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Conceptual propulsion system design for a hydrogen-powered regional train

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Abstract: Many railway vehicles use diesel as their energy source but exhaust emissions and concerns about economical fuel supply demand alternatives. Railway electrification is not cost effective for some routes, particularly low-traffic density regional lines. The journey of a regional diesel–electric train is simulated over the British route Birmingham Moor Street to Stratford-upon-Avon and return to establish a benchmark for the conceptual design of a hydrogen-powered and hydrogen-hybrid vehicle. A fuel cell power plant, compressed hydrogen at 350 and 700 bar, and metal-hydride storage are evaluated. All equipment required for the propulsion can be accommodated within the space of the original diesel–electric train, while not compromising passenger-carrying capacity if 700 bar hydrogen tanks are employed. The hydrogen trains are designed to meet the benchmark journey time of 94 min and the operating range of a day without refuelling. An energy consumption reduction of 34% with the hydrogen-powered vehicle and a decrease of 55% with the hydrogen-hybrid train are achieved compared with the original diesel–electric. The well-to-wheel carbon dioxide emissions are lower for the conceptual trains: 55% decrease for the hydrogen-powered and 72% reduction for the hydrogen-hybrid assuming that the hydrogen is produced from natural gas.

1 Introduction

Currently, most railway vehicles use electricity for propulsion, which is either supplied through wayside electrification infrastructure or on-board diesel-generator sets. In the European Union (EU), the share of electrified railway lines is about 53% and the majority of traffic is carried on those lines but, in other areas, such as North America, non-electrified lines are the norm [1]. Diesel combustion releases emissions at the point-of-use, such as particulate matter and nitrogen oxides, and reduction of these is mandated in the United States [2] and the EU [3]. Furthermore, hydrocarbon combustion leads to emission of Greenhouse Gases, and many countries, including the United Kingdom, have ambitious targets to reduce these [4]. In addition to the emission concerns, the economical supply of diesel is uncertain. In Europe, it is not cost-effective to electrify a significant additional proportion of the railway network, including regional lines. And the cost of large-scale wayside electrification is prohibitive for many railway administrations around the world. For all aforementioned reasons, an alternative energy source to diesel is required for railway motive power. Hydrogen can be produced from many feedstocks, similar to electricity, and when utilised in a fuel cell, generates electricity and heat while leaving as exhaust pure water [5, 6]. In addition, it has been shown that hydrogen-powered railway vehicles can reduce overall Greenhouse Gas emissions [7]; therefore hydrogen is an attractive alternative to diesel for railways. Globally, a few hydrogen-powered railway vehicles exist but most of these are prototypes and no full-scale heavy rail passenger train is currently in service [8–12]. Previous research [13] has considered the general feasibility of hydrogen-hybrid railway vehicles where the focus was on the control strategy between the different components, and not the detailed system design. In the current paper, a conceptual design is presented, which considers the mass and volume implications of the drive system change together with an assessment of the practicality of ahydrogen-powered solution. A benchmark diesel–electric regional railway vehicle is selected and the performance parameters and journey time over a corresponding route in Britain are determined with computer simulation. Then, a conceptual design for a hydrogen-powered and hydrogen-hybrid regional train is developed and these are simulated over the same route. Next, the performance of all three trains are compared, including range, journey time, vehicle efficiency and carbon emissions.

2 Benchmark simulation

The single train simulator software, developed by the Birmingham Centre for Railway Research and Education, was employed for the investigations presented in this paper. The simulator has been used extensively for previous research [14–17] and three new vehicles have been created for this paper, while a route that already existed in the programme was selected.

The single train simulator solves the equations of motion of a railway vehicle through numeric integration, see (1)–(5) [5, 15, 18]

$$F = ma \tag{1}$$

$$F = m(1+\lambda)a \tag{2}$$

$$F = \mathrm{TE} - \left[mg\,\sin(\alpha) + Cv^2 + Bv + A\right] \tag{3}$$

Overall

$$m(1+\lambda)a = \mathrm{TE} - \left[mg\,\sin(\alpha) + Cv^2 + Bv + A\right] \tag{4}$$

Or

$$m(1+\lambda)\frac{\mathrm{d}^2 s}{\mathrm{d}t^2} = \mathrm{TE} - \left[mg\,\sin(\alpha) + C\left(\frac{\mathrm{d}s}{\mathrm{d}t}\right)^2 + B\left(\frac{\mathrm{d}s}{\mathrm{d}t}\right) + A\right] \tag{5}$$

where a is the acceleration (metre per second squared (m/s^2)); A, B and C are the constant terms of resistance in the Davis equation [19]; d is delta, change of the following variable; F is force (kilonewton (kN)); g is the acceleration due to gravity (9.81 m/s^2); m is mass (kilograms); s is the vehicle displacement (metres); t is the time (seconds); TE is tractive effort (kN); v is the velocity (m/s); α is the angle of the gradient (degrees); and λ is the rotational allowance.

These equations fully describe the forces that occur due to the motion of railway vehicles, except for the resistance encountered due to curving forces, which was neglected in the investigation. Meegahawatte *et al.* [13] provide a more detailed description of the simulator.

2.1 Benchmark vehicle selection

A regional train of the type Gelenktriebwagen 2/6 (GTW) produced by Stadler AG was used as the benchmark diesel train. More than 500 GTWs have been sold all over the world, and the basic formation comes as two coaches and one power-module with two out of six axles powered [20]. The autonomous version of the GTW has a diesel–electric power-module between two passenger coaches; see Fig. 1 for an illustration of the vehicle.

The GTW was selected because it features a power-module, similar to a locomotive, and a diesel–electric drive-train, so a power-plant change allows the continued use of existing components, such as the traction motors. A further reason for the GTW is that the train is used both for regional services and light commuter services. The characteristics of a diesel–electric GTW 2/6 are presented in Table 1.

2.1.1 GTW power-module data: The GTW's power-module for Texas has two identical drive-systems, each consisting of a diesel engine, alternator, power converters and traction motor [21, 22], as illustrated in Fig. 2*a*.

Typical drive-train efficiencies for modern electric trains are in the range of 85–90% [29, 30] and the same range is applicable to diesel–electric drive-trains as the technology employed is similar [30]. In personal communication with Stadler employees, a similar range was given with an approximate value for the GTW 2/6 of 88%. A split of this efficiency into the various sub-components was necessary, which is presented in Table 2; these values were derived from data provided by Steimel [31] and the UIC [30]. The duty-cycle efficiency differs significantly from the maximum efficiency of a diesel-powered railway vehicle [17, 30]. A typical maximum efficiency of a diesel engine is 40% [30], whereas the

Table 1 GTW 2/6 vehicle data parameters are based on the Texas versions [21, 22] unless otherwise indicated

Train characteristics	
Axle arrangement	2′Bo2′
Vehicle length	40 890 mm
Vehicle width	2950 mm
Vehicle height[a,b]	4035 mm
Tare mass	72 t
Coach mass[c]	20 t
starting TE	80 kN
Maximum acceleration	1 m/s^2
Maximum deceleration in the present evaluation[d]	1 m/s^2
Maximum speed	120 km/h
Davis equation of resistance to motion[e]	$R = 1.5 + 0.006v + 0.0067v^2$
Power-module characteristics	
Number of powered-axels	2
Floor height in the power-module	1000 mm
Available height in the power-module	3035 mm
Length of the power-module[b]	4500 mm
Minimum corridor width in the power-module[b]	800 mm
Mass of the power-module[c]	30 t
Mass resting on the power-module[c]	40 t
Power of the two diesel engines combined[f]	600 kW
Maximum power at wheel	470 kW
Auxiliary power, such as HVAC[g]	65 kW
Drive-train efficiency[h]	88%
Diesel tank capacity[i]	15 00l–14 910 kWh[j]

[a]On the basis of the GTW delivered to Veolia Transport in the Netherlands [23]
[b]Personal communication with Stadler employees
[c]Calculated from data of the bogie manufacturer [24], GTWs for Veolia Transport in the Netherlands [23] and GTW for Capital Metro, Texas [21]
[d]Maximum service braking rate for the Texas trains is 1.3 m/s^2 according to Stadler Rail AG [22]
[e]Equation developed from personal communication with Stadler employees and existing data of the train simulator
[f]Power for a Federal Railroad Administration alternate-compliant design, such as the GTW for Denton County Transportation Authority, Texas [25]
[g]Calculated from data provided by the U.S. Department of Transportation – Federal Transit Administration [26], GTW for Capital Metro, Texas [21] and the drive-train efficiency
[h]Calculated from the power data, see Table 2, and personal communication with Stadler employees
[i]Personal communication with Stadler employees and GTW delivered to Veolia Transport in the Netherlands [27]
[j]Calculated from American data and based on the LHV of diesel at 9.94 kWh/l [28]

