Future Railway Powertrain Challenge

Fuel Cell Electric Multiple Unit (FCEMU) Project

FCEMU Project - Phase 1 Report - Issue 1

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Executive Summary

Fuel cells are an attractive alternative to diesel traction for railway applications – the technology is robust, requires minimal maintenance, and can cut both fuel costs and emissions dramatically. Fuel cells are used to power several UK bus fleets, which have power requirements similar to those of regional multiple units, and trains also return to a depot or stabling point every night, making refuelling relatively simple and cost effective.

The RSSB funded a competition to develop novel powertrain designs for rail vehicles as part of their Future Railway programme. The University of Birmingham and partners Hitachi Rail and Fuel Cell Systems Limited proposed a fuel cell based powertrain suitable for both retro-fitment to existing mid-life DMUs, and for fitment to future fleets. The proposal is for a hybrid arrangement where the fuel cell is used to meet the base load power and a high-capacity battery stores braking energy and help meet peak traction demands.

This report details the work undertaken for Phase 1 of the project, a feasibility study to establish the relative merits of the technology. This was based on a study of the Norwich to Sheringham route, currently operated by Class 156 multiple units. The work was broken down into four core packages:

- WP1 – determine the installed power required to meet or improve on current journey times, and the amount of energy required for a full operating day;
- WP2 – determine the space available for new equipment and fuel tanks and its maximum acceptable weight, and the amount of fuel needed for a typical fleet;
- WP3 – undertake industry consultation and use this and the results from WP1 and WP2 to develop a concept design that meets the requirements, based on existing available and proven technology;
- WP4 – investigate the likely first cost, operating cost and performance of the concept design in terms of both journey times and emissions;

The initial analysis suggested that each vehicle of a Class 156 or an AT200 would require installed power of in excess of 200 kW, 63 kg of hydrogen per vehicle for the Class 156 vehicle, and 75 kg for the air-conditioned AT200.

The second work package involved generating a 3D model of the Class 156 to establish the space available for new components. Given that most of the existing equipment between the bogies was to be removed, there was considerable space available on the

underframe, and it was relatively straightforward to develop a concept installation design that would provide sufficient hydrogen for a 500 mile range.

The space available on the AT200 (designed an EMU) is not as generous, and was split between underframe and roof areas. This meant that it was not possible to fit all of the equipment and storage tanks on a 2-car set. Hitachi went through a further two revisions, first for a 3-car configuration and then for a 4-car, and the addition of the second trailer car was found to provide sufficient space.

Two train leasing companies and three TOCs were consulted, and were supportive of the initiative as it would potentially help them meet their future needs in terms of performance and emissions. The concept designs were developed taking their needs into account and then re-evaluated for performance and hydrogen storage requirements.

Vehicle Type	Return Journey Time (mins)	Fuel Energy Per Car (kWh)	Hydrogen for 500 miles
Class 156 DMU	105	637 kWh	n/a
Class 156 FCEMU	98	304 kWh	62 kg
4-car AT200 FCEMU	99	346 kWh	70 kg

From the above table, the fuel cell Class 156 achieves a 7% reduction in journey time and a 52% reduction in fuel energy consumption when compared to the original diesel engine version. The AT200 FCEMU achieves a similar reduction in journey time, and a 45% reduction in fuel energy consumption.

In terms of emissions, fuel cells produce zero emissions at the point of use, but of course energy is required to generate the hydrogen used on the vehicle. There are two commercially available options to produce the 2,000 kg of hydrogen per day that would be required for a nominal fleet of 25 x Class 156 multiple units – the first is to use electricity to split water into hydrogen and oxygen (electrolysis), and the second is to spit natural gas into hydrogen and carbon (reformation). For the notional fleet the results were as follows:

- A 100% reduction in carbon emissions for the fuel cell Class 156 if the hydrogen is produced by electrolysis from nuclear or renewable energy such as wind turbines;
- A 33% increase for the FCEMU if the hydrogen is produced by electrolysis based on the current UK electricity generation mix;
- A 43% reduction for the FCEMU if the hydrogen is produced by the reformation of natural gas.

In addition, NOx and particulate emissions would be virtually eliminated, regardless of the hydrogen production method used.

Looking at the economics, the cost of conversion for the notional fleet was estimated at £41.1m, consisting of the following components:

- Engineering design & acceptance ≈ £2m
- Fleet conversion costs ≈ £26.9m
- Hydrogen generation plant & equipment ≈ £12.2m

The primary benefit is a very significant reduction in per-mile fuel costs of 63%, based on the reformation of natural gas. This translates to a predicted savings for the notional fleet of £2.2m, giving a payback period approaching 20 years. There would be further savings expected in terms of vehicle maintenance and vehicle availability, but these would be of a lower order. So when viewed purely as an alternative to diesel, conversion of existing fleets to fuel cells is unlikely to be economically viable.

However, fuel cells offer a similar range of benefits to electrification for rural lines including improved performance, substantially lower noise & vibration, no reliance upon imported fossil fuels, and the potential to considerably reduce pollution in urban areas. In terms of cost, taking the case of the Valley Lines in Wales, the estimated costs of conversion to fuel cell operation for the notional fleet is of the order of 1/7th of the cost of electrification of the infrastructure, and there are further valuable advantages:

- No disruption to services during the installation of overhead wires or modification to bridges and tunnels;
- No additional overhead infrastructure to maintain;
- No visual impact of overhead wires in sensitive areas;
- The potential to use lower cost off-peak 3-phase power instead of problematic single phase power at peak times
- The potential to help balance the grid and absorb excess wind energy during period of low electrical demand.

A further study has been commissioned internally to evaluate the alternative to electrification for the Valley Lines, including the option of fuel cell powertrains. The team have also recently been joined by Ballard Power Systems, the world's leading supplier of fuel cells for heavy duty transport applications. Together, the proposal for Phase 2 is to convert an ex-Birmingham T-69 tram to provide the UK's first full-size fuel cell powered demonstrator.

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Glossary of Terms / List of Abbreviations

Term	Explanation / Meaning / Definition
BoP	Balance of Plant – the ancillary equipment required by the fuel cell including radiators and cooling circuit
DMU	Diesel Multiple Unit
EMU	Electric Multiple Unit
FCEMU	Fuel Cell Electric Multiple Unit
FCSL	Fuel Cell Systems Limited
GB	Great Britain (England, Scotland and Wales)
Hotel Load	Non-traction power requirements including heating, ventilation, door operation etc.
HST	High Speed Train – a high speed passenger train developed in the UK in the 1970s that is still in service today
IGBT Converter	Insulated-Gate Bipolar Transistor Converters – the current generation of traction control electronics as used on modern EMUs
IPEMU	Independently Powered Electric Multiple Unit
NR	Network Rail
N-S-N	Norwich-Sheringham-Norwich – one of the two routes specified by the RSSB
PRM	Persons of Reduced Mobility
PTO	Power Take Off – a mechanical system attached to a driveshaft to power auxiliary equipment
RSSB	Rail Safety and Standards Board
SiC Converter	Silicon Carbide Converter – the new generation of traction control electronics that are smaller and more energy efficient than IGBT converters
STS	Single Train Simulator – a MATLAB based train simulator developed by the University of Birmingham and used to investigate train performance and traction energy consumption
Switching Loco	The American equivalent of a shunter in the UK
UK	United Kingdom (Great Britain and Northern Ireland)
UoB	University of Birmingham
WP	Work Package
WSP	Wheel Slide Protection – pneumatic based antilock braking system for trains

1 Introduction, Aims & Objectives

As part of their Future Railway programme, the RSSB launched a competition in November 2014 to develop novel powertrain solutions for railway vehicles to improve the efficiency of Britain's railways, and provide export opportunities for Britain's rail supply chain. The project is in two phases:

- Phase 1 – undertake a feasibility study;
- Phase 2 – design, develop and construct a demonstrator.

The University of Birmingham, Hitachi Rail and Fuel Cell Solutions Limited submitted a successful proposal for Phase 1 to develop an novel powertrain based on fuel cell technology, suitable for retro-fitment to mid-life diesel multiple unit rolling stock such as the Class 156 DMU, and for fitment to a new generation of regional multiple units, based on a modified version of Hitachi's AT200 EMU. This report described the work undertaken for the fourth of the five work packages, detailed as follows:

- WP1 – establish the requirements for the new powertrain in terms of installed power and energy storage to meet required journey times and daily operating range (Chapters 2 to 5);
- WP2 – establish the space available on each of the two vehicle types for the proposed new powertrain (Chapters 6 to 9);
- WP3 – develop a concept design that meets the requirements within the available space and weight restrictions (Chapters 10 to 14);
- WP4 – investigate the likely first cost, operating cost and performance in terms of both journey times and emissions (Chapters 15 to 21);
- WP5 – produce final report to include a draft proposal for Phase 2.

This report details the work undertaken for the above work packages, and is published for general distribution with the kind permission of the Rail Safety and Standards Board.

2 Background

There are a number of well-documented economic and environmental reasons why diesel is unlikely to be an acceptable source of motive power for the railway traction into the future. While there are moves to electrify large parts of the GB network, there will remain a substantial number of regional and branch lines for which electrification is uneconomic. Therefore the railways need to find an alternative to diesel to power future fleets.

One option is to use batteries to enable trains that normally run “under the wires” to charge up on the mainline, and then use this stored energy to power them for excursions onto branch lines, to hop over non-electrified sections, or reach the far end of lines which are only part-electrified. However, there will remain routes where trains operate continually on non-electrified routes, as clearly identified in the industry’s recently published rolling stock strategy (Rail Delivery Group, 2015).

One attractive option is fuel cells powered by hydrogen. The hydrogen is stored as a gas in pressurised tanks, fed in to the fuel cell at low pressure, and a reaction takes place with oxygen present in the air to generate electricity, waste heat and a small quantity of pure water in the process. Fuel cells tend to by hybridised, that is to say that they are usually allied to a battery pack, as shown schematically in Figure 1.

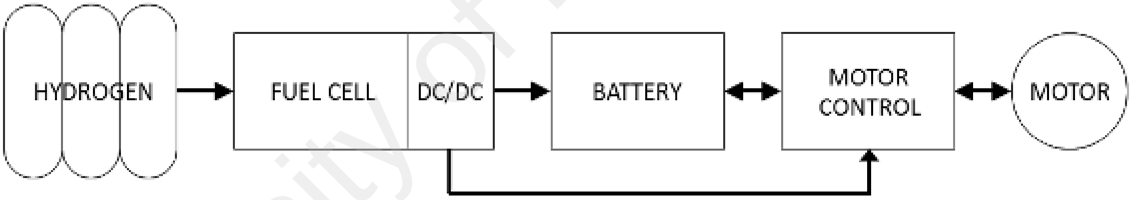

Figure 1 – Typical Hybrid Fuel Cell Powertrain Configuration (FCSL, 2016)

The battery pack absorbs energy during braking and this helps meet peaks in power demand when the vehicle accelerates.

2.1 The Rationale for Fuel Cells to Power Trains

Fuel cells were originally invented in 1838 and developed throughout the 1900s. However, it is only recently that the technology and supporting infrastructure have become sufficiently well-developed for widespread transport applications. An excellent example is the fleet of fuel cell buses currently in daily operation in Aberdeen (see Figure 2).

Figure 2 – Aberdeen Hydrogen Fuel Cell Bus (UoB, 2015)

The traction power and range required for bus applications such as this are remarkably close to those for 75 mph railway multiple units. It should be possible to take the technology developed for bus applications and transfer this to the rail industry. As with bus applications, this would provide the railways with a number of inherent advantages over diesel power:

- The hydrogen used to power the fuel cell can be generated from any number of sources including directly from natural gas, through the digestion of organic waste material, and from any electrical supply including nuclear and renewable energy;
- Fuel cells produce zero emission (i.e. no CO_2, zero NO_x and zero particulates), making them especially suitable for urban environments;
- Fuel cells have no moving / reciprocating parts, and therefore produce virtually zero noise and vibration. This is of benefit not only to passengers, but also to those neighbouring transport corridors.

Hydrogen fuel cell powered cars are now available, but their success is greatly hampered by the lack of supporting infrastructure – i.e. hydrogen filling stations. But unlike private cars, captive fleets of vehicles such as buses, trams or trains operate over regular routes and return to a depot or base every evening. This makes the use of hydrogen as a fuel far more achievable as only a limited number of re-fuelling points (possible just a single re-fueller) need be provided.

Although not yet competitive on a first-cost basis, the running and maintenance costs for fuel cells are expected to be lower than for diesel, and it is hoped that investment in fuel cell power can be justified on this basis (to be investigated as part of Work Package 4).

2.2 Previous Experience

The team have a good spread of relevant experience to evaluate the potential for using fuel cells for railway traction, and the practical feasibility of retro-fitting this equipment to existing vehicles or fitment to new fleets:

- The University of Birmingham has been investigating the use of fuel cells for railway traction for several years, and constructed the UK's first fuel cell powered narrow gauge locomotive in 2012. Other work has included an insightful PhD undertaken at the university that investigated the well-to-wheel emissions and efficiency of fuel cells in comparison with both diesel and electric traction (Hoffrichter, 2013);
- Hitachi Rail developed a full-scale fuel cell powered demonstrator in Japan between 2004 and 2007, the so-called New Energy Train. They also have experience of hybrid technology having been responsible for the hybridisation of an HST power car – the Hayabusa Project. Hitachi Rail are also experienced in re-tractioning existing rolling stock in the UK, and are now building new fleets of trains in the UK for both the UK, European and overseas markets;
- Fuel Cell Systems Limited are a systems integrator who have undertaken a large number of turn-key fuel cell projects, and who have recently been commissioned to develop a mobile hydrogen re-fueller.

The team have also been offered support by Angel Trains, one of the UK's three main train leasing companies. Further support has also been offered by Hydrogenics, one of the main suppliers of electrolysers and fuel cells for motive applications, and Ballard, another of the main fuel cell suppliers who have previous rail experience and who supplied the system fitted to the Aberdeen bus fleet.

3 WP1 – Duty Cycle Analysis & Powertrain Performance Requirements

In order to establish the requirements for installed power and energy storage, the team employed the University of Birmingham Single Train Simulator (STS). This is a proven piece of software code developed in MATLAB that provides a reasonably accurate prediction of journey times and energy consumption for a single train operating on a given route (Douglas, Weston, Kirkwood, Hillmansen, & Roberts, 2015).

3.1 Construction of Single Train Simulator Model

The RSSB provided data for two routes that were to be used as the basis for the evaluation – these were as follows:

- Norwich to Sheringham (N-S-N) – a flat regional route that takes approximate 115 minutes for a return journey, with a maximum linespeed of 75mph;
- Maidenhead to Marlow (M-M-M) – a shorter regional route that takes about 50 minutes for a return journey, with a maximum linespeed of 50mph.

