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Energy consumption and carbon dioxide emissions analysis for a concept design of a hydrogen hybrid railway vehicle

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Abstract: Diesel is the most common energy source used by many railway vehicles globally but it also has an impact on the environment due to carbon emissions from the diesel engine. Railway electrification is an effective way to reduce emissions but fails to be a very cost effective solution particularly for routes where passenger traffic is low. This paper has undertaken a propulsion system concept design based on a vehicle similar to the British class 150 diesel-powered vehicle. A return journey was simulated over the British regional route Birmingham Moor Street to Stratford-upon-Avon to set a benchmark for the development of hydrogen-powered and hydrogen-hybrid train. A fuel cell power plant and hydrogen compressed at 350 bars were used as part of the concept design. It was found that all the components essential for the train propulsion system can be installed within the space available on original diesel-powered class 150 train. The installation of equipment does not compromise passenger capacity and weighs similar to original class 150. Energy consumption was reduced by 44% on the hydrogen-powered train and by 60% on the hydrogen-hybrid train. Carbon-dioxide emissions were reduced by 59% using the hydrogen-powered train and by 77% using the hydrogen-hybrid train.

Nomenclature

F	Force [kN]
V	Velocity [m/s]
α	Gradient angle [degrees]
s	Vehicle displacement [m]
TE	Tractive effort by vehicle [kN]
A	Acceleration [m/s^2]
λ	Rotational allowance
m	Mass of the train [kg]
g	Acceleration due to gravity [m/s^2]
d	Delta-change of following variable
A	Davis equation constant coefficient [N]
B	Davis equation linear term coefficient [N/(m/s)]
B	Davis equation linear term coefficient [N/(m/s)]
C	Davis equation quadratic term coefficient [$N/(m/s^2)$]
STS	Single train simulator
DMU	Diesel multiple unit
FCMU	Fuel cell multiple unit
FCEMU	Fuel cell electric multiple unit

1. Introduction

Transport activities consume approximately 20% of prime energy globally, and road transport shares 75% of this consumed energy after eliminating the share due to air, sea and rail transport [1]. European countries consume 30% of their energy on transport, of which the railway is approximately a 2.5% share. In the USA the share for energy consumption of railway transportation is approximately 2.1% of the total 27.8% [2].

Two main sources to produce energy for railway vehicles are electricity and diesel fuel and both have their benefits and disadvantages [2]. Electricity allows production from multiple energy sources such as fossil fuels, and renewables, while eliminating the emissions produced at the point-of-use. However electrification of railway tracks requires an additional infrastructure which is expensive and cannot be implemented in many areas [2, 5]. Compared to electricity, diesel fuel allows the continuous operation of trains and ensures its travel over the routes where electrification is not economical or routes not electrified yet, but it comes with the cost of carbon emissions at the point-of-use and relying on single energy source [2, 6, 7].

To reduce the impact of the transport sector on the global climate, as well as local air quality, the use of vehicles consisting of renewable energy sources is crucial [8]. Recognised by Henry Cavendish as a distinct element in 1766 and named by Antoine Lavoiser hydrogen is the lightest element presented in the periodic table and found in abundance in universe. [2, 9, 10, 32]. When the concentration of hydrogen reaches from 4% to 75% its combustion in air is possible [11], allowing its consumption in specific combustion engines, where it is burned similarly to petroleum fuel [2, 12]. An alternative to hydrogen combustion engine, a fuel cell is a suitable device to produce clean electricity for vehicles [2]. Among numerous fuel cells, the proton membrane exchange membrane fuel cell (PEMFC) is considered to be the most suitable and reliable power source for electric vehicles [13].

Hydrogen powered automotive vehicles are commercially available on the market. They have similar operational range and refuelling time compared to the vehicles which use petroleum fuel. The water vapour produced from the use of compressed hydrogen in fuel cell vehicles is nearly the same compared to existing combustion technologies, however due to the increased efficiency of a fuel cell there is a big reduction in carbon emissions [2, 25]. Various hydrogen powered railway vehicle prototypes have been developed in the past few years, including one built at the University of Birmingham [14] The first hydrogen powered locomotive developed was by Vehicle Projects Inc. [2] and was a mining locomotive.

Full scale hydrogen powered locomotive was built for BNSF railway and is used for switching purpose [15]. It is fitted with two fuel cell stacks providing 250 kW power, in addition to lead acid batteries capable of providing 1.5 MW peak output for approximately 5 minutes [2, 16]. Alstom has recently developed a full emission-free train based on Coradia Lint platform. The Coradia Lint traction system is using fuel cells technology to produce electricity for train by using electrolysis and is perfect example of modern energy supply and storage system combined with intelligent energy management. [31]

In the current paper two hydrogen-powered trains were developed considering the mass and volume implications of the change in traction system with an evaluation of practicality of hydrogen as a fuel. A Diesel Multiple Unit (DMU) regional train was selected as a benchmark vehicle and the performance factors and drive time over a typical route in United Kingdom are determined with a computer simulation. Following the benchmark simulation a design of hydrogen-powered and hydrogen-hybrid train is developed and are simulated over same route. Finally the performance of the benchmark train is compared with two other hydrogen-powered and hydrogen-hybrid trains.

2. Benchmark Simulation

2.1. Simulation Software

Single Train Simulator (STS) software developed by Birmingham Centre for Railway Research and Education was used by author for the investigation presented in this paper. [14, 17, 18].

The Single Train Simulator solves the equation of motions of the railway vehicle, subject to the operational constraints by using Lomonosoff's equation (equation 5) per distance iteration [19]. Equation 1 represents Newton 2nd law of motion and equation 2 is expansion of equation 1 where λ is rotational allowance used to increase the required force to begin vehicle movement and was set to 0.08 which is typical value used to represent rotary allowance in regional DMUs. The equations are given below [18,19]:

$$F = ma \quad (1)$$

$$F = m(1+\lambda)a \quad (2)$$

$$F = TE - [mg\sin(\alpha) + Cv^2 + Bv + A] \quad (3)$$

Overall:

$$m(1+\lambda)a = TE - [mg\sin(\alpha) + Cv^2 + Bv + A] \quad (4)$$

Or:

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

The above equations fully describes the kinematics of rail vehicle motion, except for the resistance encountered due to curving forces, therefore they were neglected from analysis. In order to solve these equations either the distance or time must be discretised. In the STS the distance is discrete so the simulation ends once the vehicle completed its full journey. Numerical integration is used to solve these equations. Typically 1 metre is sufficient for solution accuracy. Figure 1 demonstrate the operational steps of STS.