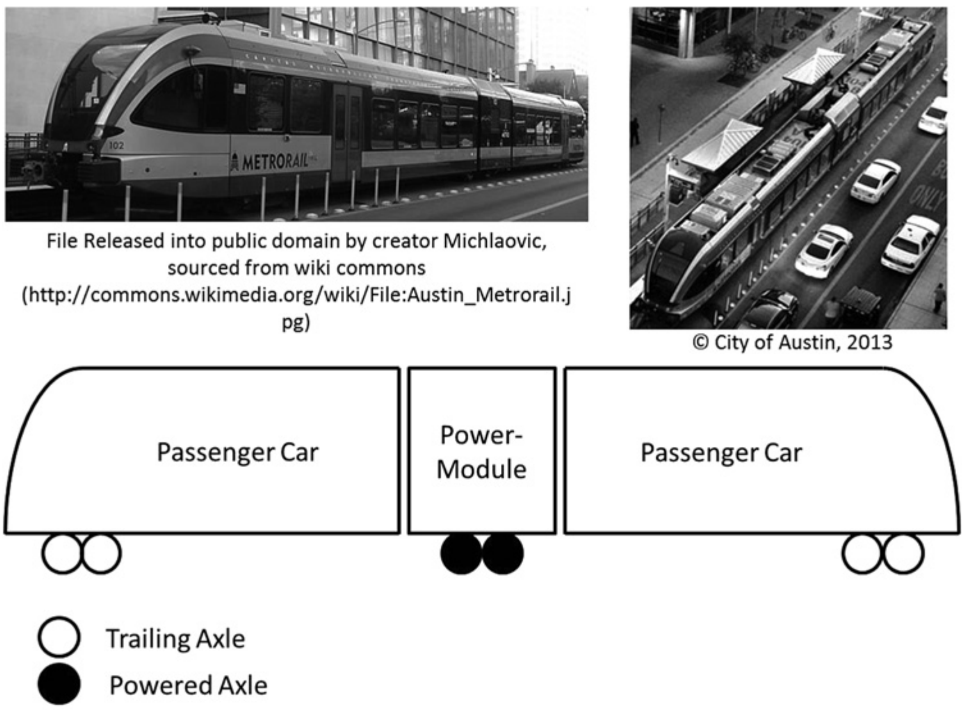

Fig. 1 *Illustration of the MetroRail diesel-electric GTW 2/6 based on information from Stadler Rail AG [21]*

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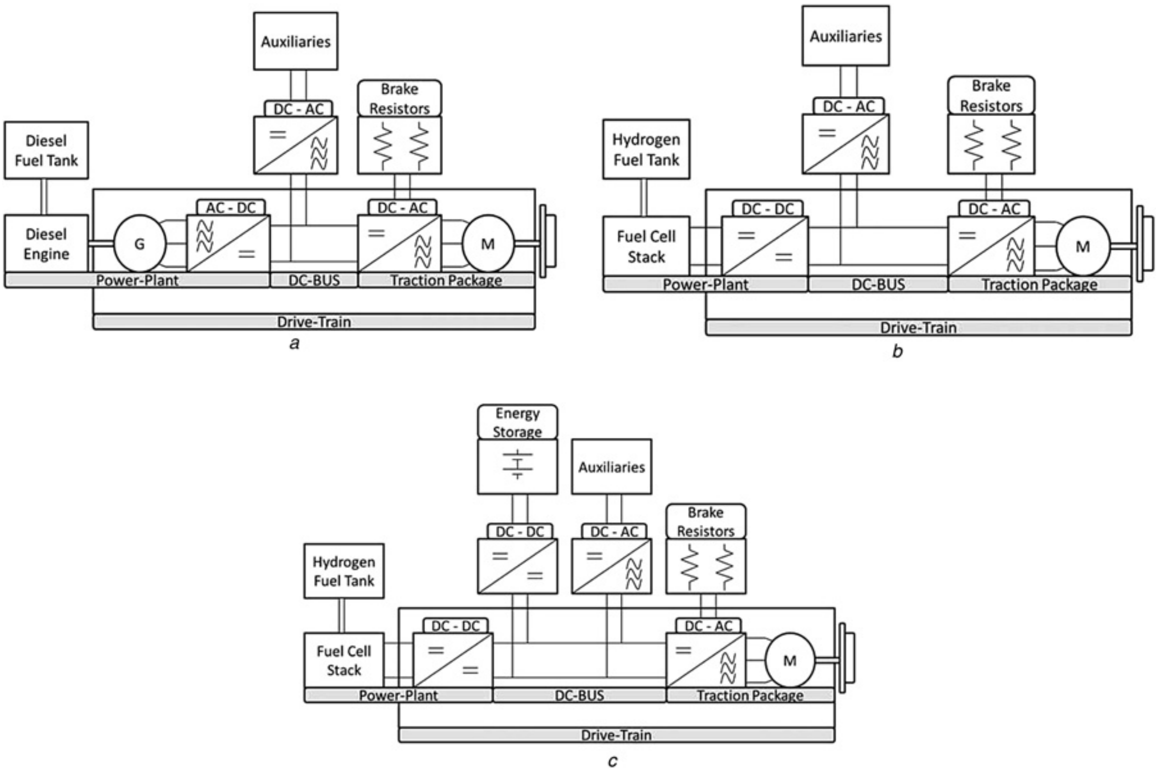

Fig. 2 *Power-module drive-system diagrams for the three different trains*

The diesel-electric drive system (a) is created from data of the Texas GTWs [21, 22] and data provided by the U.S. Department of Transportation – Federal Transit Administration [26]
a Diesel–electric
b Hydrogen
c Hydrogen-hybrid

duty-cycle efficiency for a modern diesel train is about 25% [32]. The duty-cycle efficiency of the drive-train components also vary, and in extreme cases this can be significant [30] but for many railway applications the maximum drive-train efficiency is similar to the duty-cycle efficiency and the major variation between the two is due to the prime mover, such as the diesel engine. As the comparisons in this paper are made on a duty-cycle basis, the efficiency provided by the Rail Safety and Standards Board (RSSB) [32] is used. The efficiency of the GTW power-module was determined in the following way: a duty-cycle vehicle efficiency of 25% has been assumed [32]; then the drive-train efficiency provided by Stadler of 88% has been applied, which results in a diesel engine efficiency of 29%. A more detailed account for the tank-to-wheel efficiency is shown in Table 2.

Resulting from the efficiencies presented in Table 2 is a traction-package efficiency of 92.6%, and a diesel engine drive-shaft to DC-bus efficiency of 95.6%. The data allow the simulation of the vehicle and an estimation of its fuel consumption, which together with the efficiencies will serve as the input for the hydrogen conceptual vehicles.

2.2 Route selection

The trains are simulated on the route from Birmingham Moor Street to Stratford-upon-Avon and return. It is a regional line with some commuter traffic and the current service is operated with vehicles that are similar in power and passenger capacity to the GTW 2/6 [33]. There are 16 stops between the two terminals, the line is 78.58 km long and the alignment is relatively level. The route data were pre-existing in the train simulator and sourced from network rail, as well as used in previous simulations [13]. It has been assumed that the alignment is straight throughout, as horizontal curvature has a secondary effect on journey performance results and will not differ between the comparative vehicles under investigation.

2.3 Simulation results

The dwell time at calling stations is 30 s and the turn-around time at Stratford-upon-Avon is 5 min. It was assumed that the resistance to motion based on the Davis equation stayed the same throughout the journey. The results for the diesel–electric train are presented in Table 3 and in Figs. 3–5. These figures begin with the journey's origin in Birmingham Moor Street and include a turn-around time in Stratford-upon-Avon of 5 min before the return journey starts. A terminal time of 6 min in Birmingham Moor Street is added to the energy calculations but not shown in these figures, as the starting location is reached by the train.

Fig. 3 shows the line speed and the speed that the train achieves while traversing the route.

The traction power requirements during the journey and the average power at the wheels as well as the braking power that has to be dissipated, either in mechanical brakes or in dynamic brake resistors are illustrated in Fig. 4.

The power requirements of the GTW's drive-system, including the demand of diesel, are illustrated in Fig. 5. The efficiency parameters presented earlier were applied to the at-wheel values to determine the power through the drive-system. In addition, the auxiliary power requirements have been added at the DC-bus stage. In Fig. 5, graph (a) shows the primary fuel input and power-plant output; graph (b) shows the power inputs and outputs across the DC-bus; and graph (c) illustrates the power that enters the traction-package and the power at the wheels.

The data presented above provide the benchmarking case for the design of the hydrogen-powered vehicles. From the traction power graph, Fig. 4, it is apparent that the average power is significantly lower than peak power. Furthermore, the power due to braking, denoted in Fig. 4, is considerable compared with the traction power. Both suggest that a hybrid design could lower the overall energy consumption, and therefore a hydrogen-hybrid vehicle was also developed.