Only the more demanding N-S-N route was simulated at this stage as the objective was to determine the maximum performance requirements. The performance for both routes will, however, be evaluated once the concept design has been developed. The vehicle models constructed were as follows:

- Class 156 DMU – a model of the existing 2-car Class 156 diesel powered multiple unit common on many UK regional and branch lines, with a maximum operating speed of 75 mph;
- Class 156 FCEMU – a modified version of the above with electric traction motors, suitable for powering by a fuel cell;
- AT200 EMU – a model of the new 3-car EMUs currently being built by Hitachi Rail to operate on a number of ScotRail routes, with a high level of installed power for 100 mph operation;
- AT200 FCEMU – a modified version of the above, reduced to a 2-car formation, and with the 25kV traction equipment replaced with smaller traction motors suitable for 75 mph operation.

The resistance values used for the Class 156 simulations were based on the values provided by the RSSB, and the data on the efficiency of the Voith transmission provided by the RSSB was also incorporated into the model. The AT200 EMU resistance values were provided by Hitachi Rail, but modified to represent a 2-car formation.

3.2 Motor Sizing

The time taken for a return journey on the N-S-N route was calculated using the STS and compared with the real-world value of 115 minutes. The STS Class 156 DMU model gave a return journey of 105 minutes, quicker than real-world values. However, this was considered to be reasonable given that the train in the STS simulation is driven “flat-out” and takes no account of restrictive signal aspects that would typically be encountered in real life. Appropriate station dwell times were, however, included.

A number of vehicle models were then constructed of the Class 156 FCEMU and the AT200 FCEMU with a range of installed powers to investigate the minimum traction motor size that would meet or improve on current journey times. A range of power outputs were selected from 75 kW to 200 kW based on standard motor sizes. Through this evaluation, it was established that a 150 kW motor would be insufficient to maintain current journey times, so a minimum of 200 kW of installed power is needed per vehicle. A summary of the simulations, predicted journey times and traction energy consumption is provided in Table 1 below:

Table 1 – Summary of Predicted Journey Times & Traction Energy Consumption

Vehicle Type	Nominal Traction Power Per Vehicle (kW)	Return Journey Time (mins)	Traction Energy Consumed (kWh)
Class 156 DMU	213*	105	184 kWh
Class 156 FCEMU	200	103	121 kWh**
AT200 FCEMU	200	102	99 kWh**

* Approximately 15 kW of the engine’s output is used to drive auxiliary systems.

** Includes regenerative braking at 50% overall efficiency.

Although the Class 156 has nominally higher traction power per vehicle, the predicted journey times for the Class 156 FCEMU and AT200 FCEMU were shorter for two reasons:

- A proportion of the power from the Cummins engine is used to drive Power Take Offs (PTOs) for the alternator and the hydrostatic compressor. By contrast, the auxiliaries on the FCEMU would be powered by the fuel cell, so 100% of the motor’s output can be used for traction;
- The Voith transmission is inefficient at low speeds.

Acknowledging that the N-S-N route is not electrified, a further "benchmarking" test was also undertaken using a model of a standard AT200 EMU. This has just over 600 kW of installed traction power per vehicle in order to achieve its maximum operation speed of 100 mph. However, for the purposes of the simulation, its maximum speed was limited by the 75 mph linespeed. With this substantially more powerful traction system, the journey time was predicted to fall to 93 minutes.

In terms of the traction energy, the ability to recover and re-use braking energy resulted in significant reductions in energy consumption. For the Class 156, the total traction energy consumed fell from 184 kWh for the DMU to 121 kWh for the hybrid FCEMU, a saving of 35%. The lower train resistance of the AT200 FCEMU resulted in further savings, with total traction energy falling to 99 kWh, a reduction of 46%.

Please note that the results were obtained based on the following assumptions and simplifications:

- The overall efficiency of regeneration (i.e. capturing and re-using braking energy) was assumed to be 50%* due to loses in capturing energy at the wheel, generating electrical power, feeding this to the battery, then converting this back to electrical for subsequent re-use by the motor. However, it is believed that this figure may be overly conservative, but it was felt prudent not to over-promise at this stage;
- In order to calculate the quantity of diesel consumed, the overall efficiency of the Cummins diesel engine was assumed to be 35%**, and to calculate the quantity of hydrogen consumed, the overall efficiency of the fuel cell was assumed to be 50%***;
- Generic traction motor characteristics were used in the STS model. Actual motor tractive effort and braking curves will be incorporated once a motor specification has been selected later in the project.

As the concept design develops, the simulations will be re-run, incorporating the performance characteristics of the actual components used in the design.

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* There are several factors that affect the efficiency of regenerative braking including the efficiency of the traction package and energy storage system, the brake entry speed, brake demand, the proportion of powered wheelsets, and the overall brake control philosophy. At this stage, it is not possible to define these accurately, so a conservative engineering judgement was taken that 50% would easily be achievable.

** Numerous internet sources suggest that the efficiency of modern diesel engines is around 35% to 40% when the engine is under load. The Cummins unit is not a modern engine, and it spends considerable periods at idle, further reducing overall efficiency. Therefore a value of 35% was selected for this initial set of simulations. Actual fuel consumption figures will be sought from ROSCOs and TOCs in due course.

*** Fuel cell efficiencies are typically quoted at around 50% under load. Unlike diesel engines, no fuel is consumed when a fuel cell is at idle. Therefore the overall efficiency will be close to 50% for a hybrid design such as that being proposed. Again, predicted efficiencies will be reviewed as the design develops.

4 WP1 – Battery & Fuel Cell Sizing Calculations

The output of the STS simulations is useful in understanding the traction energy required and braking energy recoverable for compete journeys. However, there are two further factors that need to be considered when sizing key traction components:

- The so-called "Hotel Loads", which are the non-traction on-train systems that also need power such as lighting, heating pumps (although the actual warmth can be provided by waste heat from the engine), compressors for the air brakes, and an increasing number of on-train electrical systems. For the Class 156 there is also a hydrostatic pump load (part of the transmission system), and for the AT200 there is the additional load from the air conditioning;
- The STS output is useful for calculating energy and power requirements for a full journey, but for any given journey there will be peaks in the energy power requirements due to particular traction or braking events.

A number of Excel spreadsheets were therefore generated to undertake supplemental analysis, and these are provided in Appendices A to F.

4.1 General Approach

In order to provide a baseline, the first stage was to determine how much energy could reasonably be captured by an on-train battery through regeneration. This could then be used to:

- Provide minimum size requirements for the battery pack;
- Inform the fuel cell sizing by determining the likely contribution to traction during sustained acceleration that the battery would make.

However, this calculation is not straightforward as it is heavily dependent on the duty cycle and specific traction or braking event being considered. Therefore a number of simplifying parameters and assumptions were made:

- Average power and requirements would be established using the output from the STS results for a complete return journey on the N-S-N route;
- Peak power requirements would be established by looking at the longest individual sustained period of traction and braking during the return journey;
- An additional sense check based on the "first-principles" calculation of the energy required to brake a vehicle from maximum speed.

A further assumption was also necessary in relation to the contribution that the battery would make to the acceleration of a vehicle from stationary, and this is described in the following section.

4.2 Calculation of Battery Pack Size

An initial calculation was done from first principles to establish the amount of energy that a battery pack would need to absorb were a vehicle to brake from maximum operating speed. The calculation for the Class 156 FCEMU is shown in Appendix A and for the AT200 FCEMU in Appendix B. In the case of the Class 156 FCEMU model, the total kinetic energy to be absorbed by the battery and/or dissipated by the friction brake is 6.9 kWh, and for the heavier AT200 it is 8.0 kWh.

However, the power that can be absorbed through regeneration is limited by the rating of the traction motor. This means that if the driver brakes gently, a large proportion of the vehicle's kinetic energy can be absorbed by the battery, but at higher brake rates, a far greater proportion has to be dissipated by the friction brakes. To size the largest likely requirement of the battery, it was therefore assumed that driver makes a gentle Step 1 brake application (nominally 3%g). On this basis:

- The battery for the Class 156 needs to be able to repeatedly store 4.8 kWh;
- The battery for the AT200 needs to be able to repeatedly store 5.7 kWh.

It should be borne in mind that to extend battery life, it is not good practice to completely discharge a battery on a repeated basis. Therefore the minimum battery rated capacity needs to be at least double this value (if not quadruple). So it is suggested that each vehicle will require a battery pack of at least 10 kWh, and ideally of 20 kWh or more.

4.3 Calculation of Minimum Fuel Cell Rating

In order to work out the minimum rating for the fuel cell in terms of its power output, the following analyses were undertaken (details shown in Appendices C and D):

- For a complete return journey, the average power required was calculated based on the traction energy calculation from the STS simulations and adding a 20 kW hotel load for the Class 156 FCEMU and a 50 kW hotel load for the AT200 for two scenarios:
    - as a non-hybrid, where the power is provided just by the fuel cell;
    - as a hybrid, where some of the power required during heavy acceleration is provided by a battery pack that is charged up during braking, cruising, or during dwell time at stations;

- The speed profile was examined to identify the longest single sustained period of acceleration and establish the power required, again for both the non-hybrid and hybrid situation.

The calculations for this are shown in Appendix E for the Class 156 FCEMU and Appendix F for the AT200 FCEMU, and are summarised in the table below:

Table 2 – Summary of Traction Power Requirements

Vehicle Type	Average Power Required	Peak Power Required
Class 156 FCEMU non-hybrid	109 kW	220 kW
Class 156 FCEMU hybrid*	90 kW	131 kW
AT200 FCEMU non-hybrid	127 kW	250 kW
AT200 FCEMU hybrid*	109 kW	156 kW

* assumes a battery capable of providing 7 kWh at up to 200 kW

From the above, it is clear that hybridisation (i.e. using a battery pack) reduces the size of fuel cell required to meet peak power requirements, and the degree to which this happens is greatly affected by the size of the battery. The base assumption used in the numbers presented above is that the battery contains the energy absorbed from a single braking event from maximum speed (approximately 5kWh for both the Class 156 FCEMU and AT200 FCEMU), plus the additional energy generated by the fuel cell during the subsequent dwell time. If a conservative dwell time of 1 minute and a 120kW fuel cell output is assumed, this gives a total of 7 kWh available to help accelerate the vehicle.

On this basis, it is suggested that the Class 156 FCEMU be equipped with a fuel cell with a rated power output of at least 131 kW, and the AT200 with at least 156 kW. In terms of standard fuel cell sizes, this suggests that the Class 156 be equipped with a 150 kW fuel cell and the AT200 with a 200 kW fuel cell.

5 WP1 – Interim Conclusions

The objective of the first work package of the FCEMU feasibility study was to establish the requirements for an appropriate fuel cell based powertrain for retro-fitment to the Class 156 DMU and fitment to future fleets of a modified AT200 EMU. The key requirements identified are as follows:

Table 3 – Overall Summary of Requirements

Requirement (per vehicle)	Class 156 FCEMU	AT200 FCEMU
Recommended minimum traction motor rating per vehicle	200 kW	200 kW
Recommended fuel cell power output rating per vehicle	150 kW	200 kW
Recommended battery capacity per vehicle	20 kWh @ 200 kW	20 kWh @ 200 kW
Recommended H2 storage capacity per vehicle per operating day	63 kg	75 kg

The following work packages identify the space available for the fuel cell based powertrain to be installed, and will then to develop a concept design that meets or exceeds the above requirements.

6 WP2 – Class 156 Installation Requirements

Two of the primary considerations for developing a fuel cell powered Class 156 are the space available for the new equipment required and the maximum allowable weight of this equipment. The new equipment that would be installed is sizeable, and in particular there will be a number of hydrogen storage tanks required to achieve a sensible operating range. In addition, the interfacing with the train's control system needs to be considered, and there are a number of auxiliary systems that would also need to be replaced as a result of the conversion.

6.1 Class 156 Weight Constraints

In terms of the allowable weight, it is understood that there are already concerns about existing vehicles' weight, particularly given the planned modification work to install CET tanks. Therefore it was important to understand what weight would be removed to set the upper limit for the replacement equipment that could be installed. The proposed list of equipment to be removed and each item's weight is listed in Table 4, with weight values taken from the Class 156 Maintenance Manual (Metro-Cammell, 1987):

Table 4 – List of Class 156 Equipment to be Removed per Vehicle

Item No	Description	Weight (kg)	Capacity (litres)	Page Ref
1	Fuel tank (dry)	490	1477	84
2	Fuel - based on 0.832 kg/l (Wikipedia)	1229		n/a
3	Engine Battery Box	230		112
4	Auxilliary Battery Box (assumed)	230		112
5	Auxilliary Heating & Ventilation Unit	164		66
6	Alternator / Rectifier	177		109
7	Driveshaft (engine to alternator)	tbc		
8	Cummins NT855-R5 (wet)	1568		77
9	Drive shaft (engine to transmission)	50		86
10	Voith T221R	720		88
11	Silencer & exhaust pipes	172		1615
12	Charged air cooler (nested pipework)	tbc		
	TOTAL	5029		

The total weight of equipment to be removed is in excess of 5,029 kg per vehicle. In view of the concerns about vehicle weight (please refer to Section 9.2), it is suggested that the weight of new equipment therefore needs to be limited to 4,000 kg.

6.2 Class 156 Space Constraints

In terms of the space available on the Class 156, the overall approach was to determine which items of equipment would be removed in order to generate a space envelope for new equipment. Retained items such as braking hardware would remain in their existing location as far as possible, and all equipment would need to be installed below the solebar and within gauging limitations. The individual steps taken were as follows:

- A 3D model was first constructed in SkecthUp Pro, based on data supplied by Angel Trains;
- The validity of this model was then verified during a visit to Etches Park Depot, hosted by East Midlands Trains;
- A list of items to be removed was determined;
- The 3D model was revised accordingly.