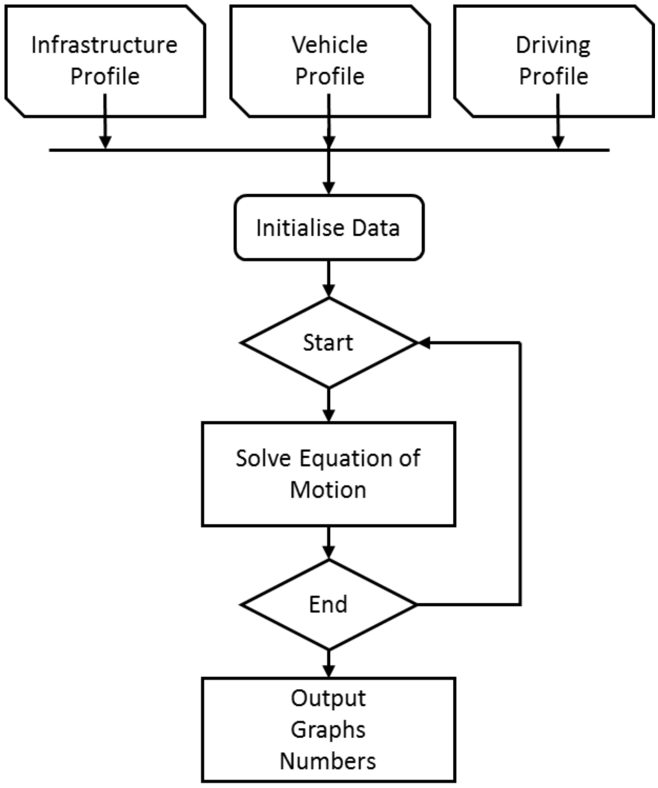

Figure 1: Single Train Simulator Flow Chart

The Single Train Simulator consists of three fundamental sections; infrastructure model, vehicle model and physics model. The infrastructure model includes track information, track speed, gradient and curvature information. The vehicle model includes Davis parameters, mass, rotational inertia, tractive and braking characteristics. The physics model computes the speed and displacement by using numerical integration [14].

For computer modelling the route information, vehicle data and driving style are essential. The selected driver style by author was assumed to be as fast as possible. Additional sections of code were written for software to investigate battery-pack capacity and generate additional graphs relating to the performance of the fuel cell and battery system.

2.2. Route Selection

The route selected for simulation is from Birmingham Moor Street station to Stratford-upon-Avon station and return. It is an intercity line with moderate commuter traffic. The route is also known as Snow Hill Lines and is operated mainly by London Midland train operating company. This route has three sub branches and the branch known as North Warwick Shire line was chosen for this project due to its moderate busy commuter services. Currently 29 return services are offered on this route starting from 6 am to 11 pm, 3 services every hour in morning and 2 services every hour afternoon. This route is non-electrified and operated by diesel multiple units. This route is one of the many typical routes on which class 150 series DMUs are operational. The frequency of traffic on this route make it ideal for operation of diesel multiple units compared to electric multiple units. [20,21] The London Midland offers its services on this route via British class 170 and 172 vehicles, which have slightly higher power but similar capacity to the British class 150. This route has sixteen stops between two given terminals which make it ideal route for harnessing regenerative energy. The length of route is 78.58 km. The route data was pre-available in single train simulator this route is also used in previous simulations [14, 18].

2.3. Vehicle Selection

The British class 150 "Sprinter" was used as the benchmark vehicle. The Sprinters were built by British Railway Engineering Limited York during 1984-1987 and are the most successful diesel multiple unit (DMU) design since its introduction, demonstrating success on urban and rural services all over the UK. The Sprinters were used on long distance services proving their flexibility. They are ideal for the services where the station stops are close together. Ideally this will provide better use of regenerative braking systems when modified. The drive train of Sprinter is very reliable since they were introduced and they have never changed the successful Cummins engines with Voith Gmeinder transmission and gear system [22]. Figure 2 illustrates the Sprinter operated by London Midlands train operating company leaving Makvern Link Station [23].

Figure 2: London Midlands Class 150 Train Leaving Makvern Link Station [23]

The British class 150 train has very generic design and most regional commuter trains replicate its design. Class 150 DMU has successfully completed its 33 years in service. The body frame and rigid chassis make it ideal for future conversions. [24] Class 150 is original generic design for a series of vehicles which number through 150, 153, 155,156, 158 and 159. The latter two are modern upgraded version colloquially known as super sprinters. Approximately 475 trains in sprinter family are manufactured which were operated on regional and branch lines in UK. The Sprinter was selected because of its Bogie Style chassis, once the engine and transmission systems are removed it will provide enough space to accommodate an alternative propulsion system and traction motors. The Sprinter has slightly wider interior due to 20 meter length of each coach and full use of C1 gauge. The roof of Sprinter does not hold any components and is fully available to accommodate Hydrogen Cylinders. Each coach of the Sprinter has its own drive train system rather than distributed throughout the train. The Sprinter design also allows the creation of longer formations with additional coaches.

The main characteristics of diesel-multiple-unit Class 150 "Sprinter" are given in Table 1. The data was sourced from literature provided by [14, 19].

Table 1: British Class 150 "Sprinter" Technical Data

Train Characteristics	
Axle Arrangement	2'Bo2'
Vehicle Length	40.12 m
Vehicle Width	2.8 m
Vehicle Height	3.77 m
Tare Mass	76.5 t
Coach Mass	35.8 t
Starting Tractive Effort	37.52 kN
Maximum Acceleration	0.5 m/s2
Maximum Speed	121 km/h
Davis Equation	R=1.5+0.006v +0.0067v2
Power Module Characteristics	
Numbers of powered-axles	4
Power of two diesel engines combined	425 kW
Maximum Power at wheels	349.36 kW
Auxiliary power	28 kW
Drive Train Efficiency	88 %
Diesel tank capacity	1500 l
Energy available in diesel tank	14910 kWh

2.3.1 British Class 150 Power Generation Data: The benchmark train "Sprinter" class 150 has two similar power-module systems, each containing one diesel engine and one transmission system as illustrated in Figure 3.