Table 2 Drive-train efficiency calculations for GTW

Component	Component efficiency[a]	Cumulative drive-train efficiency[b]	Tank-to-wheel efficiency chain
diesel in fuel tank			100%
diesel engine			29%
drive-train			
diesel engine mechanical output	1	29%	
alternator	0.98	28%	
AC–DC converter	0.975	27%	
DC–AC inverter	0.975	26%	
traction motors and mechanical drive	0.95	25%	
drive-train efficiency	0.88		88%
vehicle efficiency[c]			25%

[a]Developed by the authors to give 88% drive-train efficiency as per personal communication with Stadler employees. Estimates based on information provided by Steimel [31] and the UIC [30]
[b]Calculated backwards from vehicle efficiency and rounded to full percentage numbers
[c]Reported by RSSB [32]

3 Hydrogen simulation

3.1 Hydrogen-powered drive-system

The existing GTWs employ a diesel–electric drive-train housed in a power-module. A large part of the drive-system does not have to be altered in a conversion to operate on hydrogen and the concept of a power-module is retained. The main component that will differ is the power-plant, which is fuel cell-based in the presented investigation. The hydrogen-powered drive-system is illustrated in Fig. 2*b*. The hydrogen-powered drive-train efficiency calculation does not include an alternator, because the output of the fuel cell stack is already electricity, see Fig. 2*b*, resulting in a 90.3% drive-train efficiency, see Table 2 for details.

3.1.1 Power and energy requirements: The power-plant in the present GTW provides a maximum of 572 kW, of which 65 kW are used for auxiliaries, 507 kW are available at the traction-package and 470 kW are present at the wheels for traction. For a return journey the energy provided by the power-plant is 429 kWh, of which 108 kWh are used for auxiliaries, 321 kWh are available for the traction-package and 297 kWh are necessary for vehicle motion.

Table 3 Performance results of the diesel–electric GTW 2/6 on route Birmingham Moor Street – Stratford-upon-Avon and return

Journey time	94 min
Terminal time at Birmingham Moor Street on return from Stratford	6 min
Power	
Maximum traction power at wheels	470 kW
Average traction power at wheels[a]	189 kW
Auxiliary power	65 kW
Maximum engine power	599 kW
Energy	
Energy at wheels	297 kWh
Energy at DC-bus	321 kWh
Auxiliary energy[b]	108 kWh
Power-plant output energy	429 kWh
Diesel engine output energy	449 kWh
Energy contained in diesel	1548 kWh

[a]Calculated from the energy data: 297 kWh/1.57 h = 189 kW
[b]Includes terminal time at Birmingham Moor Street on return of six minutes to give an overall operation time on 100 min, before the journey is repeated

The GTW requires 1548 kWh of diesel to complete the return journey Birmingham Moor Street – Stratford-upon-Avon. A full diesel tank holds 14 910 kWh, thus 9.6 or nine full journeys are possible. Given a 100 min journey time, including turn-around times, the range of the vehicle is 960 min or 16 h, representing a working day. Most diesel railway vehicles in the UK are refuelled on a daily basis [32], and this situation is assumed for the benchmark. The time required to refuel a diesel railway vehicle is in the range of 30 min to 1 h, depending on the type of vehicle, fuelling station and quantity of fuel that has to be added [34] and personal communication with Rory Dickerson of Network Rail in 2013. This is comparable with the capability provided by existing hydrogen refuelling arrangements for road vehicles [5, 35]. Assuming that the drive-train components as well as auxiliary consumption do not change, then the hydrogen-powered train should ideally meet or exceed the criteria presented in Table 4.

Additional space for energy storage is available on the coach roof on either side of the power-module (personal communication with Stadler Employees, 2013), also illustrated in Fig. 1.

3.1.2 Hydrogen power-plant: Vehicle Projects' fuel cell system that was employed as a prime mover in the hydrogen-hybrid switcher locomotive has been selected as a reference for this paper. The

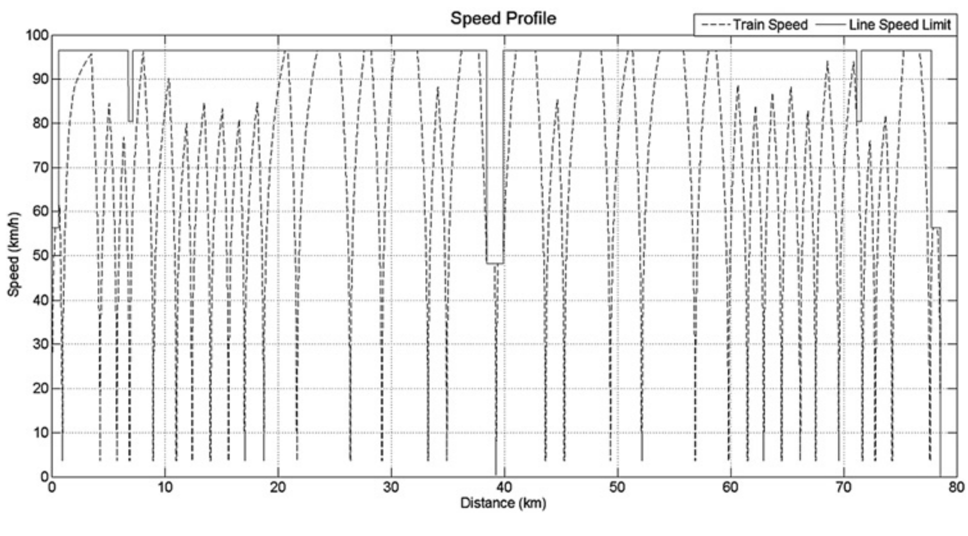

Fig. 3 *Speed profile of the GTW from Birmingham Moor Street to Stratford-upon-Avon compared with the maximum line speed*

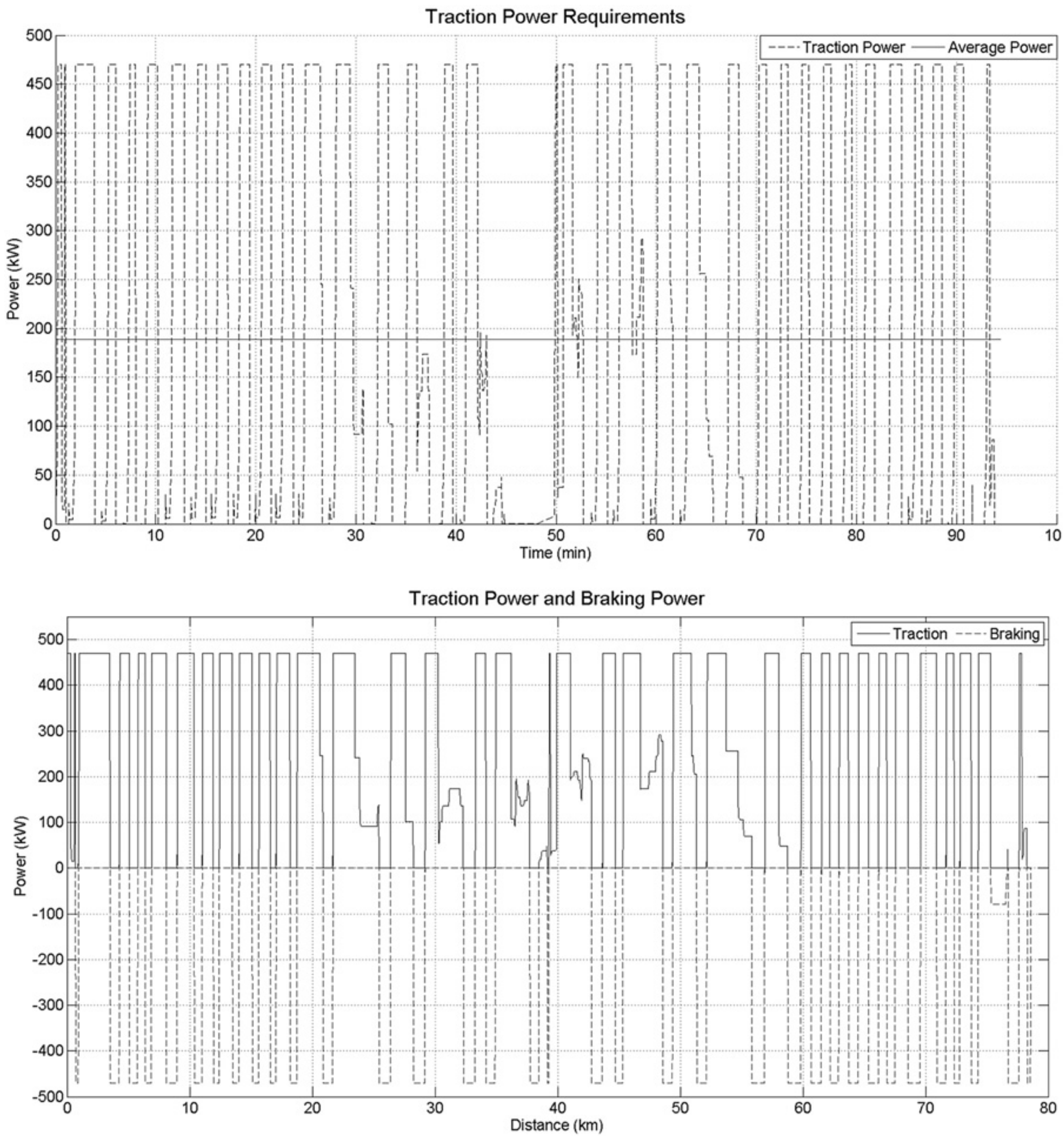

Fig. 4 *Traction power, traction power average and braking power of the GTW at wheels*