The design of the Class 156 made this process relatively straightforward as it has a relatively simple construction, with equipment bolted to the underside of its steel framework chassis as shown in Figure 3 (items to be removed shown in red):

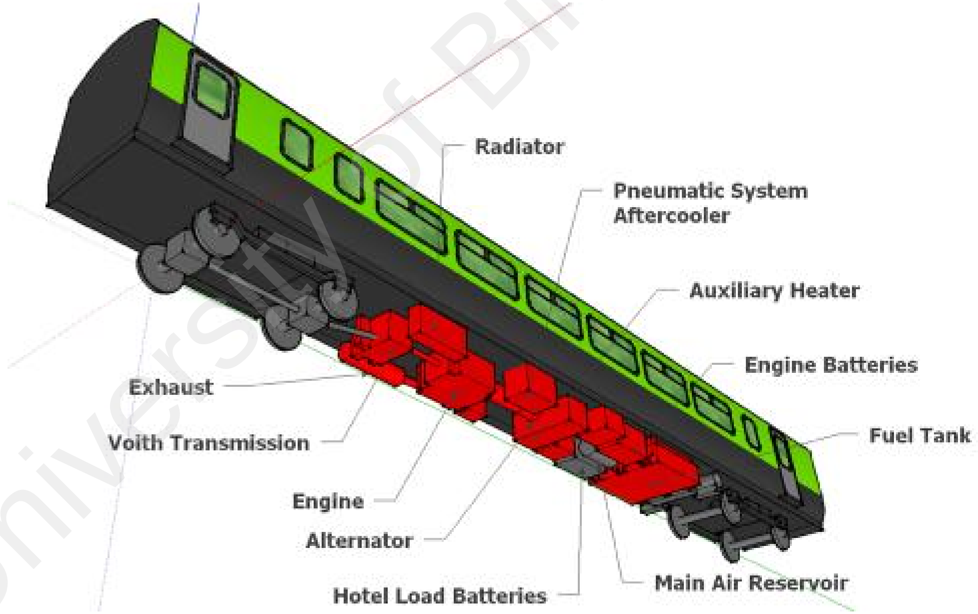

Figure 3 – Class 156 Underframe (FCSL, 2016)

It is understood that there are plans to install CET tanks on the East Midlands Trains Class 156 fleet. The tanks are to be installed forward of the leading bogies, which means that this area cannot be considered, i.e. all equipment should ideally fit between the leading and trailing bogies.

6.3 Class 156 Interfacing Requirements

An analysis was undertaken of the interface requirements that need to be considered. This considered including traction, braking and transmission.

6.3.1 Mounting Arrangements

The existing under-floor equipment is mounted to the chassis by means of bolts and vibration absorbing mounts. It is anticipated that the same means would be used to attach the replacement equipment, although it is noted that the attachment points and bracketry arrangements may be quite different.

6.3.2 Train Control System

The Class 156 has a relatively crude train control system that consists of 42 binary control wires. These control all of the primary functions of the train including throttle and brakes. These wires run down the length of the unit, and there is a large terminal box located at the intermediate end of each vehicle. It is anticipated that interfacing with these control wires should be relatively straightforward.

6.3.3 Driving Controls

In terms of the controls that relate to functions affected by the conversion, the intention is for these to remain largely unchanged as follows (please refer to Figure 4):

Figure 4 – Driving Controls on Class 156 (FCSL, 2015)

- The 3-step brake control lever to the left and the 7-notch throttle to the right would remain unchanged;
- The key to select neutral, forwards and backwards to the right above the throttle would remain unchanged;
- The gauges showing the main reservoir pressure and applied brake pressure would remain unchanged, as would the speedometer;

- In terms of fault lights, the lamps to indicate an engine fault, transmission fault, and alternator faults would be re-purposed to indicate a fault with the fuel cell, traction system and hydrogen supply system.

6.3.4 Braking & Traction Control System

The trains are friction braked with tread brakes applying approximately equal braking effort across all axles. The key challenge will be the integration of dynamic braking with the existing friction brakes to ensure that the required braking effort is achieved. The desire is to capture as much braking energy as possible to minimise energy consumption and reduce overall brake block wear, but developing an entirely new brake control system is likely to be prohibitively expensive. Therefore, any proposed conversion should aim to retain as much of the existing braking system as possible.

There is no antilock braking system (WSP) on Class 156, but there are axle end speed probes for the relatively crude traction control system. This system compares the rotational speed of the linked power axles with that of the trailer axles, and reduces the throttle if a mismatch is detected.

The new traction control electronics that would be fitted as part of any conversion would make the existing basic traction control system redundant, and would provide a degree of low adhesion protection for powered axles. However, it may be desirable to retain the existing wheelset speed probes to support the installation of a modern WSP system. This would greatly reduce the prevalence of wheel damage due to low adhesion conditions across all axles, noting that such a WSP system would need to interface with the system controlling the dynamic (i.e. regenerative) braking.

It should be borne in mind that unlike disc brakes, the existing tread brakes do not provide a linear braking force, and have a tendency to provide less braking effort at higher operating speeds. This would suit the characteristic of dynamic braking where electric motors are limited in the rate of braking energy (i.e. power) that they can absorb at higher speeds.

6.3.5 Bogies & Drivetrain

The power from the Voith transmission is transmitted to the innermost bogie of each vehicle by a driveshaft to master final drive gearbox on the inner axle of that bogie. There is then a second driveshaft across the bogie frame to a slave final drive on the outer axle of that bogie. The design concept is to install an electric traction motor where the Voith transmission currently sits, and connect this to the driveshaft down to the bogie instead.

In order to determine whether a reduction gearbox would be required on the output of the electric traction motor, it is necessary to know the maximum rotation speed of the driveshaft from motor to bogie. The Class 156 Maintenance Manual was reviewed, but this value did not appear to be stated. Therefore the calculation shown in Table 5 was undertaken:

Table 5 – Calculation of Driveshaft Rotation Speed for Class 156

Item	Value	Units	Page in Manual		
Wheel diameter - new	840	mm	76		
Wheel diameter - worn	776	mm	76		
Final drive (master)	3	gear reduction ratio	92		
Max operating speed	75	mph	56		
	120	kph			
	33.3	m/s			
Circumference - new	2637.6	mm	Circumference - worn	2436.6	mm
	2.6	m		2.4	m
Wheel rotation speed	12.6	rps	Wheel rotation speed	13.7	rps
	758.3	rpm		820.8	rpm
Drive shaft rotation speed	2274.8	rpm	Drive shaft rotation speed	2462.4	rpm

From the calculation, the maximum driveshaft speed is just under 2,500 rpm for a vehicle travelling at 75 mph with worn wheels.

6.4 Class 156 Additional Equipment Requirements

It is envisaged that a number of new auxiliary systems would be required in addition to the installation of the fuel cell powertrain. This would likely include the following:

- It is anticipated that electrical power for the train's auxiliaries would be provided by the fuel cell and hybrid battery instead of the alternator and auxiliary batteries. However, it may be prudent to retain a separate source of auxiliary power for use in the event of problems with the hybrid battery pack. This would require a much smaller enclosure than the existing auxiliary battery box, and the starter batteries would no longer be required;
- It is anticipated that a new electrical compressor with integral air treatment (cooling & drying) would be installed, powered from the fuel cell and hybrid battery pack, to replace the engine mounted piston pump. This would continue to provide air for the various on-train pneumatic systems including the brakes, suspension, doors, windscreen wipers and washers. This would allow the charged air cooler pipework to be removed;
- It may be necessary to replace the existing radiator with one that is more appropriately sized, and which has an electric cooling fan instead of the existing

hydraulically powered item. It is likely that the cooling capacity required by the fuel cell will be significantly lower than the combined cooling requirements of the engine and transmission;

- It is anticipated that waste heat from the fuel cell would be used to heat the saloon instead of the current arrangement using the auxiliary heater. A new arrangement to transfer the heat from fuel cell to saloon would therefore be required, and if insufficient heat energy is available, this would be supplemented by electric heaters powered by the fuel cell and hybrid battery;
- There would need to be additional safety equipment fitted, primarily to detect any hydrogen leaks that occur.

As mentioned previously, it may be sensible to install a modern WSP system, and this would need to integrate with any slip control that forms part of the traction control electronics.

7 WP2 – AT200 Installation Requirements

As with the Class 156, one of the primary considerations for developing a fuel cell powered 2-car version of this normally 3-car EMU is the space available for the new equipment required. In this case, the weight of the replacement equipment is less of an issue in terms of the train's structural and dynamic limitations.

A similar amount of equipment would, however, need to be installed on a fuel cell powered version of the AT200 to the Class 156. Although the train resistance values are lower, the AT200 would be equipped with air conditioning, which greatly increases the hotel load. This means that even greater space would be required for hydrogen tanks than for the Class 156.

Given that the train is already designed for electric traction, there would be less impact on auxiliary systems than for the Class 156. But with a far more complicated train control system, integration between fuel cell and traction package would be more complicated.

7.1 Development of 2-Car AT200

In terms of the space available for new equipment on a modified 2-car AT200, the initial stage required was to determine what the most sensible approach would be to converting a normally 3-car consist to 2-car. The 3-car AT200 for ScotRail will have total of 6 x 250kW motors, with all axles powered on the motor car, one vehicle with 50% powered axles and one trailer car, as shown in Figure 5 below:

Figure 5 – AT200 Configuration Showing with Motored Bogies in Red (UoB, 2016)

As discussed previously, a 75 mph 2-car set would only require 2 x 250kW motors. Therefore the sensible approach would be to remove the motor car with all axles powered and add a driving cab to the intermediate trailer car, as shown in Figure 5.

7.2 AT200 Weight Constraints

An analysis was undertaken of the components that would be removed from the AT200 if a conversion to fuel cell power to be undertaken, as shown in Table 6. As expected, the weight of the components that would be removed from the AT200 EMU is significantly less than for the Class 156 (there is no diesel fuel tank for example). This was calculated to be approximately 2,185 kg per vehicle as shown in Table 6.

Table 6 – List of AT200 Equipment to be Removed per 2-Car Unit

Item No	Description	Weight (kg)
1	Pantograph, earthing switch, high power transformer	340
2	Vacuum circuit breaker	130
3	Main transformer	3500
4	One of the main compressors	400
	TOTAL PER UNIT	4370
	AVERAGE PER VEHICLE	2185

7.3 AT200 Space Constraints

The list of equipment to be removed was used to generate an approximate space envelope for new equipment on the AT200. Unlike the Class 156, this includes a significant amount of roof space which is designed structurally for this purpose. Figure 6 and Figure 7 show the space available on the underframe:

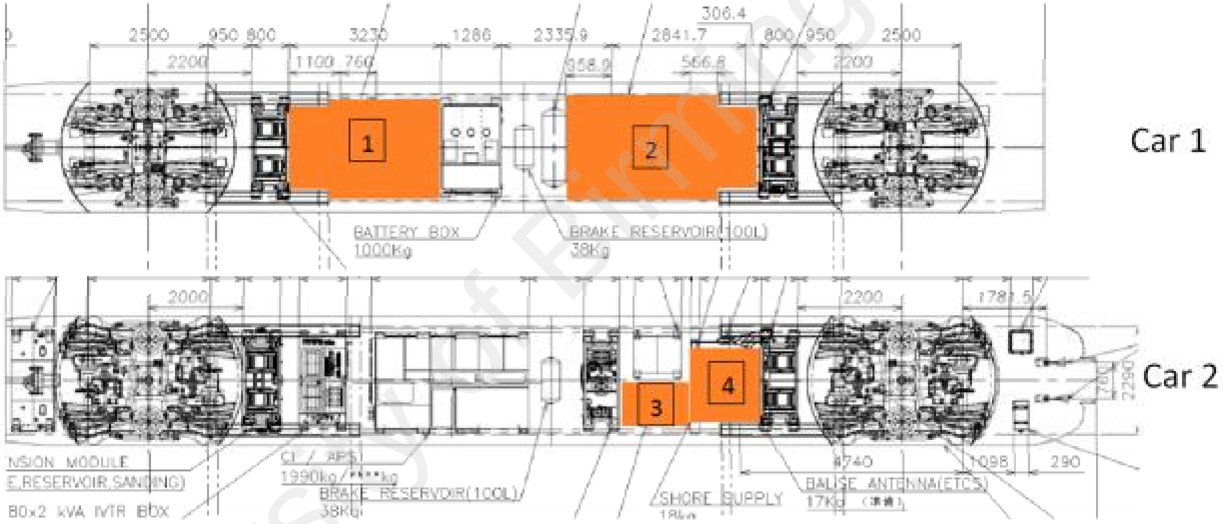

Figure 6 – AT200 Plan View of Space Available on Underframe (Hitachi Rail, 2016)

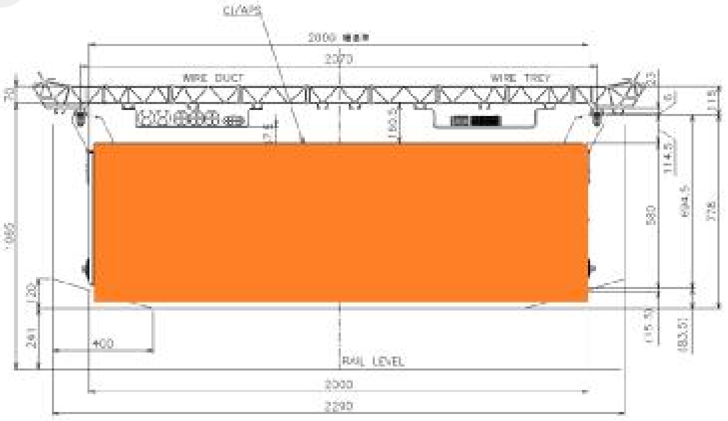

Figure 7 – AT200 Cross Section of Space Available on Underframe (Hitachi Rail, 2016)

In total, the approximate underframe space available as highlighted is as follows:

- Car 1 = 2130mm x 2290mm x 770mm (1) + 2400 x 2290 x 770 (2)
- Car 2 = 1000 x 1145 x 770 (3) + 1300 x 800 x 770 (4)

Figure 8 and Figure 9 show the space available in the roof area:

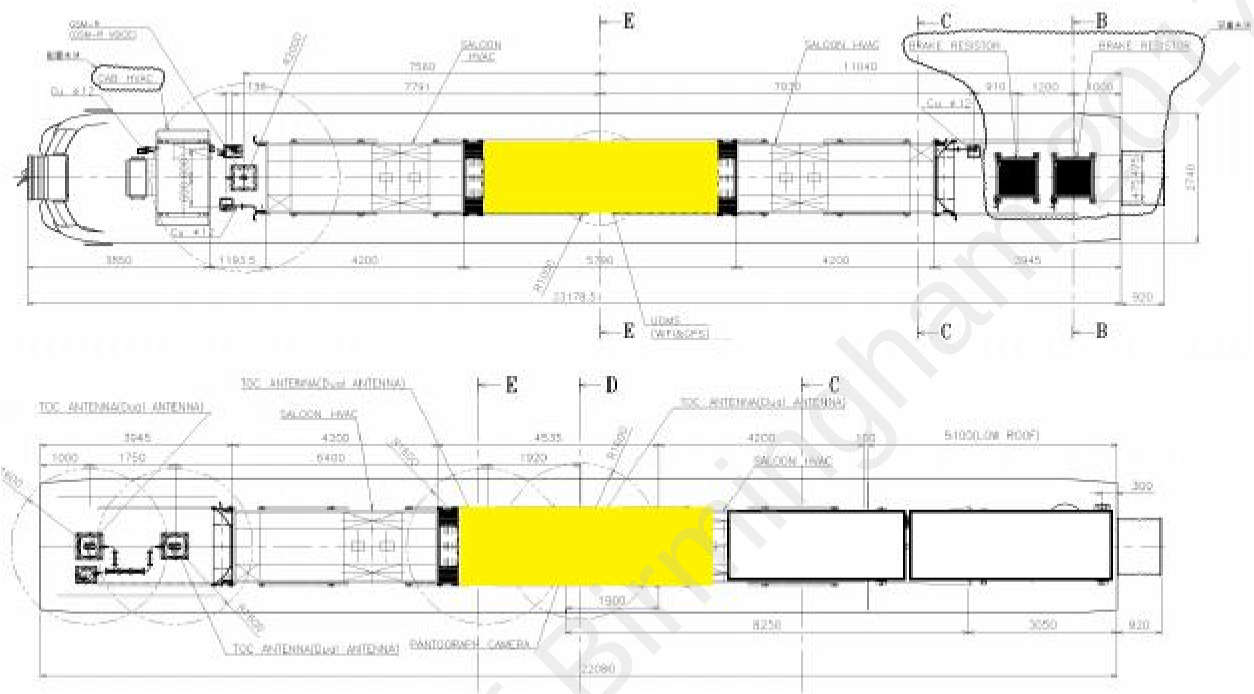

Figure 8 – AT200 Plan View of Available Roof Space (Hitachi Rail, 2016)

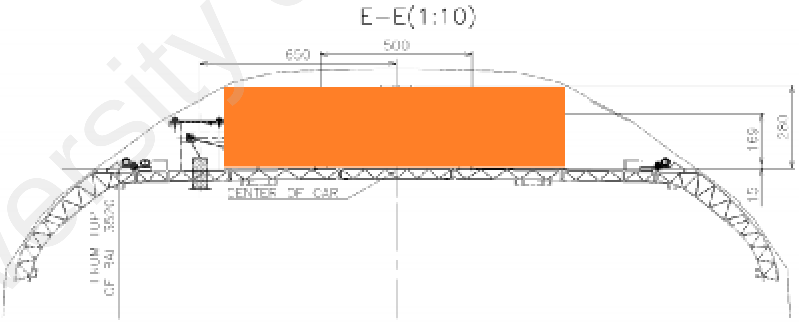

Figure 9 – AT200 Cross Section of Available Roof Space (Hitachi Rail, 2016)

The roof space available on both vehicles as highlighted in the drawings is similar, with each vehicle able to accommodate a volume of approximately 5700mm x 1200mm x 280mm.

7.4 AT200 Interfacing Requirements

As the AT200 is already equipped with electric motors and traction control electronics, the conversion to fuel cell power should in theory be more straightforward than converting a DMU. Indeed, the intention would be to retain the same traction equipment as per the

AT200 fleet currently being built for operation on ScotRail services. However, there is a far more sophisticated control system, and greater use of on-train electronics and condition monitoring equipment. These would be considered more fully at the detail design stage, but it is not anticipated that there would be significant issues designing appropriate interfaces as Hitachi has experience implementing such interfaces in projects carried out for the Japanese market.

8 WP2 – Hydrogen Production Requirements

The annual hydrogen requirement for a typical fleet was calculated based on the fleet operated by East Midlands Trains. This consists of seventeen Class 153 single car units and fifteen Class 156 two car units, totalling 47 vehicles. To simplify the presentation of figures, this was rounded-up to a typical fleet size of 50 vehicles.

In terms of mileages, the East Midlands Trains quoted a typical value of 500 miles per day for their Class 153 and 156 fleets. This agrees well with the STS simulations based on 8 return journeys per day on the N-S-N route which also equates to 500 miles per day. Therefore the annual consumption was calculated as follows:

- A fleet of 50 vehicles;
- Each vehicle does 500 miles per day, equating to 63 kg of hydrogen;
- It was assumed that each vehicle operates for 330 days per annum;
- This gives a total annual hydrogen consumption of approximately 1,040,000 kg of hydrogen per annum.

Assuming that hydrogen is generated over 360 days of the year (i.e. excluding Christmas and maintenance downtime totally 3 days), this would equate to a required generation capacity of approximately 2,900 kg of hydrogen per day. For a sense of scale, this is approximately eight times the on-site production capacity installed for the hydrogen bus fleet currently operating in Aberdeen.

However, Porterbrook Leasing subsequently suggested that their Class 156 multiple units typically cover 350 miles per day. This would reduce the required generation capacity to around 2,000 kg of hydrogen per day.

9 WP2 – Supplemental Stakeholder Requirements

Although stakeholder engagement was not due to commence until WP3, a number of discussions were held with representatives from Angel Trains, Porterbrook Leasing, Arriva Trains Wales, East Midlands Trains and Northern Rail during the course of WP2 and WP3. The following additional requirements were elicited during the course of these discussions.

9.1 Train Leasing Company Requirements

One of the key considerations for Angel Trains is range, and they suggested that the operating range for an FCEMU ideally needs to be in excess of 1,000 miles between re-fuelling to retain operational flexibility. For most fleets, this would mean that trains could continue to be re-fuelled every other day.

Porterbrook Leasing suggested that daily mileage for the routes over which their Class 156s typically operate is between 300 to 350 miles. They also highlighted that there would be an economics case to improve the traction performance of their Class 150/153/156 fleets for operation on capacity constrained routes, and it was noted that Porterbrook also have a small fleet of Class 155s which are part of the same generation of rolling stock.

Porterbrook Leasing suggested that although the majority of these fleets are to be modified in accordance with the forthcoming PRM requirements, it is conceivable that certain fleets could start to be retired as early as 2025. This would impact on the viability of such a comprehensive programme of vehicle modification, and they suggested that of these fleets the Class 150 is the most likely to continue in service beyond this point owing to its passenger door configuration. They further suggested that it would be worthwhile to consider the Class 158 fleets as these will likely also continue in service well beyond 2025.

9.2 Train Operator Requirements

Representatives from both Arriva Trains Wales and Northern Rail expressed a desire for significantly improved traction performance on the Class 150, 153 and 156 fleets, all of which have a similar drivetrain and performance. This would help to reduce journey times and thereby contribute to improvements in overall network capacity. Arriva Trains Wales also suggested that improved performance would help drivers recover lost time due to service disruption.

Northern Rail highlighted that train operators are increasingly being required to reduce their carbon footprint, and that fuel cell powered vehicles offer opportunity to make a substantial improvement in this respect. The energy source or fuel used to generate hydrogen therefore needs to have significantly lower overall carbon content per passenger mile, and would ideally be zero if renewable energy were to be used.

All three train operators are keen to improve customer experience, particularly in the following areas:

- The Class 150, 153 and 156 fleets have high levels of noise and vibration in the saloon, mostly due to the diesel engine. Any means of reducing this such as fitting a quieter powertrain would be beneficial;
- The saloon heating on the Class 156 fleet is inadequate in cold conditions, with the auxiliary heater only capable of increasing the saloon temperature to between 10 and 15 degrees above ambient. Any means of resolving this issue would be welcome;
- There is a programme to install CET on Class 156 fleets. There are concerns about the additional weight that this will incur, and any programme of modification should seek to reduce the weight of the drivetrain;
- The limited output from the alternator is already causing issues, and limits the ability to provide modern on-train facilities such as at-seat charging points. A means of providing a higher capacity electrical supply is becoming increasingly necessary.

In terms of re-fuelling arrangements, Class 150/3/6 multiple units are routinely stabled away from the main depot(s). Therefore any fleet fitment would need to consider the need for additional remote fuelling points. East Midlands Trains helpfully suggested that 3 additional fuelling points would probably be sufficient for their fleet, but that for an initial trial it may be possible to diagram modified trains to return to the depot each night.

9.3 Train Maintainer Requirements

Northern Rail, Arriva Trains Wales and East Midlands Trains need to reduce maintenance requirements and associated costs across their fleets. The prospect of replacing maintenance intensive components including the engine, transmission, mechanically driven alternator and diesel fired auxiliary heater with a relatively low maintenance electrically driven systems is therefore very attractive.

Both Northern Rail and East Midlands Trains pointed out that the Class 156 currently has no WSP, and that units suffer from significant levels of wheel damage in low adhesion conditions. They suggested that any programme of conversion should consider the opportunity of installing WSP as part of the modification programme.

10 WP3 – Concept Design Amendments

Concept designs were developed for both the Class 156 and AT200 in accordance with the identified requirements. However, a number of recent developments had immediate implications for the concept design as follows, and were discussed with Future Railway prior to the issue of the related interim report.

10.1 Fuel Cell Supplier

The intention had been to use fuel cell equipment supplied by Hydrogenics, as per Issue 2 of the proposal for this project. However, Hydrogenics and Alstom recently announced their cooperation to produce a fleet of hydrogen powered fuel cell regional trains for operation in Germany. This contract precludes Hydrogenics from developing similar relationships with other train manufacturers such as Hitachi. It was therefore necessary to find an alternative supplier for fuel cell equipment, and Ballard were selected:

- Ballard are one of the world's largest suppliers of fuel cells;
- They have worked previously on rail-related applications including mining locomotives, streetcars and switching locomotives;
- It is Ballard equipment installed on the aforementioned fleet of buses in Aberdeen, which is reportedly reliable and well-supported;
- Ballard have recently announced contracts to supply fuel cells for trams in China, and they have also announced their intention to start the large-scale manufacture of fuel cells for incorporation into Chinese bus fleets.

Of their current range, Ballard currently supply fuel cells in 104 kW modules, and it is these that have been used as the basis for the Class 156 concept design. However, it should be noted that Ballard are currently developing a 200 kW fuel cell for transport applications. Although yet to be proven in service, this 200 kW unit would potentially provide a more compact and cost-effective solution, and Hitachi elected to base their concept on this.

10.2 Design for 3-Car AT200

As discussed previously, it was agreed that the design for the AT200 would be based on a 3-car consist, as opposed to the 2-car consist originally suggested in the proposal in order to reduce the degree of vehicle modifications required and to provide greater space for new equipment.

10.3 IGBT Converters for Class 156

It became apparent that the smallest SiC converter that Hitachi are designing will be rated for 500 kW for operation on modern EMU fleets. While this would work well for the AT200 design concept which has two 250 kW rated motors on its “power car”, it would not be suitable or the Class 156 which has a single 250 kW traction motor on each vehicle. Therefore it was necessary to develop the concept design for the Class 156 based on the use of a modern IGBT converter.

11 WP3 – Concept Design for Class 156

The design philosophy for the Class 156 was in-line with the requirements specified previously, i.e. to install a 200 kW fuel cell, a minimum 20 kWh battery pack to capture braking energy, and sufficient hydrogen storage to facilitate at least a 500 mile range, estimated at 63 kg. The actual concept design was developed based on using the following "building blocks" per car:

- 2 x Ballard 104 kW fuel cell modules, including air blower, coolant pump and DC-DC converters;
- A more modern electrically driven fan cooled radiator;
- An electrically driven air compressor from Knorr-Bremse;
- A railway specific 22 kWh battery pack from SAFT including advanced thermal management system;
- A 250 kW rated traction motor from Hitachi (as used on the AT200);
- An appropriately rated IGBT traction converter from Hitachi;
- 350 bar hydrogen storage tanks from the Luxfer Group.

Please note that at this stage, the intention was to establish whether it would be feasible to develop an FCEMU version of the Class 156, and it would be expected that the actual design would be subject to significant refinement prior to any trial.

11.1 Weight Analysis

An estimate was made of the total weight of components to be installed on the Class 156 FCEMU as shown in Table 7. As shown, the overall mass of components to be installed is within the 4,000 kg limit proposed for the design.

Table 7 – List of Class 156 Equipment to be Added per Vehicle

Item No	Description	Weight (kg)	Number Required	Sub Total (kg)
1	Fuel cell modules (2 off)	500	2	1000
2	Hydrogen tanks (9 off)	43	9	387
3	IGBT converter	850	1	850
4	Battery pack	503	1	503
5	Battery thermal management system	145	1	145
6	Traction motor	600	1	600
7	Radiator for fuel-cells	100	1	100
8	Hydrogen pipework, valves & ancilliaries	100	1	100
9	Compressor	250	1	250
			TOTAL	3935

11.2 Space Analysis

The approach taken to the design was to only use the space envelopes available from equipment that was to be removed or replaced (i.e. retained components such as the main reservoir were not moved in order to accommodate the new equipment). But even with this restriction, it is clear from the model shown in Figure 10 that there is sufficient space on the underframe to comfortably accommodate all of the equipment required:

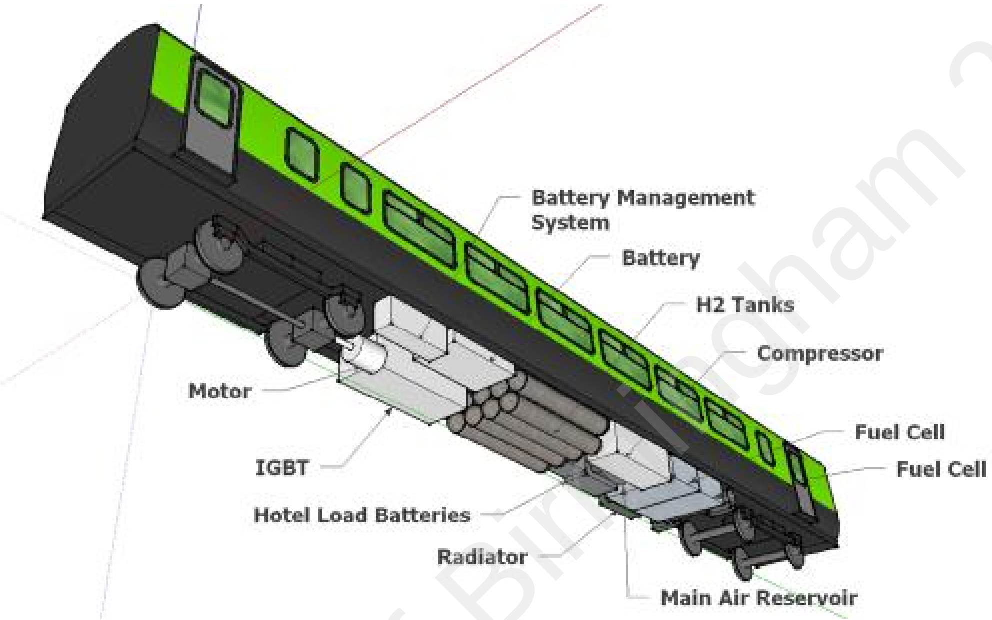

Figure 10 – Concept Design for Class 156 FCEMU (FCSL, 2016)

The raft of nine hydrogen storage tanks is capable of storing a total of 69.3 kg of hydrogen, which comfortably exceeds the 63 kg required to achieve a 500 mile operating range.