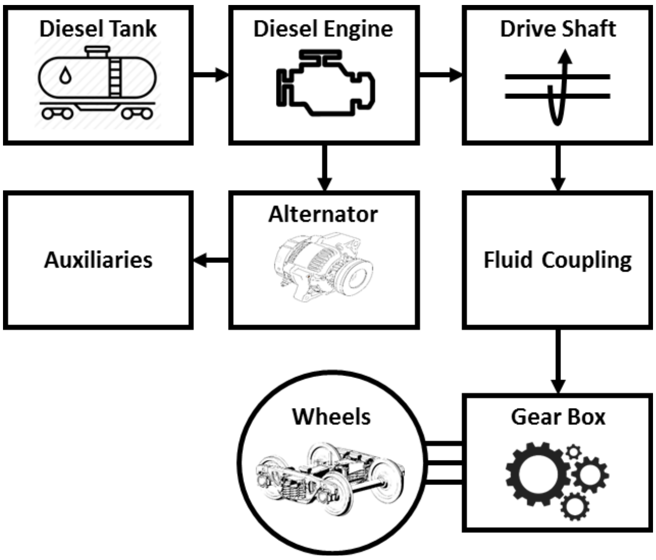

Figure 3: Sprinter, British Class 150 Diesel Train Power-Module Drive-System

The efficiencies of class 150 power-module are based on the research of [2, 14, 25]. The drive train efficiency of 88% and engine efficiency of 29% has been applied. Further efficiencies which were applied to class 150 were 92.6 % efficiency of the traction package and 95.6 % efficiency of diesel engine drive-shaft [14, 25]. These efficiencies allowed the simulation of train and assessment of fuel consumption which will assist as the base input for development of hydrogen powered trains. The power plant of original “Sprinter” class 150 has a combination of two diesel engines which provides 425 kW combined. 28 kW is reserved for auxiliaries and 397 kW power is available at traction package, therefore, 349.36 kW power is available for wheel traction. According to benchmark vehicle calculations, the energy provided by diesel power plant for a return journey is 340.36 kWh. 48.16 kWh energy is used by auxiliaries, energy available for traction package is 292.20 kWh and the energy necessary for motion of train is 270.58 kWh.

The “Sprinter” class 150 needs 1227 kWh energy from diesel to complete one return journey from Birmingham Moor Street Station to Stratford-upon-Avon Station. It has assumed that “Sprinter” class 150 holds the same amount of fuel as “GTW Stadler” [2]. According to this assumption a full diesel tank of “Sprinter” holds 14910 kWh energy. This results in 12.14 return journeys. The journey time calculated was 103 minutes, including terminal time at both end stations.

According to the above calculation the operating time range of “Sprinter” is 1250 minutes (20.84 hours). In UK most railway operators refuel their trains on a daily basis including the trains operated on selected route in this research. The refuelling time is generally 30 to 60 minutes and also depends on the amount of fuel to be re-filled [2, 25]

2.4. Simulation Results

The original diesel engine powered “Sprinter” class 150 was run over the route Birmingham Moor Street station to Stratford-upon-Avon Station and return. The total journey time was 103 minutes including 30 seconds dwell time at each station and 5 minutes stationary time at Stratford-upon-Avon station. The Davis parameters were considered the same throughout the complete journey. The results from simulation and calculations are presented in Table 2.

Table 2: Performance Results of Class 150 Diesel Train

Power	
Maximum Traction Power at Wheels	349.36 kW
Average Traction Power at Wheels1	157.31 kW
Auxiliary Power	28 kW
Maximum Engine Output	425 kW
Energy	
Energy at Wheels	270.58 kWh
Auxiliary Energy	48.16 kWh
Power-Plant Output Energy	340.36 kWh
Diesel Engine Output Energy	356 kWh
Energy Contained in Diesel	1227.58 kWh

The running diagram of train in figure 4, shows the total distance covered by train is 78.58 km in 103 minutes. The driving style in single train simulator was set to drive as fast as possible mode. The acceleration curve of the train shown in figure 3 presents the train traction performance for various speeds along with related resistance to motion at line speeds maximum acceleration applied to train in