reasons are: practical in-service demonstration and currently the most powerful fuel cell system integrated into a railway vehicle for traction. The system provides 250 kW of electricity output utilising two Ballard fuel cell stacks [38], weighs 2.2 t and has the dimensions: length 2.972 m, width 1.093 m and height 1.450 m, thus a volume of 4.7 m^3 (personal communication with Vehicle Projects).

3.1.3 Hydrogen storage: Three hydrogen storage options are considered for the vehicle design: 350 bar, 750 bar and metal-hydride. The characteristics of the storage systems are presented in Table 5.

The heaviest tank system is metal-hydride-based and the system with the lowest volume requirements for hydrogen storage is 700 bar compressed gas.

3.1.4 Train design: The power-plant has to provide 572 kW, see Table 4; consequently, the fuel cell stacks have to supply an output of 587 kW, thus five 125 kW fuel cell systems providing a total of 625 kW are needed. The fuel cell system would have a volume of 11.78 m^3 and a mass of 5.5 t.

One return journey requires 429 kWh output of the power plant, see Table 4. Thus, the fuel cell system has to provide 440 kWh electrical-output taking into account the DC–DC converter. A fuel cell system efficiency of 45% has been exercised, which is established in the following way: a 50%, low heating value (LHV), fuel cell efficiency [9, 40] demonstrated in railway applications has been selected, which was scaled by 90% to account for a lower duty-cycle efficiency for a non-hybrid vehicle, as determined with the prototype hydrogen pioneer locomotive [12]. Similar scaling effects have been reported from the automotive sector [42].

Much higher maximum fuel cell power-plant efficiencies, of up to 60%, and higher vehicle duty-cycle efficiencies have been demonstrated in automotive applications [35, 43–45] and these are likely to be applicable to railway vehicles. Nevertheless, for this paper the empirical rail reference cases, which have employed an older generation of fuel cell power-plant technology, have been exercised. On the studied route, the resulting hydrogen demand is 978 kWh for a return journey. About 16 h operation time, allowing nine return journeys, requires 9389 kWh, which is 282 kg of hydrogen, based on the LHV. Thus, the number of tanks required is 57 at 350 bar, 47 at 700 bar and 81 in a metal-hydride system.

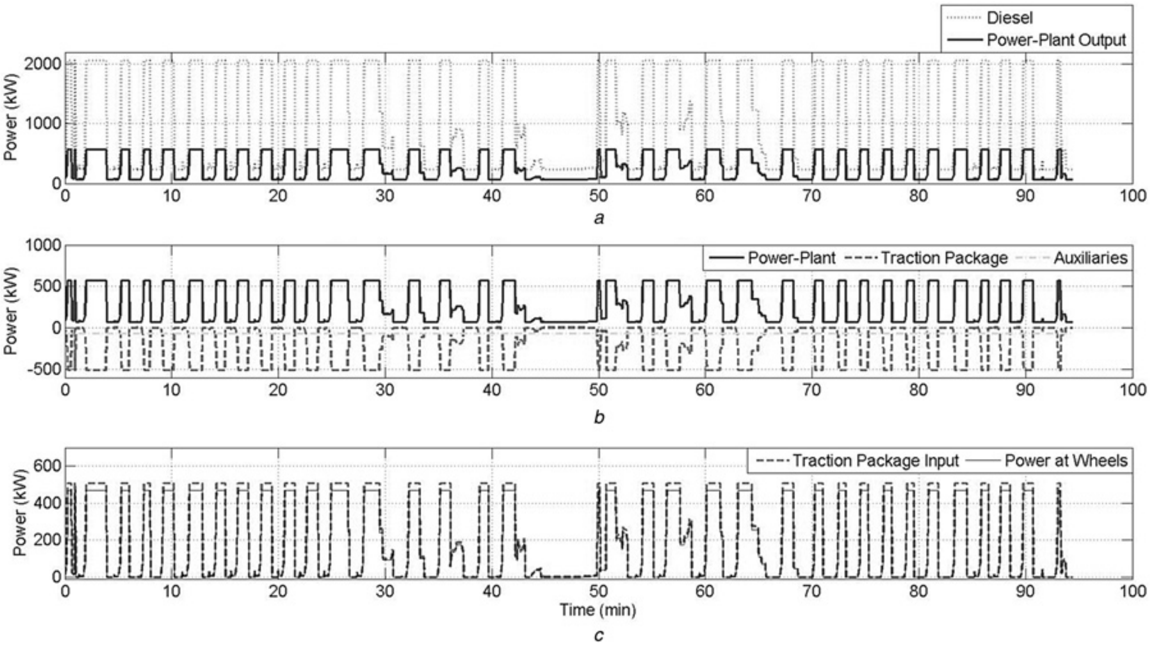

Fig. 5 *Power across the GTW drive-system*

a Diesel input and electrical power output
b Total power inputs and power outputs at the DC-bus
c Power into the traction-package and power at wheels

Table 6 shows the hydrogen vehicle possibilities with the three storage options.

None of the vehicle options meet the mass target: the compressed gas options result in a vehicle mass of ~77 t and the metal-hydride option in ~107 t. The first two are close to the benchmark and are similar to the mass of current regional trains [33], which operate over the route studied. Metal-hydride storage and 700 bar tanks meet the volume target and the compressed gas option fits fully into the power-module, while leaving additional space. About 350 bar tanks need a volume that is ~1.27 m^3 more than available. The high mass of metal-hydride storage disqualifies the option for the evaluation, as the other options provide the same range at less mass, and 700 bar storage requires less volume.

Table 4 Benchmark criteria

Component	Parameter	Parameter
Power-plant		
maximum power-output		572 kW
energy output		429 kWh
Vehicle range		
operating time		960 min (16 h)
number of full return journeys		9
Mass		
vehicle mass		72 t
mass supported by power-module		40 t
mass of diesel fuel (1500 l)[a]	1.26 t	
mass of the two power-plants[b]	5.52 t	
mass available for power-plant and hydrogen	6.78 t	
vehicle mass without power-plant and storage		65.22 t
Volume		
power-module[c] (length 4.5 m, width 2.15 m and height 3.035 m)	29.36 m^3	
power-module corridor[d] (length 4.5 m, width 0.8 m and height 3.035 m) volume cannot be used in passenger vehicles but in locomotives	10.93 m^3	
coach roof on either side of the power-module[e] 2 × (length 3 m, width 2.3 m and height 0.6 m)	8.28 m^3	
volume available for power-plant and hydrogen		37.64 m^3

[a]Mass of 1 l diesel is 0.837 t, based on American data [28]
[b]On the basis of the two QSM11 Cummins Diesel-Generator set installed in the Capital Metro GTW [36, 37]
[c]Assuming a corridor width 0.8 m
[d]Additional volume may be available on the roof of the power-module similar to the corridor width and the height of the space on the coaches However, this has not been considered in the calculations as room for other equipment such as radiators may be needed in the power-module
[e]Personal communication with Stadler employees. The available space can also be seen in Fig. 1

The 700 bar option was modelled, because it is closest to the benchmarking criteria of the diesel–electric GTW, and performance results for that vehicle are presented below. Most parameters for the simulation remained unchanged from the original version, except for the vehicle mass, which increased to 77 t, and the power provided at the wheels, which is 504 kW. It is assumed that the internal vehicle changes do not affect performance, such as the Davis parameters. A more detailed study would have to be conducted to establish the exact location of the various components, which is not part of this investigation.

3.2 Simulation results

The hydrogen GTW was run over the Birmingham Moor Street to Stratford-upon-Avon route and return, where the dwell time at calling stations was 30 s and the turn-around time at Stratford-upon-Avon 5 min. It was assumed that the Davis parameters, based on the diesel–electric GTW, stayed the same throughout the journey. The results for the hydrogen-powered train are presented in Table 7 and in Fig. 6.