Please also note that although the traction motor is rated at 250 kW, this is its rating for continuous operation, and for the purposes of this application, it would actually deliver 300 kW. Given that one of the stakeholder requirements was for improved acceleration, this would be advantageous, as well as enabling a higher proportion of braking energy to be captured and reused. The repeat STS simulations based on the concept design being undertaken for the next work package will therefore be based on the 300 kW value.

11.3 Interfacing with Existing Equipment

As discussed previously, the interfacing arrangements for the control system on the Class 156 are relatively straightforward, with the exception of requirement to integrate dynamic and friction brakes. Consideration was therefore given as to how this could most sensible be achieved for trial fitment.

The starting point for the concept design was to change or modify as little of the existing system as little as possible. It was also assumed that for any trial that only a single car would be modified in order to minimise cost, and to give the trial unit the ability to "limp home" in the event of problems with the fuel cell powered vehicle. It was also assumed that WSP equipment would not be installed as part of the modification for trial, but it is noted that this would be likely were a fleet fitment to be undertaken.

On this basis, only the braking equipment for the power bogie of the fuel cell powered vehicle would be modified. This would mean that even in the event of a complete failure of the modified braking system, 75% of the train's brakes would continue to operate as normal.

It has been assumed that there would be no change to the driver's controls, and that as far as sensibly achievable, the braking rate would match that of the existing trains, or provide a slightly improved braking performance across the speed range. It is noted that, as the units are tread braked, the actual braking rate achieved varies for a given brake step as the speed of the vehicle falls. But for the ease of analysis it was assumed that:

- Step 1 ≈ 0.3 m/s^2 ≈ 3%g;
- Step 2 ≈ 0.6 m/s^2 ≈ 6%g;
- Step 3 and Emergency ≈ 0.9 m/s^2 ≈ 9%g.

If the driver of the trial unit were to initiate an emergency or Step 3 brake demand, it is suggested that the dynamic brake be disabled and that the system revert to being fully friction-braked. This would provide increased driver confidence and assist with safety approvals, while resulting in only a marginal reduction in the energy recovered as drivers should mainly be using Step 1 and 2.

Looking at the rate of energy dissipation, ignoring the contribution from train resistance, the braking system needs to absorb or dissipate energy at a rate of 900 kW per car. Given that the maximum that the traction motor can absorb is 300 kW, this implies that there would need to be a system to blend the braking effort from friction and dynamic brakes when stopping from higher speeds. There are various options as to how this could be implemented with the simplest approach probably being to leave the trailer bogie "as is", and vary the blend between friction and dynamic brake effort only on the power bogie. This would to a degree limit the amount of braking energy recovered, but again it would help provide reassurance to the driver, and make obtaining safety approvals more straight forward.

11.4 Hydrogen Safety

This would be the first application of hydrogen as a fuel on the UK rail network, and the first rail vehicle to have hydrogen storage tanks beneath the sole bar. Consideration was therefore given at the concept design stage to the associated risks and how these could be mitigated.

While hydrogen is non-toxic, it is flammable in sufficient concentrations, and the storage of any gas at a pressure of up to 350 bar can be dangerous in the event that a storage tank ruptures for example. In mitigation of these risks:

- Modern storage tanks are tested for very high levels of impact resistance – they are literally “bullet-proof”;
- The tanks incorporate pressure relief valves that release the gas in a controlled manner in the event of an excessive pressure build-up caused by a fire for example;
- The pressure in the pipework is typically regulated down to 5 bar as soon as it leaves the tanks;
- The tanks are fitted with a system that detects the rapid flow associated with a leak or rupture and this automatically shuts off the supply of hydrogen;
- The on-train control system for the fuel cells would have a leak detection algorithm which constantly monitors the pressure and volume in the storage tanks, and any mismatch between the actual flow and what the fuel cell ought to be consuming would result in an immediate shut-down;
- This would be supplemented by dedicated leak detection equipment, but this is not considered to be appropriate as the primary form of protection;
- The proposed location of the tanks is central to the vehicle, so a train-to-train collision or collision with a car on a crossing for example would need to be very severe for damage to be sustained by the tanks.

There is precedence for the use of flammable gas stored at high-pressure on public transport applications in the UK. The UK has two fleets of fuel cell powered buses, and there are numerous fleets of buses that operate on natural gas, which is also flammable and stored at relatively high pressures. But there is a key difference between the installation on buses and the proposed Class 156 design in that UK bus fleets have the gas storage tanks mounted on the roof. In the event of a leak or a rupture of tank or pipework on a bus, hydrogen is so light that it immediately dissipates upwards. As long as the bus is not in an enclosed space such as a depot or tunnel, the risk of having a high enough concentration of the gas to ignite is extremely low.

For the Class 156 the tanks would be mounted below the sole bar. Therefore any leak or rupture of pipework would have the potential for hydrogen to enter the passenger compartment, with the attendant risk that it could build up to a sufficient concentration to be flammable. In mitigation of this risk:

- The installation would be designed such that were a leak to occur, there would be no path for the hydrogen into the passenger compartment. This would likely be achieved by installation an impermeable “shield” above the hydrogen storage tanks, pipework and fuel cell such that any hydrogen is safely vented to the side(s) of the vehicle;
- As mentioned above, the hydrogen storage tanks incorporate pressure relief valves that operate automatically in the event of excessive pressure build-up. It is proposed that additional pipework be installed such that any hydrogen released is vented from the top of the vehicle, not at sole bar level.

Further consideration needs to be given as to whether the tanks ought to be enclosed or not. Enclosing the tanks would offer an added degree of protection against damage from projectiles or debris at track level. However, care would need to be taken to ensure appropriate ventilation such that were hydrogen to escape, it would vent and dissipate in a safe and controlled manner.

It should be noted that fuel cell powered cars / automobiles have hydrogen tanks that operate at a significantly higher pressure (700 bar), and these tanks are typically located under or within the vehicle, all-be-it at much lower storage capacities (typically 5 kg).

12 WP3 – Concept Design for AT200 – Space Envelope Analysis

The design philosophy for the AT200 was originally intended to be the same as for the Class 156, with a 200 kW fuel cell working in tandem with a 20 kWh battery pack. The same "building blocks" were considered as per the Class 156 with the exception of the use of SiC traction converter technology. But as the design developed, it became apparent that, without undertaking significant modifications to the vehicle, it is still not possible to accommodate more than 127 kg to 150 kg of hydrogen per vehicle using standard 350 bar compressed gas storage technology.

As mentioned in relation to the Class 156, the use of 700 bar storage was considered as a potential solution. However, all current standards for heavy-duty transport applications for fuel cells are based on fast-fill 350 bar technology. Developing bespoke technology to go to 700 bar would therefore be prohibitively expensive, as well as resulting in a less efficient system due to the losses in compressing the gas to such high pressures.

Hitachi are continuing to seek a solution, and are currently evaluating a number of alternative options that could provide a solution including going to a 4-car configuration. This would mean that the train would consist of two power cars and two trailer cars (i.e. adding a second trailer car), thereby providing more space for equipment and hydrogen tanks without adding further traction motors. Initial analysis suggests that this would also provide sufficient space for the 300 kg of hydrogen that would be required for a 4-car set.

Another option that is being considered is to alter the balance between fuel cell rating and battery size. One of the key challenges on the AT200 is finding sufficient space for the 200 kW fuel cells and associated Balance of Plant. Hitachi are considering whether it would be possible to install a lower overall fuel cell capacity (i.e. 2 x 200 kW fuel cells for a 4-car set) and allying this to a greater capacity of traction batteries. So where the original concept used the batteries primarily to capture braking energy and boost tractive effort under hard acceleration, the new concept would see the batteries provide the primary power for traction and hotel load, with the fuel cell operating to continually re-charge the battery packs throughout the operating day.

13 WP3 – Depot Based Hydrogen Production & Filling

As presented previously, a notional fleet of 50 Class 156 FCEMU vehicles (i.e. a fleet of 25 x 2-car units), would require 2,900 kg of hydrogen to be supplied daily. Such large scale requirements would almost certainly require the hydrogen to be produced on-site, and this could be achieved in a number of different ways as follows.

13.1 Electrolysis

Industrial electrolysers typically take in 3-phase electricity from the National Grid and use this to split water into hydrogen and oxygen. The hydrogen is then stored as a compressed gas on-site and the oxygen typically released into the atmosphere. The fleet of fuel cell buses in Aberdeen are re-fuelled by three depot-based electrolysers, each contained in a standard size shipping container, as shown in Figure 11:

Figure 11 – Hydrogenics Electrolysers for Aberdeen Bus Fleet (UoB, 2015)

As noted previously, it would require 24 such electrolysers to provide sufficient supply for a 50 vehicle train fleet. This is unlikely to be economically viable, and would require a large land-take (i.e. 24 x standard shipping containers). However, there are larger electrolysers available, with the largest standard commercially available electrolyser produced by Siemens under the “Silyzer 200” brand. Rated at 1.25 MW, each skid-mounted unit is capable of producing approximately 500 kg per day.

13.2 Steam Reforming

The most common means of generating large quantities of hydrogen within the process industry is to use Steam Methane Reforming (SMR) to extract hydrogen from natural gas.

Linde Group have recently started selling modular steam reformation plants under the "HydroPrime" brand. This is a relatively compact modular system with each unit able to generate around 720 kg of hydrogen per day.

Figure 12 – Linde HydroPrime Steam Reformation Plant (Linde, 2016)

13.3 High Temperature Fuel Cells

There exist static fuel cells that operate at high temperatures that are typically used to generate electricity for distributed generation. These units internally reform natural gas and then use the hydrogen directly in a high-temperature fuel cell to generate electricity. However, the output of these plants can be configured such that they can be used to generate a variable balance between electricity and outputting a source of high-grade hydrogen. This offers the possibility of using natural gas to generate electricity to feed in to the local grid or power the depot (particularly during peak hours), and then generating hydrogen for use for traction during off-peak periods. Fuel Cell Energy provide such units under their "Direct Fuel Cell" brand, with standard units in hydrogen generation configuration producing up to 1,270 kg of hydrogen per day.

13.4 Comparison of Options for Hydrogen Generation

The three options described above could sensibly generate sufficient quantities of hydrogen for a notional 50 vehicle fleet of FCEMUs on-site at a railway depot. The following work package will compare their capital and operating costs, as well as the emission levels from each.

13.5 Hydrogen Filling Arrangements

It is proposed that standard TK25 high flowrate re-fuelling dispensers as used for bus fleets would also be suitable for re-fuelling trains. The dispensers incorporate various safety features including a failsafe hose that self-seals should the vehicle be driven off with the hose still attached, and they have an appropriate rate of delivery. The Aberdeen bus fleet for example typically takes 6 minutes to fill 24 kg of hydrogen. The quantity of hydrogen required for a railway vehicle is substantially higher, but even at 60 to 70 kg, this would still mean that a completely empty tank could be re-charged in under 20 minutes, i.e. less than the time currently taken to fill a DMU with diesel.

14 WP3 – Interim Conclusions

The objective of this third work package was to develop a concept design for installation of the fuel cell based traction system for both the 2-car Class 156 and 3-car AT200, as well as to establish a concept design for the generation and fuelling arrangement that would be required for a notional fleet of FCEMUs.

14.1 Summary of Class 156 Concept Design

The weight of equipment to be added to the Class 156 is estimated to be just under the proposed 4,000 kg limit. In terms of the space available, a concept has been developed that accommodates all of the equipment required to achieve a 500+ mile range as specified by the TOCs consulted during this study. It is likely that with further design refinement, this could be increased to a limited degree, but there is insufficient space available using existing 350 bar compressed gas storage technology to achieve the 1,000 mile range specified by Angel Trains.

Other than the braking system, interfacing with the existing train control system is likely to be relatively straightforward. A simplified approach has been suggested for integration of dynamic and friction brakes for the purposes of a trial that would significantly reduce the effort required to design and obtain approvals for the required modifications.

Consideration has also been given to the risks associated with use of a flammable gas and its storage at high pressure. A number of appropriate mitigations have been proposed including both passive and active safety measures, including specific measures as a result of the storage tanks being located below the sole bar.

14.2 Summary of AT200 Concept Design

Using standard 350 bar compressed gas storage technology, it has not been possible to develop a concept design with the required range of 500 miles for a 3-car AT200. Hitachi are currently evaluating a number of alternative approaches including going to a 4-car configuration, and adopting an alternative design philosophy with smaller fuel cell capacity allied to higher capacity battery packs, as used on the New Energy Train project led by Hitachi for the Japanese market.

14.3 Summary of Hydrogen Generation & Refuelling Concept

There are three practical ways of generating sufficiently high-grade hydrogen in the required quantities on-site through electrolysis, steam reformation and high temperature "direct" fuel cells. The first cost and operation costs of each will be compared in the next work package to determine which is the most promising.

15 WP4 – Revisions to Concept Designs & Models

The original STS simulations were based on a range of nominal traction motors with typical tractive effort curves. The predictions of journey time, energy and fuel consumption therefore needed to be re-assessed based on the actual components selected for the concept design. However, there were also a number of enhancements made to the base Class 156 DMU model, as discussed below, and the next iteration of a design for the AT200 was also developed.

15.1 Class 156 DMU

The Voith transmission modelled in the original simulations was based on a single efficiency value throughout the speed range of 80%. This was subsequently refined to incorporate the actual efficiency curve as supplied by the Future Railway, with a varying efficiency across the speed range. This had the effect of reducing the predicted traction energy consumption of the Class 156 DMU. This lower energy consumption figure was used as the basis for all subsequent comparisons between diesel and fuel cell powertrains.

The guideline fuel consumption quoted by both Angel Trains and Porterbrook was 1 litre of diesel per vehicle per mile. It is understood to be difficult to be more accurate than this as the actual fuel consumption varies significantly according to duty cycle, route and driving style, and that this is the benchmark value they therefore use internally for comparison and prediction purposes. According to the output from the STS modelling, this suggests that the engine efficiency of the Class 156 DMU is lower than originally assumed at around 30%. This value is entirely plausible given the age of the Cummins diesel engines, and the significant time spent at idle during coasting, braking and dwell time at stations and depots.