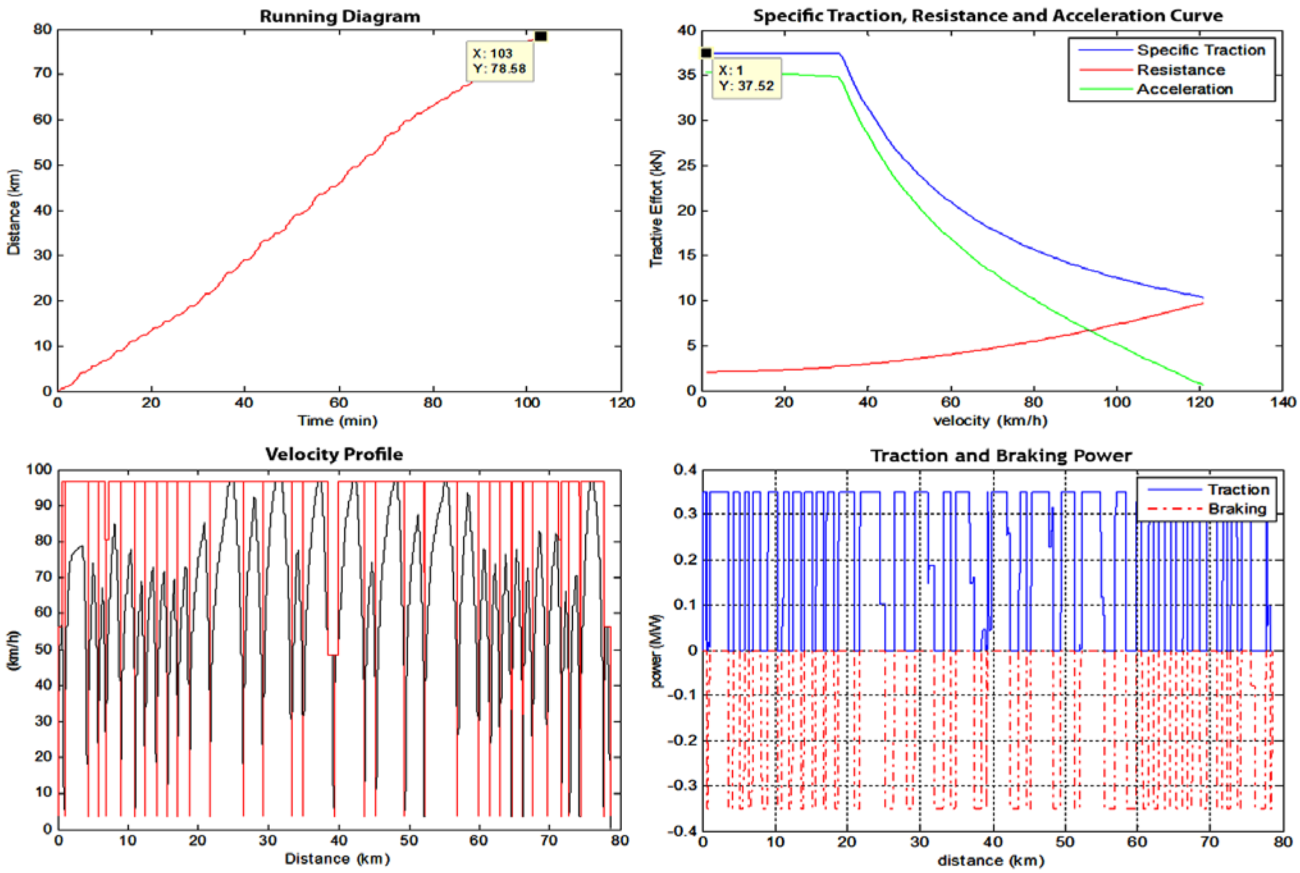

Figure 4: Simulation Results for Class 150 Diesel "Sprinter"

simulation was 0.5 m/s^2, calculated from maximum traction and mass and the average power is expressively less than peak power. To achieve this acceleration the required tractive effort is 37.52 kN. In figure 4, velocity profile shows the journey of the Sprinter travelled along the line against time. The sixteen stops where train stops and dwells for 30 seconds can be seen as well as the terminal time of five minutes can be seen in fragments where the train is motionless but time is elapsing. Traction power and braking power in figure 4 illustrates the traction power demand and the braking power demand which is dissipated in braking resistors and the power of braking is sizable compared to the traction power.

All data presented in the above simulation results sets the benchmark for the design of the hydrogen-powered train and hydrogen-hybrid train.

3. Hydrogen–Powered Vehicle Development

3.1. Hydrogen-Powered Train Drive-System

The existing "Sprinter" Class 150s are diesel-mechanical multiple units, where energy from diesel engines are directly transmitted to wheels via a gearbox and a drive shaft. In the concept design of the hydrogen powered train the complete engine, gearbox system and mechanical shafts were replaced with fuel cell and traction motors. Due to the compact size of fuel cell and traction motors the replacement of engines and gearbox didn't require modifications or extensions. The hydrogen-powered drive system is presented in figure 5.

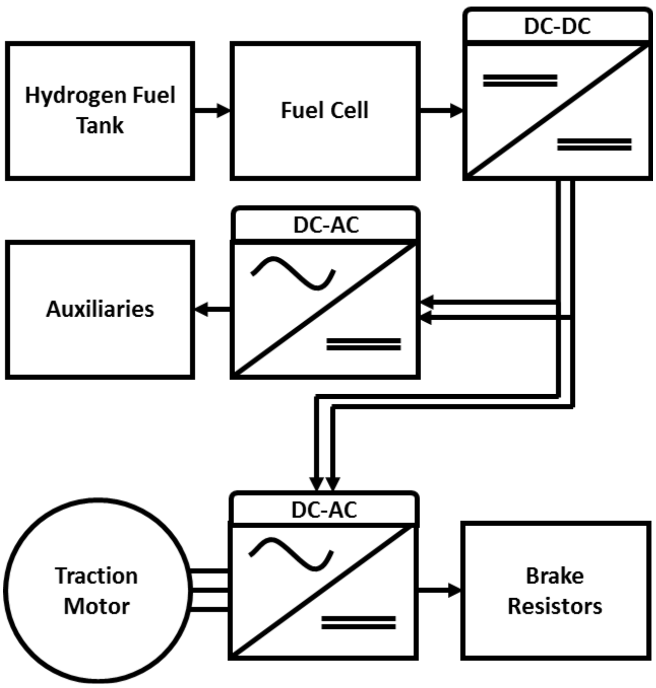

Figure 5: Hydrogen Power Module Drive System

The Hydrogen powered train does not require an alternator as the output of fuel cell is already electricity. Therefore no efficiency of alternator was added in calculations. Followed by efficiencies of original diesel powered Sprinter power modules, 90.3% efficiency was derived for power module of drive train for hydrogen powered train [2, 25].

3.1.1 Power and Energy Requirements: The power and energy requirements discussed in section 2.3 for original "Sprinter" class 150 must remain same for hydrogen-powered train supposing that the drive train module's power requirement and auxiliary power consumption do not alter, therefore the hydrogen-powered train should meet or slightly surpass the benchmark measures presented in Table 1.

3.1.2 Hydrogen Power Plant: Hydrogenics fuel cell systems were implemented rather than custom fuel cell design or a fuel cell technology used in past research projects. The fuel cell is based on latest compact, lightweight technology and offers a higher overall efficiency. The selected fuel cell system for hydrogen powered train consist of five 99 kW fuel cells with a combined power of 495 kW. The total fuel cell system has mass of 1.835 t and volume of complete fuel cell system is 2.50 m^3 including the weight and volume of coolant and air subsystem for fuel cells [26].

3.1.3 Hydrogen Storage: 350 bar compressed hydrogen tanks were used as the hydrogen storage. This has already used in past projects [15, 16] and proved to be ideal for transport vehicles. 170 carbon fibre tanks [28] stored 263.50 kg hydrogen which provides 8774 kWh energy. The volume of tank system is 68.85 m^3.

3.1.4 Hydrogen-Powered Train Design: The power plant must deliver 425 kW power as discussed in section 2.4 and table 2. In the pure hydrogen powered train all the power has to be delivered by the fuel cells. The fuel cells generated an additional 70 kW compared with the original diesel engines. Due to the increase in power provided by the fuel cell system, the power at wheels has also been increased to 421 kW. The benchmark calculation given in table 2 shows that one return journey requires 340 kWh output energy from the power plant. It follows that the fuel cell system installed in hydrogen powered train must provide 363.61 kWh output energy after considering the efficiency of DC-DC converter. The 55% efficiency of fuel cell has assumed [26].