From Table 7, it can be seen that the energy at wheels requirement has been increased by 16 kWh compared with the diesel–electric version, which is due to the higher mass. The impact is carried throughout the drive-train and the fuel cell stack, and results in an energy requirement of 1017 kWh for the journey compared with the 978 kWh initial estimation, which was based on a mass of 72 t. Given the 9416 kWh stored in the hydrogen tanks, 9.25 journeys would be possible and the nine benchmarked journeys are achieved, whereas the 960 min operating time is not achieved, instead 925 min are reached. However, one 700 bar tank stores 200 kWh, so the addition of two tanks would raise the energy stored to 9816 kWh allowing 9.65 journeys or 965 min operation

Table 5 Characteristics of considered hydrogen storage systems for vehicle design

	350 bar	700 bar	Metal-hydride
storage capacity	5 kg	6 kg	3.5 kg
tank system mass	116 kg	133 kg	450 kg
tank system volume	0.476 m^3	0.26 m^3	0.283 m^3
demonstrated in railway use	yes[a]	no[b]	yes[c]
reference	personal communication with Vehicle Projects (2013)	Steinberger-Wilckens and Pour [39]	personal communication with Vehicle Projects (2013)

[a]Tank system employed in the hydrogen-hybrid switcher [40]
[b]Demonstrated in automobile applications [41]
[c]Implemented in mining locomotives [8]

time. The additional volume of 0.52 m^3 can be accommodated, and the extra mass of 266 kg, or approximately three passengers, may be neglected in the simulation and corresponding results. As the benchmark should be achieved in the evaluation, the addition of tanks to the vehicle is performed. Fig. 6 presents the power across the drive-train and the fuel cell stack, in the same way as in the diesel–electric results.

Table 6 Hydrogen vehicle parameters with various storage options

Storage system	350 bar	700 bar	Metal-hydride
number of tanks	57	47	81
energy stored	9516 kWh	9416 kWh	9466 kWh
Mass			
mass of the fuel cell system	5.5 t	5.5 t	5.5 t
mass of storage system	6.612 t	6.251 t	36.45 t
mass of train without power-plant and fuel storage	65.22 t	65.22 t	65.22 t
total mass	77.332 t	76.971 t	107.17 t
mass of original train	72 t	72 t	72 t
maximum axle load	22.7 t	22.5 t	37.6 t
benchmark met	*no*	*no*	*no*
Volume			
volume required by fuel cell system	11.78 m^3	11.78 m^3	11.78 m^3
volume of storage system	27.13 m^3	12.22 m^3	22.92 m^3
total volume	38.91 m^3	24 m^3	34.7 m^3
volume available for power-plant and fuel in original train	37.64 m^3	37.64 m^3	37.64 m^3
benchmark met	*no*	*yes*	*yes*

The 199 kW average traction power demand is ~2.5 times lower than the peak power demand at 504 kW, as shown in Table 7, which indicates a high potential for hybridisation. In addition the braking power is significant for the diesel as well as the hydrogen vehicle, as illustrated in Fig. 4, further strengthening the case for an on-board energy storage device. In general, the results show that a hydrogen-powered train is able to meet the benchmark performance, while reducing primary energy consumption, although bearing more mass. Therefore it is established that such a vehicle is technically feasible while operating over a typical duty cycle.

4 Hydrogen-hybrid vehicle development

4.1 Hydrogen-hybrid drive-system

The main alteration to the hydrogen-powered drive-system is the addition of an energy storage device and associated converter, illustrated in Fig. 2*c*. In the conceptual design presented here, the energy storage device is based on a battery-pack system, as implemented in the hydrogen pioneer locomotive [46]. The battery technology in the design is lithium-ion, due to the more favourable energy capacity parameters compared with competing batteries [42]. A drive-train efficiency of 90.3% from the fuel cell stack to

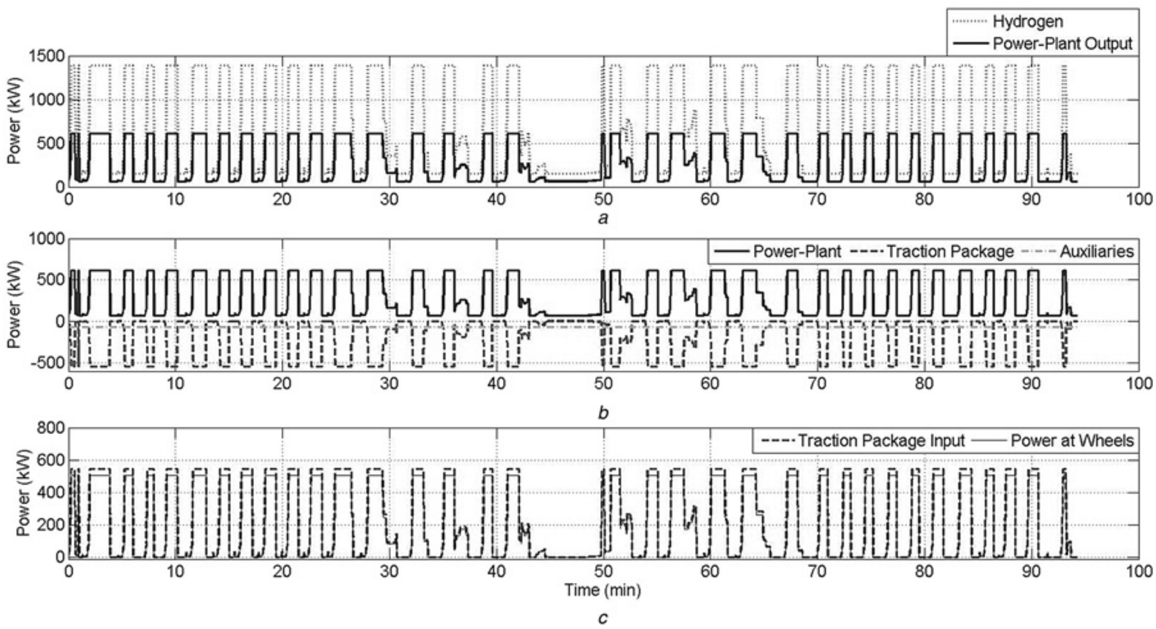

Fig. 6 *Power across the hydrogen GTW drive-system*

a Hydrogen input and electrical power output
b Total power inputs and power outputs at the DC-bus
c Power into the traction-package and power at wheels

Table 7 Hydrogen-powered train, Moor Street – Stratford-upon-Avon and return

Journey time	
Terminal time at Birmingham Moor Street on return from Stratford	94 min 6 min
Power	
Maximum traction power at wheels	504 kW
Average traction power at wheels[a]	199 kW
Auxiliary power	65 kW
Power-plant output	609 kW
Maximum fuel cell system output	625 kW
Energy	
Energy at wheels	313 kWh
Energy at DC-bus	337 kWh
Auxiliary energy[b]	108 kWh
Power-plant output energy	446 kWh
Fuel cell stack output energy	457 kWh
Energy contained in hydrogen	1017 kWh

[a]Calculated from the energy data: 313 kWh/1.57 h = 199 kW
[b]Includes terminal time at Birmingham Moor Street on return of 6 min to give an overall operation time on 100 min, before the journey is repeated

the wheels is assumed, which is the same as in the hydrogen-powered vehicle. The DC–DC converter associated with the battery-pack is taken to have an efficiency of 97.5%, identical to the other converters. A battery-pack charging and discharging efficiency of 87%, including battery losses [47], is assumed.

A duty-cycle fuel cell stack efficiency of 50% has been reported for hydrogen-hybrid railway vehicles, which was established both in experimental demonstrations and during in-service operation [9, 40] and the range in the automotive sector across the power range of the fuel cell stack is from 60% at ~¼ of the power to 53% at full power [35, 45]. The fuel cell stack efficiency has been increased to the reported railway cases, resulting in a power-plant efficiency of ~49%. In Table 8, the hydrogen storage requirements are determined, taking account of regenerative braking. The data were established with the simulation of the diesel–electric GTW, which is employed as a benchmark and information from the hydrogen-powered vehicle.