15.2 Class 156 FCEMU

The original simulations established that a minimum installed power to maintain or improve on current journey times was around 200 kW per vehicle. The concept design for the Class 156 FCEMU was therefore based on the standard 250 kW rated motor from Hitachi, as used on their new build of AT200 EMUs for ScotRail. However, it became apparent that the 250 kW rating is for continuous power, and when the traction curve was examined more closely, each motor actually outputs up to 330 kW under hard acceleration.

It is acknowledged that the use of a motor with 65% greater power output than the minimum deemed acceptable could be considered excessive. However, it was felt that the combined benefit of improved acceleration and the ability to capture significantly more braking energy justify the continued use of these motors for the concept design.

For the FCEMU, the compressor for the train's pneumatic system would be electrically powered, rather than driven directly from the engine. It was therefore felt necessary to increase the hotel load from 15 kW for to 20 kW to account for this.

The efficiency of the regenerative braking system was originally assumed to be 50%. This was acknowledged at the time to be pessimistic, but was felt to be a good starting point for the original benchmark simulations. However, data from Hitachi's Hayabusa project suggests that an efficiency of 80% was achieved (Railway Gazette International, 2007). The models were therefore revised to incorporate this new value.

As calculated previously, the drive shaft to the powered bogie of the Class 156 DMU rotates at approximately 2,500 rpm at maximum speed, but calculations showed that the Hitachi 250 kW rated motors go up to 5,000 rpm. This suggested that the gear ratio would probably need to change in order to obtain the best performance. The optimum ratio is dependent on various factors including the duty cycle, train resistance characteristics, and the shape of the motor's tractive effort curve, and is difficult to predict from calculation / first principles. Therefore models with three different gear ratios were simulated to try to establish an optimum (or close to optimum) ratio:

- A gear ratio of 3.00, as currently installed on the Class 156 and representing the direct connection of the new traction motor to the existing drive shaft to the powered bogie;
- A gear ratio of 4.87 as used on the ScotRail AT200 EMU (4.87), noting that these units are intended to operate at 100 mph. Selection of this ratio would require either a modified final drive on the power bogie, or an additional gear reduction unit on the output of the traction motor;
- A gear ratio of 6.00 to reflect the lower top speed of the Class 156 FCEMU when compared to the ScotRail AT200 EMU. This could possibly be achieved using a modified final drive on the power bogie, but more likely an additional gear reduction unit on the output of the traction motor would be required.

The selection of the best gear ratio was based on the evaluation of each variant in terms of performance and energy efficiency, as discussed in Chapter 16.

15.3 AT200 FCEMU

As discussed previously, there is insufficient space on a 2-car or 3-car AT200 to install sufficient hydrogen storage to achieve the required 500 mile range. A third iteration was therefore developed based on a 4-car AT200, the addition of a second trailer car offering additional space for hydrogen storage, as indicated in Figure 13.

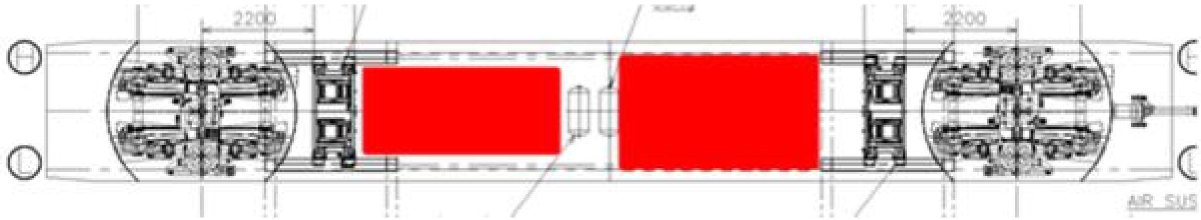

Figure 13 – Space Available on AT200 Trailer Underframe (Hitachi, 2015)

The total estimated hydrogen storage for this arrangement was approximately 250 kg. Although the original prediction was 75 kg per car to achieve the required 500 mile range (i.e. a total of 300 kg for a 4-car train), it was felt that there would probably be scope to reduce the hotel load by, for example, fitting a more efficient air-conditioning system. The model was therefore updated to reflect this new design with a range of power options, based on different numbers of installed motors. Three sets of simulations were undertaken with the following levels of installed power on the 4-car unit:

- 2 x 250 kW rated motors (i.e. an actual power output of 660 kW in total)
- 3 x 250 kW rated motors (i.e. 990 kW in total)
- 4 x 250 kW rated motors (i.e. 1,320 kW in total)

The selection of the best option was again based on performance and energy efficiency, as discussed in Chapter 16, noting that the 4 x 250 kW option would be the easiest to implement as this could be configured as a standard power bogie on each of the leading vehicles.

In order to improve traction in low adhesion conditions, it may be preferable to distribute the installed power across a higher proportion of axles. The most likely arrangement would then be to have two power bogies on each of the leading vehicles with, for example an 8 x 125 kW rated motor configuration instead of a 4 x 250 kW configuration.

16 WP4 – Concept Design Performance Analysis

The STS simulations were repeated for the concept design Class 156 FCEMU and 4-car AT200 FCEMU, and compared with those for the updated model of the Class 156 DMU.

16.1 Class 156 FCEMU

The results for the Class 156 FCEMU were as shown in Table 8 in terms of predicted journey time and total traction energy consumption for the range of gear ratios discussed in Chapter 15.

Table 8 – Concept Design Class 156 FCEMU Performance

Vehicle Type	Gear Ratio	Return Journey Time (mins)	Fuel Energy Consumed (kWh)	Quantity of Hydrogen for 500 miles
Class 156 DMU	3.00	105 mins	637 kWh	n/a
Class 156 FCEMU	3.00	104 mins	301 kWh*	61 kg**
	4.87	99 mins	308 kWh*	63 kg**
	6.00	98 mins	304 kWh*	62 kg**

* Includes regenerative braking at 80% overall efficiency.

* Includes an allowance of 20 kW for auxiliary systems & hotel load.

For a small increase in traction energy consumption, it was concluded that there would be a significant improvement in traction performance for the higher gear ratios. Therefore the concept design and all subsequent simulations, calculations and comparisons were based on the Class 156 FCEMU with a gear ratio of 6.00. It was also noted that the reduced hydrogen storage requirements would require only 8 storage tanks instead of the 9 tanks originally estimated.

Subsequent to this, it was realised that the hydrogen storage tanks from Luxfer are considerably heavier than the original estimate. This additional weight is partly offset by the reduction in hydrogen storage requirements from 9 tanks to 8, but the overall weight saving is lower than originally estimated at around 300 kg, as shown in Table 9.

Table 9 – Revised Weight of Class 156 Equipment Added

Item No	Description	Weight (kg)	Number Required	Sub Total (kg)	Source
1	Fuel cell modules (2 off)	500	2	1000	Ballard
2	Hydrogen tanks (8 off)	138	8	1104	Luxfer
3	IGBT converter	850	1	850	Hitachi
4	Battery pack	503	1	503	SAFT
5	Battery thermal management system	145	1	145	SAFT
6	Traction motor	600	1	600	Hitachi
7	Radiator for fuel-cells	100	1	100	estimate
8	Hydrogen pipework, valves & ancilliaries	100	1	100	estimate
9	Compressor	250	1	250	Hitachi
10	Hydrogen	63	1	63	previous calculations
			TOTAL	4715	

However, the mass of the two 100 kW fuel cells has yet to be confirmed by Ballard, and the expectation is that these units will weigh significantly less than that quoted in Table 9. It is likely that the overall weight of the fuel cell powertrain will therefore be around 500 kg less than that of the diesel powertrain.

16.2 AT200 FCEMU

The results for the AT200 FCEMU were as shown in Table 10 for the various configurations with different levels of installed power.

Table 10 – Concept Design AT200 FCEMU Performance

Vehicle Type	Installed Power Per Car (actual)	Return Journey Time (mins)	Fuel Energy Consumed (kWh)	Quantity of Hydrogen for 500 miles
Class 156 DMU	106 kW	105 mins	637 kWh	n/a
AT200 FCEMU	164 kW (2 motors)	111 mins	341 kWh*	69 kg**
	246 kW (3 motors)	102 mins	349 kWh*	71 kg**
	328 kW (4 motors)	99 mins	346 kWh*	70 kg**

* Includes regenerative braking at 80% overall efficiency.

** Includes an allowance of 50 kW for auxiliary systems & hotel load.

From the above table, it is clear that the option with 2 motors does not provide satisfactory performance, with journey times in excess of the existing Class 156 DMU. Both the 3 motor and 4 motor options achieve improved journey times, with a reduction in overall fuel consumption. Therefore the concept design and all subsequent simulations, calculations and comparisons were based on a 4-car AT200 FCEMU with a total installed power of 4 x 250 kW rated motors.

The simulations using the concept design powertrain all achieved a better overall efficiency than the original benchmark simulations. This resulted in a reduction in the quantity of hydrogen per vehicle from 75 kg to 70 kg, giving a revised total hydrogen storage requirement for a 4-car set of 280 kg. As noted previously, the 4-car set can accommodate approximately 250 kg of hydrogen. While there remains a 30 kg shortfall, it is likely that steps could be taken to reduce the relatively high hotel load in order to make this a viable design. Calculations showed that, were it possible to bring the hotel load down from 50 kW per car to 40kW per car by using a more efficient air conditioning system, the overall hydrogen required for a 4-car set would fall to 63 kg per car, to give a total hydrogen storage requirement of 252 kg for a 4-car set.

17 WP4 – Concept Design Emissions Performance

In stark contrast to diesel engines, fuel cells are zero emissions at point of use, generating only electricity, excess heat, and a small quantity of pure water. However, depending on how the hydrogen used to power the fuel cell is generated, the overall emissions situation is more complicated. The ideal is to generate the hydrogen through electrolysis from electricity from nuclear or renewable sources such as wind turbines so that the overall process becomes truly zero emissions. However, it was felt that two further scenarios needed to be analysed in order to provide a more balanced view:

- Hydrogen generated through electrolysis using wholesale electricity;
- Hydrogen generated through the reformation of natural gas.

The comparison was made based on predictions for a notional fleet of 50 vehicles (i.e. 25 x 2-car Class 156 units), with an annual mileage of 115,500 miles (i.e. 330 days at 350 miles per day). The wholesale electricity option was analysed based on the current UK generation mix, and calculations for diesel or natural gas from the point at which the fuel is delivered to the railway depot.

17.1 Carbon Emissions

The annual CO2 emissions were estimated to be as shown in Table 11, with the detailed calculations contained in Appendix G.

Table 11 – Predicted Carbon Emissions

Vehicle Type	Energy Source	Tonnes CO2 per Fleet (tonnes
Class 156 DMU	Diesel	15,500 tonnes
Class 156 FCEMU	Electrolysis	20,600 tonnes
	Gas Reformation	8,900 tonnes

This suggests that the production of hydrogen from electrolysis would result in a significant overall increase in carbon emissions of 33%, and hydrogen produced through the reformation of natural gas would results in an overall decrease of 43%.

17.2 Other Pollutants

There is increasing concern globally about NOx and particulate emissions from diesel engines, with particulates now accepted to be a carcinogen by the World Health Organisation (2012).

It was not possible to obtain emissions data for the existing Cummins diesel engine, but anecdotal evidence suggests that they produce considerable particulate emissions. It is understood from one of the TOCs consulted that a silencer can weight 40 kg more when it is removed from a vehicle than when it was fitted. This is perhaps not surprising diesel engines of this generation were designed before these dangers of NOx and particulates were widely acknowledged. They do not feature modern clean burn technology, nor the exhaust gas after-treatment that is now commonplace for diesel traction.

By contrast, regardless of how the hydrogen is generated, converting to a fuel cell powertrain would massively reduce the overall NOx and particulate emissions levels. In the case of hydrogen from electrolysis from nuclear or renewable energy, and the reformation of natural gas, NOx and particulates would be virtually eliminated.

18 WP4 – Concept Design Capital Cost

An estimate was made of the cost of converting a fleet of 50 vehicles (i.e. 25 x 2-car Class 156 units), and supplying and installing the necessary hydrogen generating plant and equipment on-depot. Indicative costs were obtained from potential suppliers and used to form the basis of this cost estimate, with all costs quoted exclusive of VAT.

18.1 Engineering & Design Costs

The engineering and design costs were based on those of the recent IPEMU trial (Network Rail, 2012). This was felt to offer a reasonable initial benchmark as the scope of work involved would be of a similar order to that for conversion to a fuel cell powertrain.

18.2 Cost of Key Components

The most expensive components are the two 104 kW fuel cells on each vehicle, with a combined cost of £250k. However, it is noted that Ballard are planning to mass produce fuel cells for the Chinese bus market within the next two years, and it is likely therefore that the price will fall significantly. Ballard are also planning to supply a rail-specific 200 kW fuel cell in the near future, with full EU approvals. While these rail-specific units will be sold in smaller numbers, the underlying technology will be the same, with similar expected reductions in cost.

The second most expensive single component is expected to be the hybrid battery and associated battery management system. It has proven difficult to obtain an indicative quotation from SAFT, the supplier whose batteries were selected for the concept design, and alternative suppliers are now being approached as a result. However, based on previous informal discussions with battery experts at Warwick Manufacturing Group, a budget of £50k per vehicle has been included in the costing.

The other key high-cost items include the IGBT converter, traction motors and hydrogen storage tanks. Indicative costs for the first two were obtained from Hitachi Rail, and indicative costs for the hydrogen tanks were based on previous quotes obtained by FCSL from Luxfer Group.

18.3 Vehicle Conversion Costs

The costs of undertaking the conversion work were based on an indicative price supplied by Chrysalis Rail, who undertake re-tractioning and refurbishment work within the UK. They have a base at Long Marston which is currently being used to refurbish GWR rolling stock. The estimate provide by Chrysalis Rail was made on the following basis:

- A fleet of 50 x vehicles (i.e. 25 x 2-car Class 156 multiple units);
- Successful prior completion of an IPEMU type trial;
- Prior completion of design and associated approvals;
- Conversion undertaken over a 2 year rolling programme;
- Delivery and collection of units from Long Marston.

Please also note that the cost specifically excludes refurbishment of the saloon, which would in all likelihood be undertaken at the same time as re-tractioning. A new saloon heating system would also be required to replace the current diesel fired auxiliary heater, but insufficient detail was available for Chrysalis Rail to include this within their quotation.

18.4 Hydrogen Generation & Refuelling Equipment

BOC Linde were consulted about the cost of large scale supply / production of hydrogen. They stated that their preferred business model would be to install and operate electrolysis or gas reformation plant at zero direct cost, incorporating these costs into either:

- A single “per kg” cost for hydrogen, as per the bus fleet in Aberdeen, or;
- An annual facilities charge, plus a correspondingly lower “per kg” charge.