The roof of "Sprinter" class 150 is empty and no components are installed on the roof of both coaches. Each coach has 56 m^2 area available. Therefore after the installation of 85 tanks on each coach 23 m^2 area will be covered, resulting in 33 m^2 available free area on each coach.

The total mass of "Sprinter" class 150 is 76.5 tonne. When the diesel engine and transmission system from the "Sprinter" class 150 were removed its mass becomes71.8 tonne. After adding the fuel cell to the hydrogen powered train, the final mass of train becomes 77.30 tonne, which is approximately an 800 kg increase compared to the benchmark "Sprinter" class 150 train. According to [2, 25] 0.7 tonne increase in additional mass to benchmark train is acceptable.

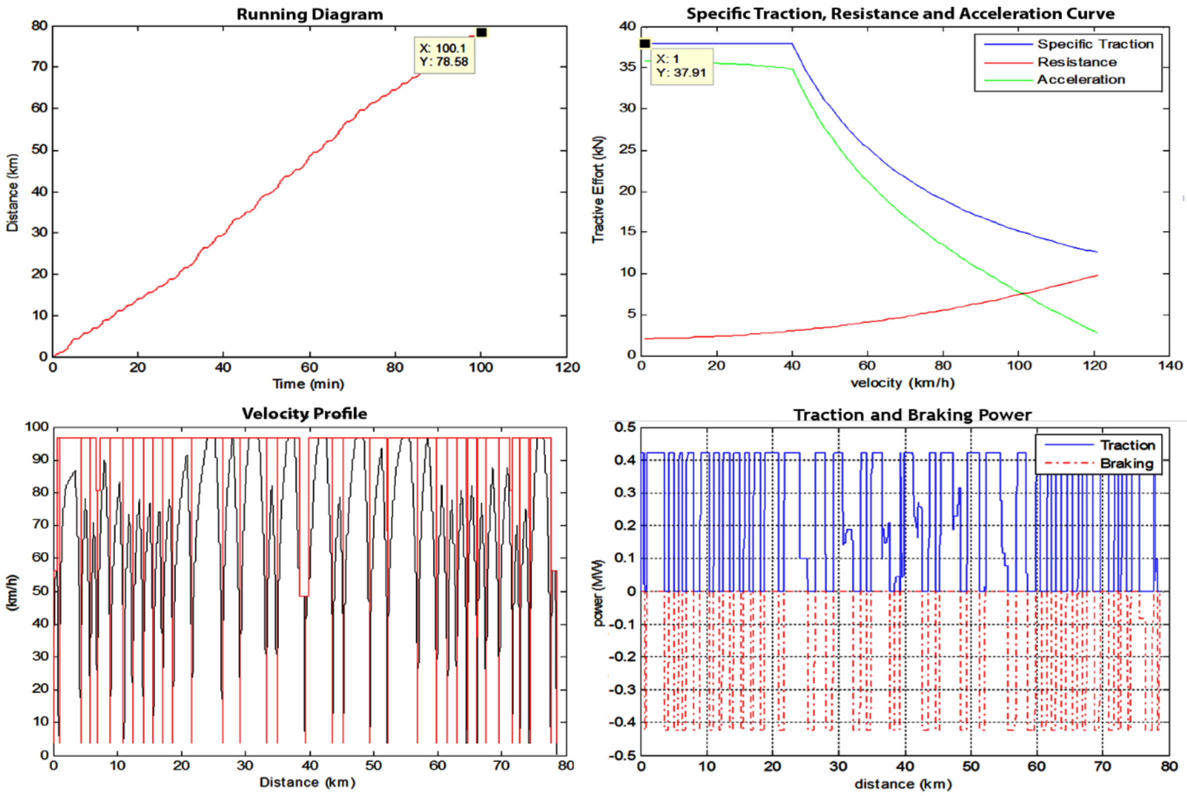

Figure 6: Simulation Results for Hydrogen -Powered "Sprinter"

3.2. Simulation Results

The hydrogen "Sprinter" class 150 was run over the route Birmingham Moor Street station to Stratford-upon-Avon Station and return. The total journey time was 100.1 minutes including 30 seconds dwell times and 5 minutes stationary time at Stratford-upon-Avon station. The Davis parameters were considered the same throughout complete journey. The results from simulation and calculations are presented in table 3.

Table 3: Performance Results of Hydrogen-Powered British Class 150

Power	
Maximum Traction Power at Wheels	422 kW
Average Traction Power at Wheels	176 kW
Auxiliary Power	28 kW
Power-Plant Output	482 kW
Maximum Fuel Cell System Output	495 kW
Energy	
Energy at Wheels	293 kWh
Energy at DC-BUS	317 kWh
Auxiliary Energy	47 kWh
Power-Plant Output Energy	364 kWh
Fuel Cell System Output Energy	380 kWh
Energy Contained in Hydrogen	692 kWh

Table 3, shows the energy at wheels for hydrogen powered train has been increased by 22.82 kWh compared to the benchmark diesel "Sprinter" class 150 train, this was due to higher mass of hydrogen powered train. The energy requirement for one complete return journey of hydrogen powered train is 691 kWh compared to 1228 kWh of benchmark diesel "Sprinter" class 150 train. Given the total energy stored in hydrogen tanks is 8775 kWh, 12.69 returned journeys would be possible resulting in a range of 1270.27 minutes, which satisfies the benchmark range of 1250.42 minutes.

The remaining results of performance of hydrogen powered trains are illustrated in figure 6. Running diagram in figure 6 shows, that the train covered 78.58 km in 100.1 minutes, which is approximately 3 minutes less than benchmark diesel powered "Sprinter". This is a significant improvement in journey time, while carrying 800 kg extra weight compared to benchmark diesel Sprinter. In figure 6, the traction, resistance and acceleration curves shows, the tractive force is slightly increased by 0.39 kN, while maintaining 0.5 m/s^2 acceleration. Results are nearly like the original diesel powered "Sprinter". However, there is an increase of 0.39 kN in Tractive Effort of Hydrogen-Powered Sprinter. Velocity profile in figure 6, illustrates the velocity of the train and the maximum allowable line speed. The results are nearly the same to benchmark diesel powered "Sprinter". 5 minutes terminal time where the train stopped can be seen in segments. The speed limit of the train at a few places exceeds the maximum line limit but that increase does not affect benchmark criteria and is acceptable. Traction and Braking power in figure 6, illustrates the traction power and braking power at wheels. According to these results 175.69 kWh average traction power is around 2.4 times less than maximum traction power at wheels. This shows high potential for hybridization of train. The braking power is significant which increases the energy availability on board for energy storage devices.