Table 8 Hydrogen energy storage requirements and minimum power-plant contribution at the wheels

Regenerative braking		
Maximum energy at wheels from braking	196 kWh	
Energy available from braking, assuming 90% employment of regenerative braking	176 kWh	
At the DC-bus	163 kWh	
At the battery-pack ready for charging	158 kWh	
Energy in the battery-pack	137 kWh	
Energy required for one journey		
Energy required at the wheels	297 kWh	
At the DC-bus	321 kWh	
Output required at the battery-pack	330 kWh	
Battery-pack energy from regenerative braking	137 kWh	
Energy required from power-plant for battery charging	193 kWh	
At the battery-pack ready for charging	222 kWh	
At the DC-bus	228 kWh	
Auxiliaries	108 kWh	
Power-plant output	336 kWh	
Fuel cell stack	345 kWh	
Energy as hydrogen for one journey		690 kWh
Hydrogen storage capacity		
Energy as hydrogen for one journey	690 kWh	
Number of journeys	9.6	
Hydrogen energy required for all journeys		6624 kWh
Hydrogen storage system size		
Hydrogen energy required for all journeys	6624 kWh	
Energy contained in one 700 bar tank	200 kWh	
Number of tanks required for all journeys	34	
Mass of one tank	133 kg	
Mass of hydrogen storage		4.522 t
Volume of one tank	0.26 m^3	
Volume of hydrogen storage		8.84 m^3

Table 9 Fuel cell stack and battery power requirements

Fuel cell stack power		
Fuel cell stack energy required for the journey	345 kWh	
Average power required for the 1.67 h (100 min) journey	207 kW	
Resulting fuel cell stack power	250 kW	
Mass of the fuel cell system	2.2 t	
Volume of the fuel cell system	4.7 m^3	
Battery-pack power		
Peak power at wheels		470 kW
At DC-bus		508 kW
Power-plant contribution at DC-bus, operating at 85% of the maximum capacity	207 kW	
–Auxiliary power	65 kW	
–Power-plant power available for traction at the bus		142 kW
Power required from the battery-pack at the DC-bus		366 kW
Required output power of battery-pack		376 kW

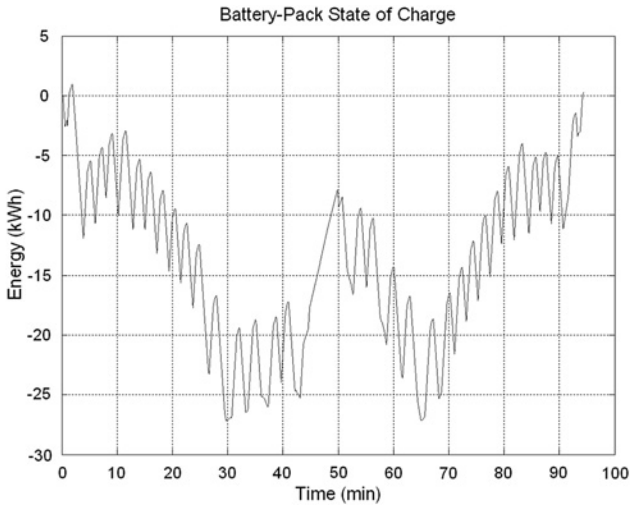

Fig. 7 *Battery-pack state of charge during the duty cycle*

The power requirements of the power-plant and the battery-pack are determined in Table 9.

Markel and Simpson [48] describe that 50% is the maximum discharge depth of lithium-ion batteries to ensure a lifetime suitable for a vehicle and, therefore, this parameter was applied in this paper. The power-plant and the energy captured during regenerative braking will provide the total energy required for the vehicle.

The battery-pack size is dependent on the charge and discharge rates during the duty cycle, and the size was determined in the following way: the cumulative power requirement of the battery-pack was subtracted from the cumulative regenerated energy in the battery-pack. The result is the charging-power needed

Table 10 Battery-pack characteristics

Power basis	
Power required from battery-pack	376 kW
Power of one battery	80 kW
Number of batteries needed	5
Energy basis	
Energy storage requirement for battery-pack	60 kWh
Energy storage capability of one battery	16 kWh
Number of batteries needed	4
Battery-pack	
Number of batteries needed for the battery-pack	5
Power	400 kW
Energy storage	80 kWh
Mass of the battery-pack	0.725 t
Volume of the battery-pack	0.65 m^3

Table 11 Hydrogen-hybrid train characteristics

Energy	
Energy stored in hydrogen	6624 kWh
Maximum energy stored in battery-pack	80 kWh
Maximum energy available from battery-pack considering discharge limits	40 kWh
Power	
Fuel cell stack power	250 kW
Battery-pack power	400 kW
Power at wheels[a] (limited to the same as the diesel–electric version)	470 kW
Mass	
Mass of the tanks, fuel cell stack and battery-pack	7.447 t
Train mass	72.7 t
Mass benchmark met?	no[b]
Volume	
Volume of the tanks, fuel cell stack and battery-pack	14.2 m^3
Maximum volume available in the power-module	29.36 m^3
Volume available in the power-module for other equipment	15.16 m^3
Volume benchmark met?	yes

[a]Maximum power possible for short periods of time: fuel cell stack 250 kW, battery-pack 400 kW, leading to power at wheels of 587 kW
[b]Author considers the 0.7 t additional mass as an acceptable increase compared with the benchmark

Table 12 Performance results of the hydrogen-hybrid train on route Birmingham Moor Street – Stratford-upon-Avon and return

Journey time	94.5 min
Terminal time at Birmingham Moor Street on return from Stratford	5.5 min
Power	
Maximum traction power at wheels	470 kW
Average traction power at wheels[a]	189 kW
Auxiliary power	65 kW
Power-plant output	207 kW
Maximum fuel cell system output	250 kW
Battery-pack output	376 kW
Maximum battery-pack output	400 kW
Energy	
Energy at wheels	298 kWh
Energy at DC-bus	322 kWh
Braking energy at wheels	198 kWh
Available regenerative braking energy in the battery-pack	138 kWh
Auxiliary energy[b]	108 kWh
Power-plant output energy	336 kWh
Fuel cell stack output energy	345 kWh
Energy contained in hydrogen	690 kWh

[a]Calculated from the energy data: 298 kWh/1.58 h = 189 kW
[b]Includes terminal time at Birmingham Moor Street on return of $5\frac{1}{2}$ min

from the power-plant. Next, the mean of the charging power was determined, not considering the terminal time at Birmingham Moor Street. Thereafter, the mean was added to the difference between the cumulative charging power and the cumulative discharging power, which resulted in the graph displayed in Fig. 7.

The highest point on the graph is 0.95 kWh and the lowest is −27.22 kWh, so the range between the two is 28.17 kWh or rounded to 30 kWh. Thus, the battery-pack is required to have an energy capacity of 60 kWh, after applying the maximum discharge depth of 50%.

A reference lithium-ion battery that is designed for mobile applications has the following characteristics: 80 kW power, 16 kWh energy stored, 145 kg mass and has a volume of 0.13 m^3 [49]. The train's battery-pack characteristics are calculated in Table 10.

A hydrogen-hybrid train with the characteristics presented in Table 11 could be developed.

4.2 Simulation results

The hydrogen-hybrid GTW was run over the Birmingham Moor Street to Stratford-upon-Avon route and return, while all other parameters and assumptions stayed the same as the previous cases. The results for the hydrogen-hybrid train are presented in Table 12 and in Fig. 8.

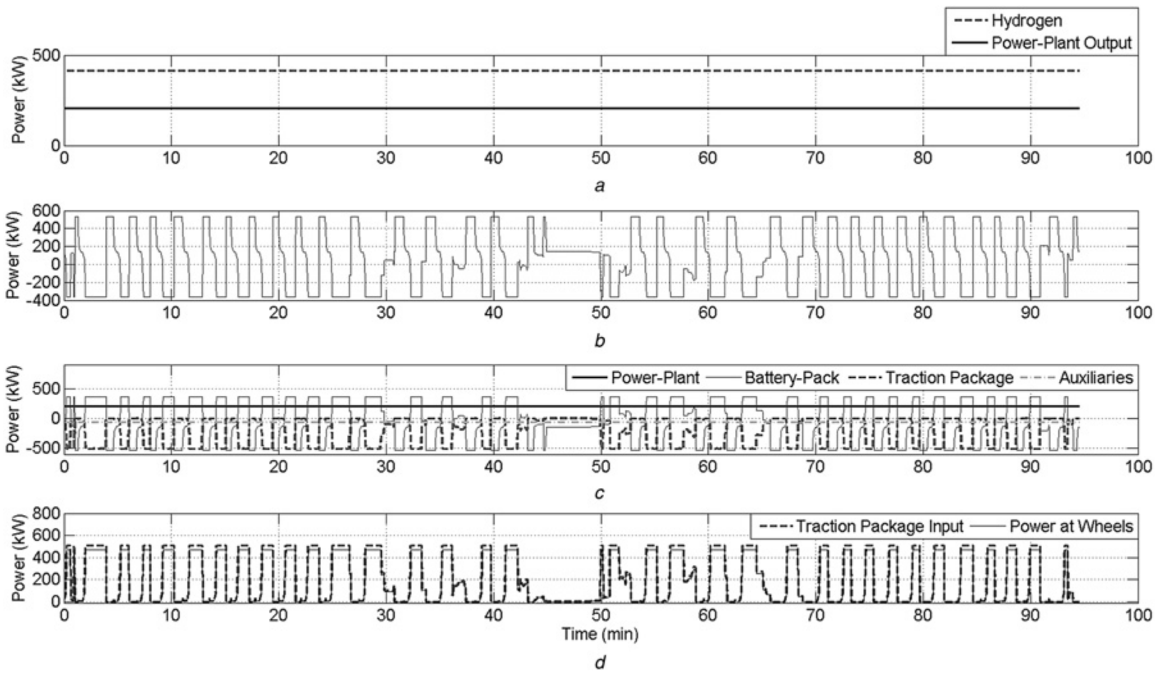

Fig. 8 *Power across the hydrogen-hybrid train drive-system*

a Hydrogen input and electrical power output
b Battery-pack power input and output at DC-bus
c Total power inputs and power outputs at the DC-bus
d Power into the traction-package and power at wheels

The power across the drive-system of the hydrogen-hybrid train is shown in Fig. 8.