But for comparison purposes, indicative costs for hydrogen production equipment were obtained for three options:

- 32 x Hydrogenics HYSTAT 60 electrolysers ≈ £16.3m
- 9 x Siemens SILZYER 200 electrolysers ≈ £8.7m
- 4 x Linde HYDROPRIME Natural Gas Reformers ≈ £6.8m

Of these options, the Siemens SILZYER appears to offer the most cost-effective solution for electrolysis, and was selected along with the Linde HYDROPRIME for further analysis and comparison with diesel traction.

18.5 Summary of Capital Costs

Table 12 shows the summed capital costs for the notional fleet of 50 vehicles (i.e. 25 x 2-car Class 156 units), based on the production of hydrogen through the reformation of natural gas using Linde HYDROPRIME reformers.

Table 12 – Summary of Capital Costs for Notional Fleet

Design, Engineering & Approvals				
Ref No.	Item			Cost
1.1	Engineering / Design Approvals & Project Management			£2,000,000
	Total Design Engineering & Approvals (fleet)			£2,000,000
Conversion Costs (per car)				
Ref No.	Item	No Per Car	Cost Each	Sub-Total
2.1	Conversion cost	1	£60,000	£60,000
2.2	Fuel-cell	2	£125,000	£250,000
2.3	Battery pack & BMS	1	£50,000	£50,000
2.4	IGBT	1	£80,000	£80,000
2.5	Traction motor	1	£15,000	£15,000
2.6	Hydrogen tanks	9	£8,000	£72,000
2.7	Air compressor	1	£5,000	£5,000
2.8	Pipework, valve & ancilliaries	1	£5,000	£5,000
2.9	Radiator for fuel-cells	1	£2,000	£2,000
	Total Conversion Cost (per car)			£539,000
	Total Conversion Cost (fleet)			£26,950,000
Infrastrucutre Costs (per fleet)				
Ref No.	Item	No Reqd	Cost Each	Sub-Total
3.1	Natural gas reformers	4	£1,700,000	£6,800,000
3.2	Compressor	4	£250,000	£1,000,000
3.3	Large volume storage	450	£6,000	£2,700,000
3.4	Pipework to refuelling point	500	£300	£150,000
3.5	Fueling point	1	£400,000	£400,000
3.6	Installation	1	£1,105,000	£1,105,000
	Total Infrastructure Cost (fleet)			£12,155,000

From the values in Table 12, the total capital cost including design, engineering approvals, components, re-tractioning and hydrogen infrastructure is £41.1m for the notional fleet.

19 WP4 – Concept Design Operating Cost

The most significant change in operating costs was expected to be a reduction in fuel costs, with additional benefits in terms of vehicle maintenance costs and availability. A comparison of fuel costs was therefore made of fuel costs based on current wholesale prices for diesel, electricity and natural gas, and work is currently ongoing to establish the expected benefits in terms of maintenance and vehicle availability.

19.1 Calculated Fuel Costs

The annual cost of fuel was calculated for the notional fleet of 50 vehicles (i.e. 25 x 2-car units), assuming a daily vehicle mileage of 350 miles, and operation 330 days per annum. The comparison (shown in detail in Appendix H) was based on the industry standard cost of £0.60 per litre for diesel fuel, with fuel consumption of 1 litre per vehicle per mile. This was then compared with two hydrogen generation options:

- Electrolysis using 9 x Siemens SILZYER 200 electrolysers, assuming 95% availability, operation only during off-peak hours (i.e. 50% of full capacity), and a wholesale electricity price of £0.092 per kWh;
- Reformation of natural gas using 4 x Linde HYDROPRIME reformers, assuming 95% availability, operation at 90% of full capacity, and a wholesale price of gas of £0.025 per kWh.

The use of off-peak electricity was assumed to give a 35% reduction on the current wholesale price, reducing it to £0.060 per kWh. On this basis the predicted annual and "per mile" fuel costs were as follows:

- Class 156 DMU – annual cost of diesel ≈ £3.5m or £0.60 per mile;
- Class 156 FCEMU (electrolysis) – annual cost of electricity ≈ £2.7m or £0.46 per mile;
- Class 156 FCEMU (natural gas) – annual cost of natural gas ≈ £1.3m or £0.22 per mile.

From this analysis, it is clear that there are significant savings to be made in terms of fuel costs, with a 23% saving in the case of electrolysis and a 63% saving in the case of hydrogen from natural gas.

It is expected that there would additionally be scope to leverage the ability of large-scale electrolysis plants to help balance the grid to reduce the per kWh cost of electricity through so-called "Balancing Payments". For example, it is understood that the electrolysers installed in Hamburg city centre to supply the local fuel cell bus fleet use excess electricity generated by offshore wind farms, supplied at negative cost (i.e. they are paid to absorb excess electricity from the grid). The costs of electrolysis should be therefore be considered highly variable, with the figure presented above representing the worst case scenario.

19.2 Maintenance Costs

In terms of maintenance costs, a typical diesel engine requires regular servicing and a comprehensive overhaul at around 20,000 hours. By contrast a fuel cell requires minimal servicing involving new air filters on a periodic basis. The latest generation of fuel cell achieve a comparable 20,000 hours between major overhaul. But it should be noted that, unlike diesel engine, the fuel cell only runs when energy is needed. In the case of the Class 156, it is estimated that the fuel cell would only be operating for approximately 50% of the operating day. This suggests that the interval between major overhaul would be approximately double that of a diesel engine.

These savings are currently being evaluated, and it is expected that the results of this evaluation will be available for the final project presentations.

20 WP4 – Concept Design Cost Benefit Analysis

The primary benefit is the reduction in fuel costs, calculated for the notional fleet to be approximately £2.2m per annum based on hydrogen from natural gas. Given the total cost of design, approvals, vehicle conversion, hydrogen generation plant and equipment was previously calculated at £41.1m, the financial payback period would therefore be approaching 20 years. This suggests that the conversion cannot be justified in terms of savings in fuel costs alone. Further work is ongoing to establish the value of savings in other areas such as vehicle maintenance costs.

One further option considered was to view the use of fuel cells as an alternative to electrification for rural lines, on the basis that fuel cells brings a similar range of benefits:

- Improved train performance comparable to that of EMUs;
- Like electrification, a wide range of primary energy sources can be used, thereby breaking the dependency on diesel;
- Like electrification, there are zero emissions at the point of use;
- As with electrification, there is the potential to reduce carbon emissions depending on the energy source used to generate hydrogen, with the potential of zero emissions if based on nuclear or renewable energy;
- As with electrification, both NOx and particulate emissions are virtually eliminated;
- Fuel cells offer a similar reduction in noise and vibration in the passenger saloon.

Furthermore, these benefits could be achieved at a fraction of the cost of electrification. As an example, the cost of electrifying the Valley Lines has been estimated at £295m (Wales Online, 2014). These services are currently operated using a fleet of 35 multiple units, mostly of the “Pacer” type. The capacity of this fleet (≈ 3,968 seats) is comparable to that of the notional fleet of 25 x Class 156 multiple units (≈ 3,750 seats). The cost of converting a fleet of Class 156 multiple units is therefore of the order of 1/7th of that of electrification, with the following advantages:

- No disruption due to the installation of Overhead Line Equipment (OLE), the modification of tunnels, bridges and viaducts, the installation of sub-stations etc.;
- No visual impact of catenary and electrification masts in sensitive areas;
- No increase in infrastructure maintenance costs;
- No risk of dewirements and associated service delays;
- No additional large single phase load on the UK’s National Grid.

With the move to increase the use of renewables in the UK generation mix, the ability of electrolysers to absorb excess energy during certain periods (i.e. Grid Balancing) is a further benefit, particularly where there is a local supply of wind energy.

21 Concluding Remarks

The study has shown that it is feasible to power a regional train such as a Class 156 using a hybrid fuel cell powertrain based on existing, proven technology. The traction performance of such as train would be significantly better than the existing diesel powertrain, and the operating range would be more than sufficient to enable daily refuelling. There would be a substantial reduction in overall energy consumption, an accompanying drop in CO2 emissions, the virtual elimination of NOx and particulate emissions, as well as a 63% reduction in "per mile" fuel costs.

The conversion of a modern EMU such as Hitachi's AT200 to a fuel cell powertrain is more challenging in terms of the space available for new equipment. However, there would be sufficient space to achieve a 500 mile range if the conversion were based on the standard 4-car AT200 configuration, rather than a 2-car unit originally considered. This would additionally require a 20% reduction in hotel load, which it is suggested could reasonably be achieved through the installation of a more efficient air-conditioning system.

Large quantities of hydrogen would need to be generated on a daily basis to fuel a typical fleet. However, again the technology required to do so exists, and is considered reliable and proven. The capital costs of plant and equipment to generate sufficient hydrogen on-site are high, and the total including train modification for the notional fleet of 25 x Class 156 multiple units is £41.1m. The savings in terms of fuel costs alone do not justify this level of expenditure, with a payback period approaching 20 years. However, there are further savings to be made as a result of reduced train maintenance and increased fleet availability, and further work is ongoing to establish the value of these benefits.

Alternatively, conversion to fuel cell operation could reasonably be viewed as an alternative to electrification for UK rural lines, bringing the same core benefits without the disruption associated with installation of masts, catenary and sub-stations. Taking the Valley Lines as a typical example, the costs of conversion to fuel cell operation are of the order of 1/7th that of electrification. Considered in this light, the benefits of a fuel cell powertrains are considerable, with additional potential to reduce the load on the UK's power generators and the National Grid.

The team propose a full-size demonstrator be developed for Phase 2, installing a hybrid fuel cell on an ex-Birmingham T-69 tram stabled at a private test-track. An internal project has also been commissioned to evaluate the alternatives to electrification for the Valley Lines, and this will include consideration of fuel cell powertrains as one of the options.

22 List of References

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Appendix A – Class 156 FCEMU Kinetic Energy Calculations

The table shows the calculation of the total kinetic energy to be dissipated by a Class 156 FCEMU braking from maximum operating speed. There then follows a calculation of the split between the energy that can be absorbed by the electric motors for regeneration (limited by motor rating at higher speeds), and that which needs to be dissipated by the friction brakes.

Class 156 FCEMU Battery Sizing - Theoretical Energy Dissipation from Max Speed

Author: S Kent
Issue Date: 9 November 2015

Energy to be dissapated	Figures	Units	Source / Notes
Approximate mass per vehicle (includes passengers & inertial mass)	45,000	kg	STS
Max operating speed	75	mph	Wikipedia
	120	kph	
	33.3	m/s	
Total kinetic energy to be dissipated or absorbed	25,000,000	Joules	based on kinetic energy = 0.5 x mass x (velocity)^2
	6.9	kWh	

Max speed at which motor can absorb all energy	Figures	Units	Source / Notes
Assumed deceleration rate	3%	g	assumed
	0.3	m/s^2	
Motor rating	200	kW	STS
Max speed for energy absorbtion	15.1	m/s	based on power = mass x acc x speed
	54	kph	
	34	mph	

Energy abosorbtion calculation	Figures	Units	Source / Notes
Speed range over which motor rating limits energy absorbtion	18.2	m/s	
Time taken to lose this speed range	62	s	
Energy absorbed during this time	12,389,796	Joules	based on energy = power x time
	3.4	kWh	
Speed range for which motors absorb all energy	15.1	m/s	
Kinetic energy being absorbed from this speed	5,131,413	Joules	
	1.4	kWh	
Total energy absorbed by electric motor (i.e. min battery capacity)	4.9	kWh	note - excludes train resistance, so actual values will be lower
Total energy dissipated by friction brakes	2.1	kWh	

Appendix B – AT200 FCEMU Kinetic Energy Calculations

The table shows the calculation of the total kinetic energy to be dissipated by a AT200 FCEMU braking from maximum operating speed. There then follows a calculation of the split between the energy that can be absorbed by the electric motors for regeneration (limited by motor rating at higher speeds), and that which needs to be dissipated by the friction brakes.

AT200 FCEMU Battery Sizing - Theoretical Energy Dissipation from Max Speed

Author: S Kent
Issue Date: 9 November 2015

Energy to be dissapated	Figures	Units	Source / Notes
Approximate mass per vehicle (includes passengers & inertial mass)	52,000	kg	STS
Max operating speed	75	mph	Wikipedia
	120	kph	
	33.3	m/s	
Total kinetic energy to be dissipated or absorbed	28,888,889	Joules	based on kinetic energy = 0.5 x mass x (velocity)^2
	8.0	kWh	

Max speed at which motor can absorb all energy	Figures	Units	Source / Notes
Assumed deceleration rate	3%	g	assumed
	0.3	m/s^2	
Motor rating	200	kW	STS
Max speed for energy absorbtion	13.1	m/s	based on power = mass x acc x speed
	47	kph	
	29	mph	

Energy abosorbtion calc	Figures	Units	Source / Notes
Speed range over which motor rating limits energy absorbtion	20.3	m/s	
Time taken to lose this speed range	69	s	
Energy absorbed during this time	13,771,331	Joules	based on energy = power x time
	3.8	kWh	
Speed range for which motors absorb all energy	13.1	m/s	
Kinetic energy being absorbed from this speed	4,440,646	Joules	
	1.2	kWh	
Total energy absorbed by electric motor (i.e. min battery capacity)	5.1	kWh	note - excludes train resistance, so actual values will be lower
Total energy dissipated by friction brakes	3.0	kWh	

Appendix C – Class 156 FCEMU Battery Sizing Calculations

The table shows the calculation of the energy to be absorbed by the battery pack for the longest duration braking event from the STS simulations.