The overall results show that hydrogen-powered train meet all the parameters established by benchmark diesel Sprinter and proved itself feasible for development over a usual duty cycle.

4. Hydrogen–Hybrid Vehicle Development

4.1. Hydrogen-Hybrid Train Drive-System

Two different changes have been done to pure hybrid drive system in order to develop hydrogen-hybrid drive system. Energy storage device was added and the type of fuel cell was changed due to different power specification of hybrid system. The hydrogen-hybrid drive system is illustrated in figure 7.

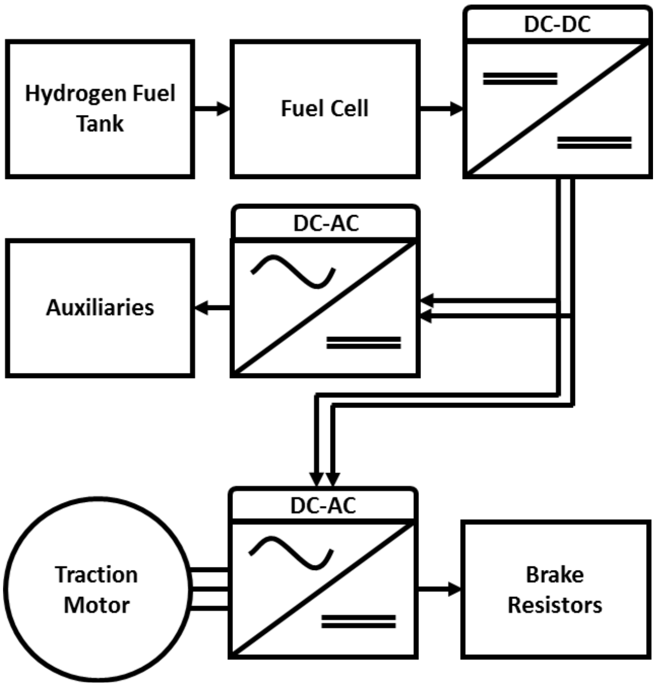

Figure 7: Hydrogen-Hybrid Power Module Drive System

In hydrogen-hybrid train the energy storage device added is battery pack system. Other energy storage devices that could have been used are super capacitors or fly wheels. Due to power to weight ratio and continuous peak power supply, battery was chosen as a storage device. The selected battery for hydrogen-hybrid train is lithium-ion due to its high efficiency around 90 % to 95 %, approximately 10 kW to 10 MW peak power [25]. Drive train efficiency from the fuel cell system to wheels is the same as pure hydrogen train, which was 90%. The efficiency applied on the DC-DC converter associated with battery-pack is 97.5%. Based on the efficiency calculation of [1, 25] the charging and discharging efficiency of battery-pack counting battery losses was assumed 87%.

4.1.1 Hydrogen Power Plant: Fuel cell of different power capacity was installed in hydrogen-hybrid train compared to fuel cell used in pure hydrogen train. The fuel cell was provided by and the continuous power of fuel cell was 198 kW and 55 % efficient. The total fuel cell system weighs 0.755 t and volume of complete fuel cell system is 1.578 m^3 including the weight and volume of Coolant and Air subsystem for fuel cells [27]. The total weight of fuel cell system used by author has three times less weight and one and a half times less volume than a fuel cell system used by [2, 25] in hydrogen-hybrid train.

4.1.2 Hydrogen Storage: In hydrogen-hybrid train 350 bar hydrogen tanks were used for hydrogen storage. Compared to pure hydrogen-powered train, only 120 tanks carbon fibre tanks [28] were installed on the roof of hydrogen-hybrid train, which can store 186 kg hydrogen and provides 6194 kWh energy. The volume of tank system is 48.6 m^3.

4.1.3 Hydrogen-Hybrid Train Design: The Hydrogen storage requirements are determined in table 4. The calculations were done with respect to regenerative braking. The data was based on the simulation of diesel powered “Sprinter”, which is used as a benchmark train, described in section 2.

Table 4: Hydrogen Energy Storage Requirements and Minimum Power-Plant Contribution at the Wheels

Energy at Wheels – Non-Hybrid	270 kWh
Energy at Wheels - Hybrid	100 kWh
Regenerative Braking	
Maximum energy at wheels from braking	170 kWh
Energy available from braking	153 kWh
Energy at the DC-BUS	142 kWh
Energy at the battery-pack ready for charging	139 kWh
Energy in the battery-pack	120 kWh
Energy Required for one Returned-Journey	
Energy Required at Wheels	270 kWh
At the DC-BUS	291 kWh
Output required at the battery-pack	300 kWh
Battery pack energy from regenerative braking	120 kWh
Energy required for battery charging	180 kWh
Energy at the battery-pack ready for charging	207 kWh
Energy at the DC-BUS	212 kWh
Auxiliaries	48 kWh
Power-plant output	260 kWh
Fuel cell stack	272 kWh
Energy as hydrogen for one journey	495 kWh
Hydrogen Storage Capacity	
Energy as Hydrogen for one Journey	495 kWh
Available Hydrogen in Tanks	6194 kWh
Numbers of Journeys	12.50
Hydrogen Storage System Size	
Energy contained in one 350 bar tank	52 kWh
Number of tanks installed	120
Mass of one tank	20 kg
Mass of Hydrogen storage	2.4 t
Volume of one tank	0.405m^3

Power requirements of fuel cell power-plant and battery-pack are presented in table 5. The data is established from the simulation of diesel powered “Sprinter” and the hydrogen-powered train.