Graph (a), in Fig. 8, shows the hydrogen input and the power-plant output, and it is apparent that only the average power is supplied compared with hydrogen-only train, see Fig. 6.

In graph Fig. 8*b*, the battery-pack power at the DC-bus is presented, and it can be seen that the variations in power demand are met by the batteries. Furthermore, the power contribution resulting from regenerative braking can be seen in the positive peak values.

Graph Fig. 8*c* shows all the powers across the DC-bus. The inputs are presented as positive values and the outputs as negative values; note the reversal of the battery-pack graph for the representation.

The power input to the traction motors and the power at the wheels of the vehicle are illustrated in graph Fig. 8*d*.

In general, the modelled hydrogen-hybrid vehicle performed well, leading to a similar journey time and range compared with the other vehicles, while reducing primary energy consumption.

5 Performance comparison and discussion

A diesel–electric GTW operated over the route Birmingham Moor Street to Stratford-upon-Avon provided the benchmark parameters for a hydrogen-powered and a hydrogen-hybrid version of the train. The parameters that vary between the trains are presented in Table 13.

Table 13 Characteristics of the three trains for an overview comparison

	Diesel-electric GTW	Hydrogen GTW 700 bar	Hydrogen-hybrid GTW
journey time	94 min	94 min	94.5 min
range	963 min (16 h)	965 min (16 h)	960 min (16 h)
Mass			
train mass, t	72	77	72.7
maximum axle load, t	20	22.5	20.4
Energy			
primary energy consumption for the journey	1548 kWh	1017 kWh (34% less than diesel)	690 kWh (55% less than diesel)
energy from regenerative braking	–	–	138 kWh
duty-cycle vehicle efficiency, %	25	41	45[b]
well-to-wheel efficiency[a], %	21	24	26[b]
well-to-wheel carbon emissions[a], kg	1895	862 (55% less than diesel)	533 (72% less than diesel)
primary energy source	diesel	hydrogen	hydrogen
primary energy storage quantity (LHV)	14 918 kWh (1500 l)	9816 kWh (294 kg)	6624 kWh (204 kg)
Power			
maximum power at wheels, kW	470	504	470[c]
power-plant power, kW	572	609	207[d]
prime-mover power, kW	600	625	250
maximum battery-pack power, kW	–	–	400

[a]Calculated with data from Hoffrichter [5] and Hoffrichter *et al.* [7], based on the LHV. Only natural gas steam methane reforming production of hydrogen was considered, no renewables contribution was added
[b]Efficiency of the primary drive system, which does not include regenerative braking, to allow easy comparison with the other two trains Inclusion of regenerative braking would increase the vehicle efficiency and subsequently the well-to-wheel efficiency
[c]Limited to 470 kW to provide the same range and journey time as the diesel–electric GTW
[d]Fuel cell stack operating at 85% of maximum capacity

Both hydrogen trains could meet all but the mass benchmark, with the hydrogen-only train being the heaviest at 77 t, whereas the hybrid version weighs 72.7 t compared with the original of 72 t. None of the mass increases are prohibitive for vehicle operation, and current vehicles operated over the line have a similar mass to the hydrogen-only train. The maximum axle load for the hydrogen-powered train is considerably higher than that of the original diesel–electric GTW, which is already high. An alternative load-bearing system to support the power-module, comprised of articulated bogies, can decrease the maximum axle load significantly, although the train mass increases.

The power-plant and the 700 bar compressed hydrogen tanks can be fully installed in the power-module, while leaving additional room for other equipment and this configuration was the option modelled. Battery-pack, power-plant and hydrogen storage all fit in the power-module for the hydrogen-hybrid case.

All trains have an operating range of 16 h, which requires daily refuelling, which is consistent with current practice in the UK. Primary energy requirements for the return journey are reduced by 34% with the hydrogen-powered train and reduced by 55% with the hydrogen-hybrid train, employing regenerative braking. Moreover, the highest vehicle efficiency is achieved with the hydrogen-hybrid train. For a return journey the well-to-wheel efficiencies are 21% for diesel, 24% for the hydrogen-only propulsion and 26% for the hydrogen-hybrid train, calculated with data available from [5, 7] assuming that all the hydrogen is produced from natural gas. This is accompanied by a carbon emission reduction of 55% for the hydrogen vehicle and a 72% reduction for the hydrogen-hybrid, compared with the diesel version.

Traction characteristics are similar for all trains, and the additional power of the hydrogen-only train is needed to compensate for the higher mass. In general, a performance improvement is achieved with either of the hydrogen trains, as is apparent in the higher vehicle efficiencies, lower energy consumption and reduction in carbon emissions, while providing the same service as the diesel–electric train. These results suggest the feasibility of hydrogen and fuel cells in railway vehicles. In a next step, the authors recommend a more detailed design study and subsequent construction of a hydrogen-powered regional railway vehicle.

6 Conclusion

The GTW 2/6 diesel–electric regional train was modelled over the journey from Birmingham Moor Street to Stratford-upon-Avon and return, with the aid of a single train computer simulation. The results served as a benchmark for a hydrogen-powered and a hydrogen-hybrid version of the train.

All the equipment necessary for the hydrogen drive-system can be accommodated in the power-module if 700 bar storage is employed, which formed the basis for the vehicles modelled in the evaluation. The 72 t diesel–electric train achieved a journey time of 94 min, while consuming 1548 kWh of energy, which leads to an operational range of 16 h. The 77 t hydrogen-only train also achieved a journey time of 94 min, with an energy consumption of 1017 kWh, resulting in an operational range of 16 h. Results for the hydrogen-hybrid train are: 94.5 min journey time, 690 kWh hydrogen consumption with a vehicle mass of 72.7 t and an operational range of 16 h. Both hydrogen-based trains reduce energy consumption compared with the diesel version: 34% for the hydrogen-only and 55% for the hydrogen-hybrid employing regenerative braking, savings that the authors consider significant.

The diesel–electric train has a vehicle efficiency of 25%, the hydrogen-powered vehicle an efficiency of 41% and a 45% vehicle efficiency is achieved with the hydrogen-hybrid train. Furthermore, a reduction in carbon emissions compared with the diesel train on a well-to-wheel basis is achieved: 55% for the hydrogen-only train and 72% for the hydrogen-hybrid vehicle. All efficiencies and carbon emission reductions are based on the duty cycle of a return journey and the LHV of the fuel while hydrogen is solely produced through steam methane reforming without renewables contribution.

The presented results are derived from a wide range of data sources but there are limitations to the approach taken and the assumptions have a degree of variability within them. Nevertheless, the results support further development of this system in a prototype trail, in which conclusive experimental data on vehicle performance and efficiency could be determined.

The evaluation demonstrates, on the basis of benchmarking, computer simulation and the associated results analysis that hydrogen and fuel cells are feasible for train propulsion systems. The energy savings and carbon reductions that are achieved in the simulation, while the trains are performing the same service, provide a strong case for more detailed design and construction of a demonstration train.

