainline running. Three mainline tests were conducted in September 2020, between Long Marston, the site at which the train had been tested and operated, to Evesham.

All test runs were successful with only minor issues encountered. The GPS data from one of these runs are shown in Fig. 8, with performance and electrical data shown in Fig. 9. During mainline testing, performance data were also harvested from the traction system, allowing for tuning of the system for later runs. These data will also inform the design of subsequent types of hydrogen-hybrid train. Figure 9 shows the main system data plotted as a function of time for the test runs. The whole test cycle takes a considerable amount of time because the train needed to be prepared and ready, and to meet certain timing points. This means that the duty cycle comprises of extended periods of idling where the train is held before given the authority to advance to the next section.

The green line in Fig. 9 shows the train speed. The initial movements are in the test site and are characterised by several short and slow movements. The train then enters the mainline and travels on a low-speed branch to join the live railway. Once given permission to move onto the high-speed section, the train then was permitted to travel at its highest speed to Evesham station. After a stop, the train moved beyond the station and returned on the adjacent track for the return journey.

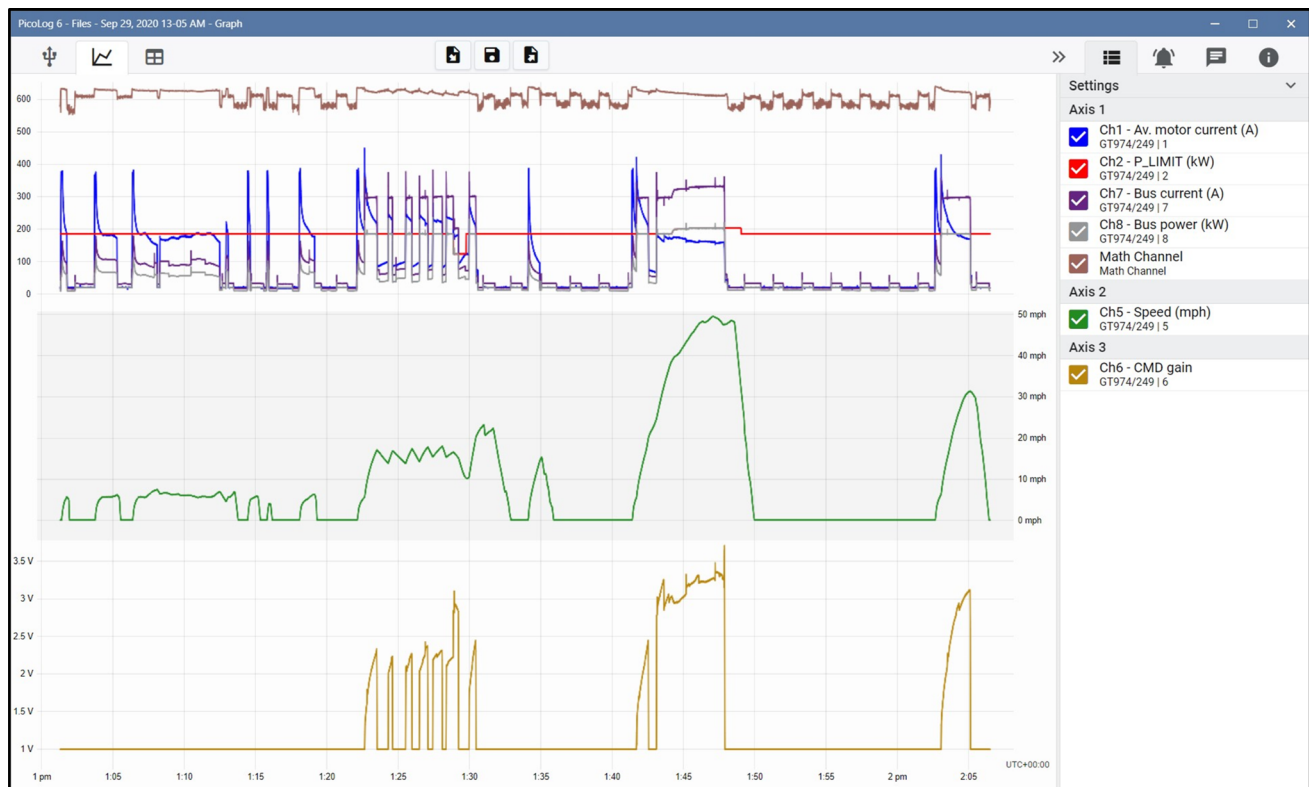


Fig. 9 Performance data plot for the same run from Long Marston to Evesham, showing electrical data for the base Class 319 (top), speed data (middle) and data from the current monitoring device (bottom)

A few other data values are included on the plot. These include the system DC bus voltage, the traction motor current, the DC link bus current, the available power, and the CMD gain which moderates the power demanded by the train to within the capability of the propulsion system.

The propulsion system needed to be dynamic enough to cope with rapid demand changes from the driver, and considerable effort has gone into the design to cope with changes in notch power settings at different speeds.

6 Conclusion

The HydroFLEX team showed the possibility of operating hydrogen-hybrid trains on the British railway network. This was achieved by developing a concept design, consisting of new equipment mounted inside the PMOS carriage, and progressing this design through detailed design and installation to testing. The resulting HydroFLEX train was successfully demonstrated at Rail Live.

Beyond this its potential was developed through modifications to the design, and the train was approved to run on the mainline railway, with numerous documents produced to support this. The learning experience and data gathered

from the HydroFLEX project will continue to inform the design of follow-on classes of hydrogen train.

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