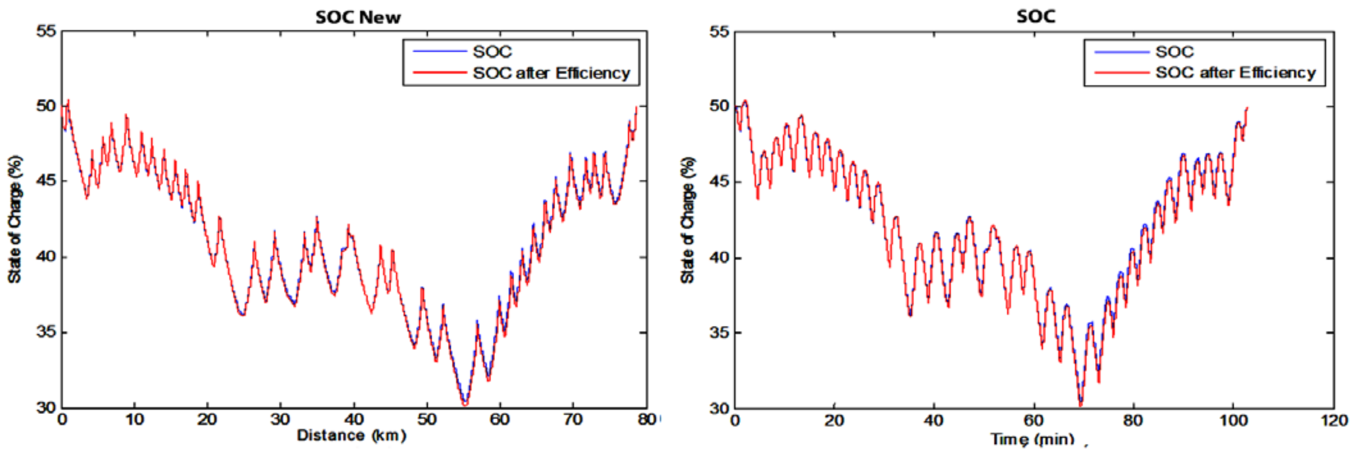

Figure 8: Battery-Pack State of the Charge during the Duty Cycle against Distance and Time

Table 5: Fuel Cell Stack and Battery Requirements

Fuel Cell Stack Power	
Energy required from fuel cell	272 kWh
Average power required for journey	158 kW
Resulting fuel cell system power`	198 kW
Mass of fuel cell system	0.0755 t
Volume of fuel cell system	1.578 m^3
Battery–Pack Power	
Peak power at wheels	349 kW
Power at DC-BUS	377 kW
Power plant contribution at DC-BUS	158 kW
Auxiliary power	28 kW
Available fuel cell power for traction at DC-BUS	130 kW
Required power at DC-BUS from battery	219 kW
Required output power of battery-pack	246 kW

The complete battery system consists of balancing, monitoring and management system. The battery management system has direct impact on battery performance and it is used to control the power consumption to lengthen battery life. The lithium ion batteries have a typical 50% discharge depth and this parameter was applied to ensure the suitability of battery for the train [2, 25]. The energy captured during regenerative braking and the power-plant together will provide the total energy required for hydrogen-hybrid train.

The capacity of the battery was determined by the subtraction of cumulative power requirement of battery-pack from cumulative regenerated energy, thus providing the charging power required from power-plant. After that the mean charge power was calculated and was added to difference of cumulative charging and discharging power. The state of charge of battery pack is illustrated in figure 8. The battery was assumed to have 50% charge at the start of journey. During journey the battery was 30% used and again recharged 30%. The battery pack characteristics are given in Table 6.

The characteristics of hydrogen-hybrid train developed in this project are given in table 7. Most of the given parameters are changed compared to benchmark diesel “Sprinter” class 150 train due to difference in weight of trains and power requirements of both trains.

Table 6: Battery-Pack Characteristics

Power Basis	
Power required from battery-pack	246 kW
Power of one battery	45 kW
Number of batteries needed	6
Energy Basis	
Energy storage requirements for battery-pack	1801 kWh
Energy storage capability of one battery	22.6 kWh
Number of batteries needed	8
Battery-Pack	
Number of batteries needed for battery-pack	8
Power	360 kW
Energy storage	181 kWh
Mass of battery-pack	1.048 t
Volume of battery-pack	1.288 m^3

Table 7: Hydrogen-Hybrid Train Characteristics

Energy	
Energy stored in hydrogen	6194 kWh
Maximum energy stored in battery-pack	1801 kWh
Maximum energy available from battery-pack considering discharge limits	90 kWh
Power	
Fuel cell stack power	198 kW
Battery pack power	360 kW
Power at wheels	349 kW
Mass	
Mass of tanks, fuel cell system and battery-pack	3.406 t
Train mass	76.15 t
Mass benchmark met?	Yes
Volume	
Volume of fuel cell and battery pack	2.866 m3
Maximum volume available to install battery & fuel cell	18.501 m3
Volume available for other equipment’s	15.635 m3
Volume benchmark met?	Yes
Area covered by tanks	23.18 m2
Maximum available area on roof for tanks	56.168 m2
Area available for other equipment’s on roof	32.99 m2
Tanks installation benchmark met?	Yes

Based on calculations and simulation results presented in section 4, the mass of hydrogen-hybrid decreased approximately 0.354 tonne compared to benchmark diesel train "Sprinter" class 150. The hydrogen-hybrid train developed by the author met all benchmarks and author proceeds with final design of hydrogen-hybrid train.

4.2. Simulation Results

The hydrogen-hybrid "Sprinter" class 150 train was run over the route Birmingham Moor Street station to Stratford-upon-Avon Station and return. The total journey time was 100.1 minutes including 30 seconds dwell times and 5 minutes stationary time at Stratford-upon-Avon station. The Davis parameters were considered same throughout complete journey. The results from simulation and calculations are given in table 8.

Other results of performance of hydrogen powered trains are illustrated in the figure9. The running diagram in figure 9 shows that the train covered 78.58 km in 102.9 minutes which is approximately the same as benchmark diesel powered "Sprinter" journey time. Due to decrease of 354 kg weight in hydrogen-hybrid Sprinter, the minor difference of 0.1 minute is achieved which is negligible. In figure 9, the curves of traction, resistance and acceleration are approximately identical to benchmark diesel powered "Sprinter" with decrease of 0.17 kN tractive effort to maintain 0.5 m/s^2 acceleration. The power at wheels is same to the power at wheels of benchmark diesel powered "Sprinter". Velocity profile in figure 9, shows the maximum allowable line speed compared to velocity of hydrogen-hybrid train. Stops at sixteen stations and five minutes terminal time can also be seen. Compared to hydrogen-powered Sprinter, hydrogen-hybrid velocity exceeds at only two places, which again shows train suitability for track speed.