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8 References

1 International Union of Railways (UIC) and International Energy Agency (IEA): 'Railway handbook 2012: energy consumption and CO_2 emissions' (UIC, IEA, Paris, 2012)
2 U.S. Environmental Protection Agency (EPA): 'Locomotives – exhaust emission standards', 1 April 2012. Available at http://www.epa.gov/otaq/standards/nonroad/locomotives.htm
3 European Commission: 'Mechanical engineering: directives on emissions from non-road mobile machinery', 1 April 1997–2012. Available at http://www.ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/emissions-non-road/
4 HM Government: 'Climate change act 2008' (The National Archives, London, 2008)
5 Hoffrichter, A.: 'Hydrogen as an energy carrier for railway traction'. PhD, Birmingham Centre for Railway Research and Education, University of Birmingham, Birmingham, 2013. Available at http://www.etheses.bham.ac.uk/4345/
6 Winter, C.-J.: 'Hydrogen energy – abundant, efficient, clean: a debate over the energy-system-of-change', *Int. J. Hydrog. Energy*, 2009, **34**, pp. S1–S52
7 Hoffrichter, A., Miller, A.R., Hillmansen, S., Roberts, C.: 'Well-to-wheel analysis for electric, diesel and hydrogen traction for railways', *Transp. Res. D, Transp. Environ.*, 2012, **17**, pp. 28–34
8 Miller, A.R., Hoffrichter, A., Hillmansen, S., Roberts, C.: 'Well-to-wheel analysis of hydrogen-fueled railways'. Presented at the 19th World Hydrogen Energy Conf. 2012, Toronto, 2012
9 Yamamoto, T., Hasegawa, H., Furuya, T., Ogawa, K.: 'Energy efficiency evaluation of fuel cells and batteries hybrid railway test vehicles', *Q. Rep. RTRI*, 2010, **51**, pp. 115–121
10 Kawasaki, J., Takeda, S., Furuta, R.: 'Development of the fuel cell hybrid railcar', *Jpn. Rail. Eng.*, 2008, **160**, pp. 6–8
11 TIG/m Modern Street Railways: 'TIGm modern street railways sends world's greenest streetcars to Aruba toward 100% sustainability'. ed. Chatsworth, CA, 2012
12 Hoffrichter, A., Fisher, P., Tutcher, J., Hillmansen, S., Roberts, C.: 'Performance evaluation of the hydrogen-powered prototype locomotive 'hydrogen pioneer'', *J. Power Sourc.*, 2014, **250**, pp. 120–127
13 Meegahawatte, D., Hillmansen, S., Roberts, C., Falco, M., McGordon, A., Jennings, P.: 'Analysis of a fuel cell hybrid commuter railway vehicle', *J. Power Sourc. [Proc. Pap.]*, 2010, **195**, (23), pp. 7829–7837
14 Hoffrichter, A., Silmon, J., Iwnicki, S., Hillmansen, S., Roberts, C.: 'Rail freight in 2035 – traction energy analysis for high performance freight trains', *Proc. Inst. Mech. Eng. F, J. Rail Rapid Transit*, 2012, **226**, pp. 568–574
15 Hoffrichter, A., Silmon, J., Schmid, F., Hillmansen, S., Roberts, C.: 'Feasibility of discontinuous electrification on the great western main line determined by train simulation', *Proc. Inst. Mech. Eng. F, J. Rail Rapid Transit*, 2013, **227**, pp. 296–306
16 Hillmansen, S., Roberts, C.: 'Energy storage devices in hybrid railway vehicles: a kinematic analysis', *Proc. Inst. Mech. Eng. F, J. Rail Rapid Transit*, 2007, **221**, pp. 135–143
17 Lu, S., Hillmansen, S., Roberts, C.: 'A power-management strategy for multiple-unit railroad vehicles', *IEEE Trans. Veh. Technol.*, 2011, **60**, pp. 406–420
18 Hoffrichter, A.: 'The feasibility of discontinuous electrification: case study of the great western main line'. Master's dissertation, College of Engineering and Physical Sciences: School of Civil Engineering, University of Birmingham, Birmingham, 2012
19 Davis, W.J.: 'The tractive resistance of electric locomotives and cars', *Gen. Electr. Rev.*, 1926, **29**, pp. 685–707
20 Stadler Rail AG: 'Vehicles: GTW articulated railcar', 11 March 2013. Available at http://www.stadlerrail.com/en/vehicles/gtw/
21 Stadler Rail AG: 'DTW DMU 2/6 low-floor: light-weight diesel rail vehicle for capital metro, Austin, Texas, USA'. Bussnang: Author, 2008
22 Stadler Rail AG: 'GTW DMU 2/6 low-floor for Denton county transportation authority (DCTA), Texas, USA'. Bussnang: Author, 2012
23 Stadler Rail AG: 'GTW DMU-II 2/6 and GTW DMU-II 2/8 low-floor multiple units for VEOLIA Transport Nederland'. Bussnang: Author, 2007
24 LRS Engineering AG: 'Examples of realised and current projects: range of rail vehicles: OEM-bogies (projects for Stadler, Bussnang)', 12 March 2008. Available at http://www.lrs-engineering.ch/en/referenzen/index.html
25 LTK Engineering Services: 'Sonoma-Marin area rail transit district: vehicle technology assessment final draft report' (Sonoma-Marin Area Rail Transit, Petaluma, CA, 2009)
26 U.S. Department of Transportation – Federal Transit Administration: 'in diesel/electric multiple unit: a modern light rail vehicle: Camden-Trenton river line'. ed. Washington, DC: Author, 2011
27 CBRail S.a.r.l.: 'GTW DMU/EMU-II 2/6 & 2/8', 13 March 2007. Available at http://www.cbrail.com/#/gtw-dmu-emu/4540429836
28 U.S. Department of Energy (DOE): 'Lower and higher heating values of hydrogen and fuels', 01 September 2008. Available at http://www.hydrogen.pnl.gov/cocoon/morf/projects/hydrogen/datasheets/lower_and_higher_heating_values.xls
29 Jeunesse, A., Rollin, M.: La motorisation du TGV POS. Revue Générale des Chemins de Fer., March 2004, pp. 19–39
30 International Union of Railways (UIC): 'Evaluation of energy efficiency technologies for rolling stock and train operation of railways (EVENT)', Paris, 2003
31 Steimel, A.: 'Elektrische Triebfahrzeuge und Ihre Energieversorgung' (Oldenburger Industrieverlag, Muenchen, 2006)
32 RSSB: 'Research Programme Engineering: T531 Feasibility Study into the use of hydrogen fuel'. 'Final Report', Author, London, 2005
33 Marsden, C.J.: 'Traction recognition' (Ian Allan Publishing Ltd., Hersham, 2007)
34 McDonnell, G.: Fill'er up – and fast! Trains, January 2012, pp. 20–21
35 Eberle, U., Muller, B., von Helmolt, R.: 'Fuel cell electric vehicles and hydrogen infrastructure: status 2012', *Energy Environ. Sci.*, 2012, **5**, pp. 8780–8798
36 Cummins Power Generation Inc.: 'Specification sheet: diesel generator set QSM11 series engine', Minneapolis, MN: Author, 2013
37 Vantuono, W.C.: 'Texas-sized transit'. Railway Age, June 2007, Available at http://www.nxtbook.com/nxtbooks/sb/ra0607/index.php?startid=40
38 Miller, A.R., Hess, K.S., Barnes, D.L., Erickson, T.L.: 'System design of a large fuel cell hybrid locomotive', *J. Power Sourc.*, 2007, **173**, pp. 935–942
39 Steinberger-Wilckens, R., Pour, A.M.: 'A fuel cell system for railbus application'. Seventh Int. Hydrail Conf., Birmingham, 2012
40 Miller, A.R., Erickson, T.L., Dippo, J.L., Eisele, R.I., Johnson, M.D., Lambrecht, T.: 'Hydrogen fuel-cell locomotive: switching and power-to-grid demonstrations'. Presented at the Ninth World Congress on Railway Research (WCRR), Lille, 2011
41 Hansen, G.P., Sato, M., Yan, Y.: 'Pressure vessels for hydrogen vehicles: an OEM perspective'. Int. Hydrogen Fuel and Pressure Vessel Forum, Beijing, 2010
42 Von Helmolt, R., Eberle, U.: 'Fuel cell vehicles: status 2007', *J. Power Sourc.*, 2007, **165**, pp. 833–843
43 U.S. Department of Energy (DOE): 'Progress and accomplishments in hydrogen and fuel cells', Washington, DC, 2013
44 Yokoyama, T.: 'Progress and challenges for TOYOTA's fuel cell vehicle development'. 2009 ZEV Symp., Sacramento, CA, 2009
45 Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G.: 'National fuel cell electric vehicle learning demonstration'. Final Report, NREL/TP-5600–54860, National Renewable Energy Laboratory, Golden, CO, 2012
46 Coombe, D., Fisher, P., Hoffrichter, A., *et al.*: 'Development and design of a narrow-gauge hydrogen-hybrid locomotive', *Proc. Inst. Mech. Eng. F, J. Rail Rapid Transit*, 2014
47 Bossel, U.: 'Does a hydrogen economy make sense?', *Proc. IEEE*, 2006, **94**, pp. 1826–1837
48 Markel, A.J., Simpson, A.: 'Plug-in hybrid electric vehicle energy storage system design' (National Renewable Energy Laboratory, Golden, CO, 2006)
49 Brusa Elektronik AG: 'EVB1-HV-Battery (16 kWh/400 V or 14 kWh/350 V)', Sennwald: Author, 2012