Class 156 FCEMU Battery Sizing for N-S-N Route - Analysis of Longest Braking Event

Author: S Kent
Issue Date: 9 November 2015

Deceleration calculation for longest braking event	Figures	Units	Source / Notes
Time at start of braking event	5352	s	STS
Distance at start of braking event	81388	m	STS
Speed at start of braking event	32.9	m/s	STS
	118.4	kph	
	74.0	mph	note - vehicle never actually reaches 75mph
Time at end of braking event	5455	s	STS
Distance at end of braking event	83380	m	STS
Speed at end of braking event	0.0	m/s	STS
Braking time	103	s	
Braking distance	1992	m	
Change in speed	32.9	m/s	
Average deceleration rate	0.32	m/s^2	

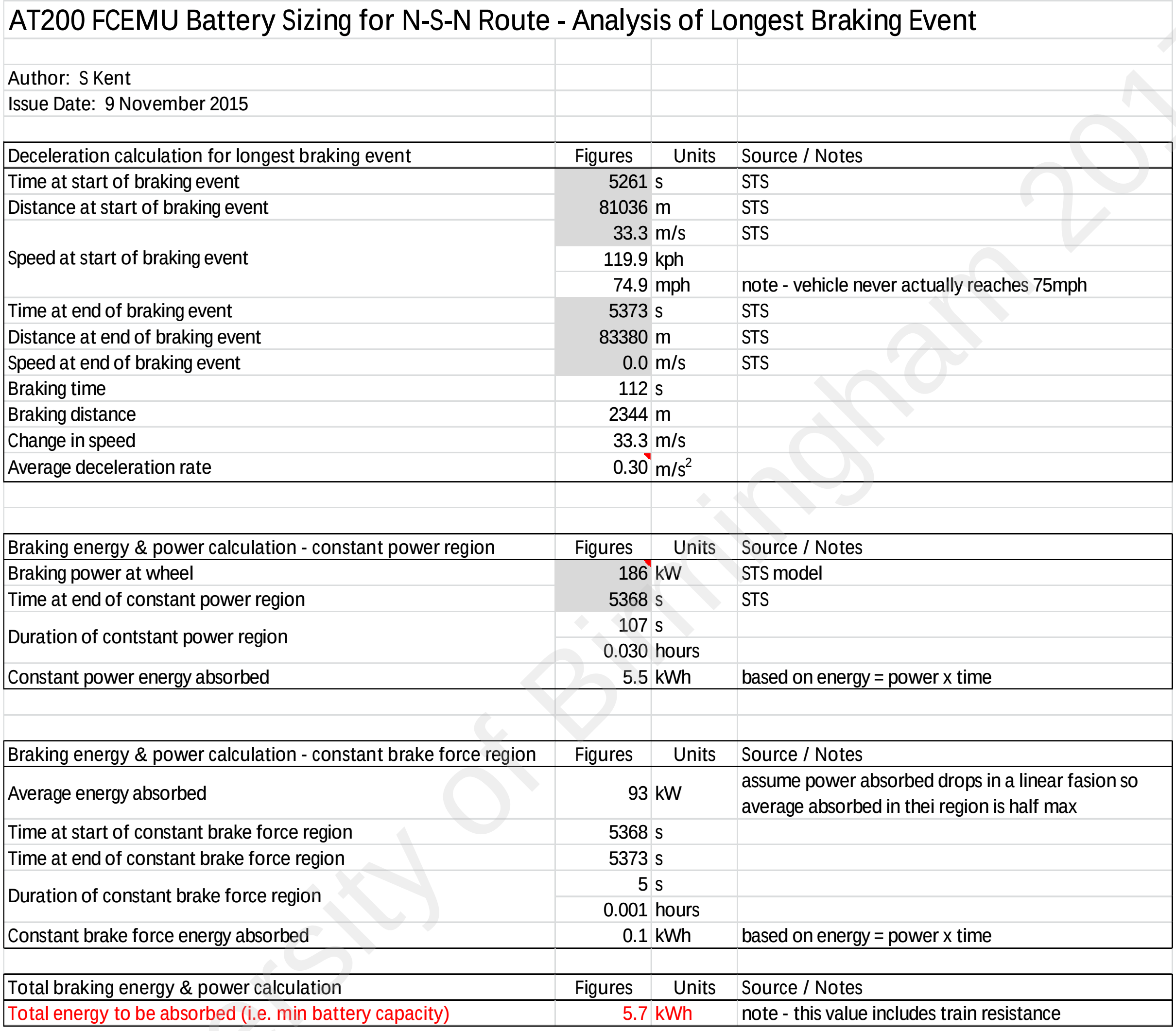
Braking energy & power calculation - constant power region	Figures	Units	Source / Notes
Braking power at wheel	180	kW	STS model
Time at end of constant power region	5440	s	STS
Duration of contstant power region	88	s	
	0.024	hours	
Constant power energy absorbed	4.4	kWh	based on energy = power x time

Braking energy & power calculation - constant brake force region	Figures	Units	Source / Notes
Average energy absorbed	90	kW	assume power absorbed drops in a linear fasion so average absorbed in thei region is half max
Time at start of constant brake force region	5440	s	
Time at end of constant brake force region	5455	s	
Duration of constant brake force region	15	s	
	0.004	hours	
Constant brake force energy absorbed	0.4	kWh	based on energy = power x time

Total braking energy & power calculation	Figures	Units	Source / Notes
Total energy to be absorbed (i.e. min battery capacity)	4.8	kWh	note - this value includes train resistance

Appendix D – AT200 FCEMU Battery Sizing Calculations

The table shows the calculation of the energy to be absorbed by the battery pack for the longest duration braking event from the STS simulations.



AT200 FCEMU Battery Sizing for N-S-N Route - Analysis of Longest Braking Event

Author: S Kent
Issue Date: 9 November 2015

Deceleration calculation for longest braking event	Figures	Units	Source / Notes
Time at start of braking event	5261	s	STS
Distance at start of braking event	81036	m	STS
Speed at start of braking event	33.3	m/s	STS
	119.9	kph	
	74.9	mph	note - vehicle never actually reaches 75mph
Time at end of braking event	5373	s	STS
Distance at end of braking event	83380	m	STS
Speed at end of braking event	0.0	m/s	STS
Braking time	112	s	
Braking distance	2344	m	
Change in speed	33.3	m/s	
Average deceleration rate	0.30	m/s^2	

Braking energy & power calculation - constant power region	Figures	Units	Source / Notes
Braking power at wheel	186	kW	STS model
Time at end of constant power region	5368	s	STS
Duration of contstant power region	107	s	
	0.030	hours	
Constant power energy absorbed	5.5	kWh	based on energy = power x time

Braking energy & power calculation - constant brake force region	Figures	Units	Source / Notes
Average energy absorbed	93	kW	assume power absorbed drops in a linear fasion so average absorbed in thei region is half max
Time at start of constant brake force region	5368	s	
Time at end of constant brake force region	5373	s	
Duration of constant brake force region	5	s	
	0.001	hours	
Constant brake force energy absorbed	0.1	kWh	based on energy = power x time

Total braking energy & power calculation	Figures	Units	Source / Notes
Total energy to be absorbed (i.e. min battery capacity)	5.7	kWh	note - this value includes train resistance

Appendix E – Class 156 FCEMU Fuel Cell Sizing Calculations

The table shows the calculation of the energy to be absorbed by the battery pack for the longest duration braking event from the STS simulations.

Class 156 FCEMU - Fuel Cell Sizing for N-S-N Route

Author: S Kent
Issue Date: 9 November 2015

Traction energy & power required for return journey (excluding regen)	Figures	Units	Source / Notes
Time taken for return journey	102.4	minutes	STS
	1.71	hours	
Total traction energy used	152	kWh	STS
Hotel load power	20	kW	ref email from Dave Bridges
Total energy required to support hotel load	34	kWh	
Average total energy from fuel-cell for a return journey	186	kWh	note - assume that battery is discharged at beginning of journey
Minimum rating of fuel cell for return journey	109	kW	

Traction energy & power required for return journey (including regen)	Figures	Units	Source / Notes
Time taken for return journey	103.1	minutes	STS
	1.72	hours	
Total traction energy used	121	kWh	STS
Hotel load power	20	kW	ref email from Dave Bridges
Total energy required to support hotel load	34	kWh	
Average total energy from fuel-cell for a return journey	155	kWh	note - assume that battery is discharged at beginning of journey
Minimum fuel cell output for return journey for vehicle with regen	90	kW	

Traction energy & power required for longest traction event	Figures	Units	Source / Notes
Time at start of traction event	5516	s	STS
Distance at start of traction event	83381	m	STS
Speed at start of traction event	0.0	m/s	STS
Time at end of traction event	5800	s	STS
Distance at end of traction event	90553		STS
Speed at end of traction event	33.0	m/s	STS
Average acceleration rate	0.12	m/s^2	note - low average due to poor acceleration at higher speeds
Traction power	200	kW	STS
Hotel load power	20	kW	
Total power required	220	kW	
Elapsed time	284	seconds	
	0.079	hours	
Total energy required during traction event	17.4	kWh	
Energy available from battery	7.0	kWh	nominal battery
Energy to be provided by fuel-cell	10.4	kWh	
Power from fuel-cell for vehicle with regen	131	kW	

Appendix F – AT200 Fuel Cell Sizing Calculations

The table shows the calculation of the energy to be absorbed by the battery pack for the longest duration braking event from the STS simulations.

AT200 FCEMU - Fuel Cell Sizing for N-S-N Route

Author: S Kent
Issue Date: 9 November 2015

Traction energy & power required for return journey (excluding regen)	Figures	Units	Source / Notes
Time taken for return journey	101.6	minutes	STS
	1.69	hours	
Total traction energy used	130	kWh	STS
Hotel load power	50	kW	ref email from Dave Bridges
Total energy required to support hotel load	85	kWh	
Average total energy from fuel-cell for a return journey	215	kWh	note - assume that battery is discharged at beginning of journey
Minimum rating of fuel cell for return journey	127	kW	

Traction energy & power required for return journey (including regen)	Figures	Units	Source / Notes
Time taken for return journey	101.6	minutes	STS
	1.69	hours	
Total traction energy used	99	kWh	STS
Hotel load power	50	kW	ref email from Dave Bridges
Total energy required to support hotel load	85	kWh	
Average total energy from fuel-cell for a return journey	184	kWh	note - assume that battery is discharged at beginning of journey
Minimum rating of fuel cell for return journey	109	kW	

Energy & power required for longest traction event	Figures	Units	Source / Notes
Time at start of traction event	5434	s	STS
Distance at start of traction event	83381	m	STS
Speed at start of traction event	0.0	m/s	STS
Time at end of traction event	5701	s	STS
Distance at end of traction event	90277		STS
Speed at end of traction event	33.3	m/s	STS
Average acceleration rate	0.12	m/s^2	note - low average due to poor acceleration at higher speeds
Traction power	200	kW	STS - note - it actually drops off slightly towards the end of the event
Hotel load power	50	kW	
Total power required	250	kW	
Elapsed time	267	seconds	
	0.074	hours	
Total energy required during traction event	18.5	kWh	
Energy available from battery	7.0	kWh	nominal battery
Energy to be provided by fuel-cell	11.5	kWh	
Power from fuel-cell for vehicle with regen	156	kW	

Appendix G – CO2 Emissions Analysis

The table shows the calculation of the CO2 emissions for a notional fleet of 25 x Class 156 DMUs and FCEMUs with hydrogen produced by electrolysis and reformation of natural gas.

Factor	Values	Units	Source
Fleet size	50	vehicles	Nominal fleet size
Daily mileage	350	miles/day	Porterbrook Leasing
Operating days per year	330	days/year	Estimate
Annual mileage per vehicle	115500	miles	
DMU			
Fuel consumption	1.00	litre/mile	Porterbrook / Angel Trains
Diesel consumed per vehicle per annum	115500	litres	
Total diesel consumed per fleet	5775000	litres	
CO2 per litre of diesel	2.68	kg/litre	T W Davies, Exeter University
Total fleet CO2 for DMU	15477000	kg	
	15477	tonnes	
FCEMU			
Fuel consumption	0.124	kg per mile	UoB STS simulations
Hydrogen consumed per vehicle per annum	14322	kg	
Hydrogen consumed per fleet per annum	716100	kg	
Electrolysis			
Volume of hydrogen per kg	11.986	m3	Air Products website
Hydrogen consumed per fleet per annum	8583175	m3	
Energy consumed per m3 of hydrogen	5.2	kWh	Hydrogenics website
Total energy consumed per fleet per annum	44632508	kWh	
CO2 per kWh electricity from UK grid	0.462	kg CO2 per kWh	UK Department for Environment, Food & Rural Affairs
Total fleet CO2 per annum - electrolysis	20628699	kg	
	20629	tonnes	
Reformation of Natural Gas			
CO2 per kg of hydrogen	12.4	kg CO2 per kg H2	CleanTechnica website
Total fleet CO2 per annum - natural gas	8879640	kg	
	8880	tonnes	

Appendix H – Hydrogen Production Costs

The table shows the calculation of the cost of production of hydrogen from a number of sources sufficient to operate a notional fleet of 25 x Class 156 FCEMUs with a daily mileage of 350 miles for 330 days per annum.

Factor	Values	Units	Source
Unit Energy Costs			
Electricity	£0.092	£/kWh	"gov.uk" website
Reduction for off-peak	35%		Estimate
Off-peak electricity	£0.060	£/kWh	
Gas	£0.025	£/kWh	"gov.uk" website
Diesel	£0.600	£/l	Angel Trains & Porterbrook Leasing
Diesel			
Total cost	£3,465,000		
£ per mile	£0.60		
Gas			
Correction Factor	1.02		Envantage Energy website
Calorific Value	39.3		Envantage Energy website
kWh Conversion Factor	3.6		Envantage Energy website
Hydrogenics HySTAT 60			
Cost	£508,831		Mark Kammerer, Hydrogenics
H2 Production per electrolyser	130	kg/day	Mark Kammerer, Hydrogenics
H2 Production per electrolyser	47,450	kg/year	
H2 Required	716,100	kg/year	
% Day electrolyser operation	50%		Estimate for off-peak only
% Year Availability	95%		Estimate
No. Electrolysers Required	32		
Capital Cost	£16,282,592		
Siemens SILYZER 200			
Cost	£970,000		Jeremy Wilkinson, Siemens
H2 Production per electrolyser	480	kg/day	Jeremy Wilkinson, Siemens
H2 Production per electrolyser	175,200	kg/year	
H2 Required	716,100	kg/year	
% Day electrolyser operation	50%		Estimate for off-peak only
% Year Availability	95%		Estimate
No. Electrolysers Required	9		
Capital Cost	£8,730,000		
HYDROPRIME			
Cost	£1,700,000		Kyle Finley, Hydro-Chem
H2 Production per reformer	7920	m3/day	Kyle Finley, Hydro-Chem
H2 Production per reformer	661	kg/day	
H2 Production per reformer	241,181	kg/year	
H2 Required	716,100	kg/year	
% Day reformantion operation	90%		Estimate
% Year Availability	95%		Estimate
No. Reformers Required	4		
Capital Cost	£6,800,000		
Electrolysis Cost Per Mile			
Total Electricity Required	44,632,508	kWh	
Total Electricity Cost	£2,669,024		
£ per mile	£0.46		
Natural Gas Cost Per Mile			
Gas Consumption per reformer	155	m3/hour	
Gas Consumption per reformer	1726	kWh	energylinx.co.uk
Total Gas Consumption	51,707,332	kWh/year	
Total Gas Cost	£1,292,683		
£ per mile	£0.22		