Table 8: Performance results of Hydrogen-Hybrid British Class 150 "Sprinter"

Journey time	100.1 min
Power	
Maximum traction power at wheels	349 kW
Average traction power at wheels	158 kW
Auxiliary power	28 kW
Power-plant output	138 kWh
Maximum fuel cell system output	198 kWh
Battery-pack output	246 kW
Maximum battery-pack output	360 kW
Energy	
Energy at wheels	270 kWh
Energy at DC-BUS	291 kWh
Braking energy at wheels	170 kWh
Available regenerative braking energy in the Battery-Pack	120 kWh

According to the above simulation results and

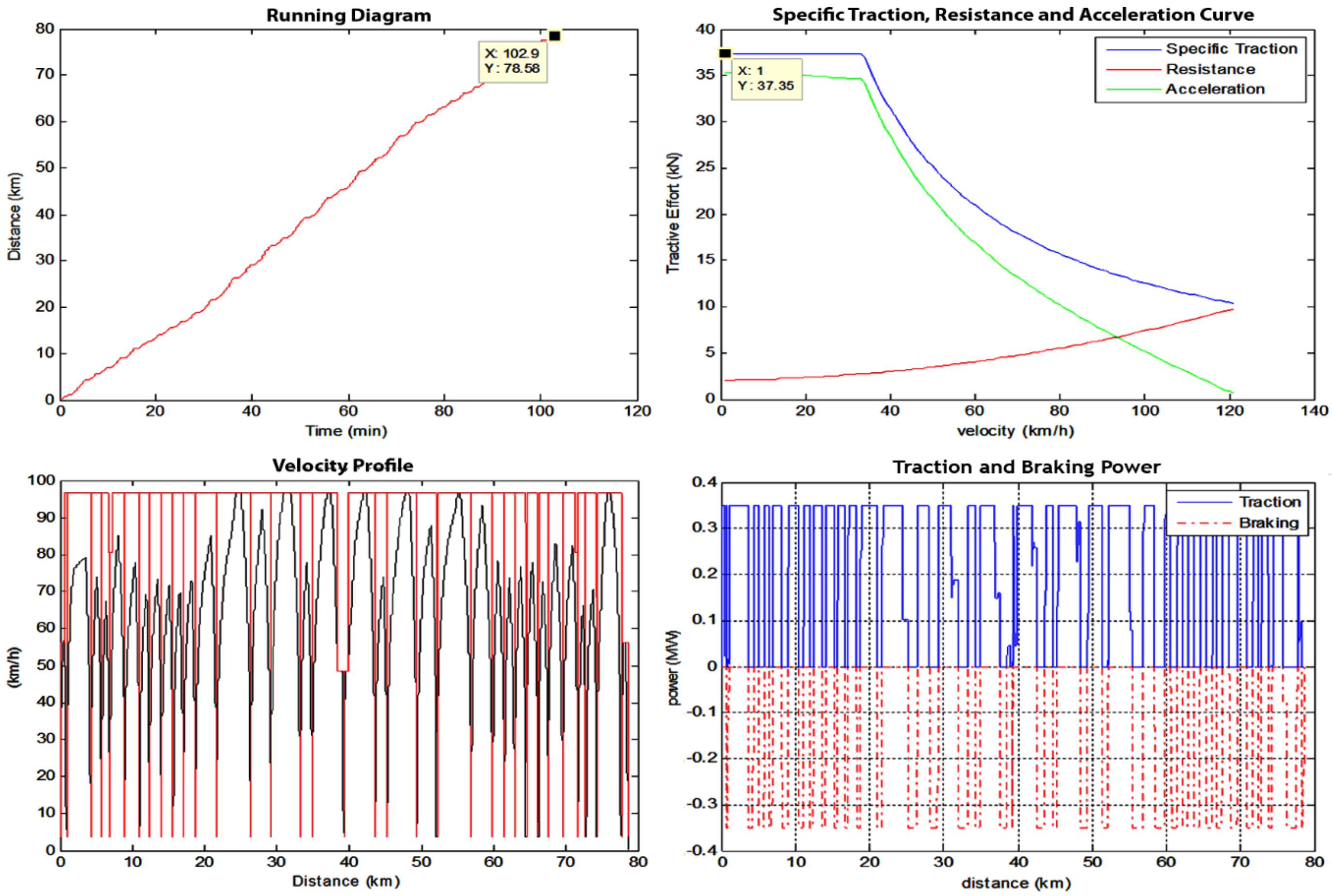

Figure 9: Simulation results of Hydrogen- Hybrid Powered "Sprinter".

calculations the hydrogen-hybrid train performed very well proving its feasible development in terms of journey time and range compared to benchmark diesel powered "Sprinter", hence reducing the energy consumption.

5. Performance Comparison and Discussion

A diesel powered "Sprinter" class 150 was run over the route Birmingham Moor Street station to Stratford-upon-Avon station providing the benchmark parameters for pure hydrogen powered train and hydrogen-hybrid train. The parameters for all trains are given in table 9. Davis equation parameters are not shown in table as they were similar for all trains and presented in benchmark train specification section.

Both hydrogen and hydrogen-hybrid trains met the benchmark criteria in terms of weight and volume. Hydrogen powered train exceeds 0.8 t mass compared to original benchmark vehicle which is considered acceptable. The mass of hydrogen-hybrid train decreased due to decrease in weight of fuel cell. The decrease in weight of hydrogen hybrid train allows increase in 3 to 4 passenger seats.

Table 9: Characteristics of the Three Trains for an Overview Comparison

Parameters	Diesel Powered Sprinter Class 150	Hydrogen Powered Sprinter Class 150	Hydrogen-Hybrid Sprinter Class 150
Journey Time	103 min	100.1 min	102.9 min
Range	1250 min 20.85 hours	1270 min 21.17 hours	1193 min 19.89 hours
Mass	76.5 t	77.30 t	76.15 t
Energy			
Primary Energy consumption for the journey	1228 kWh	692 kWh (44 % less than diesel)	495 kWh (60 % less than diesel)
Energy from regenerative braking	-	-	120.45 kWh
Primary energy source	Diesel	Hydrogen	Hydrogen
Primary energy storage quantity (LHV)	14918 kWh (1500 l)	8775 kWh (263.5 kg)	6194 kWh (186 kg)
Power			
Maximum power at wheels	349 kW	422 kW	349 kW
Power-plant power	425 kW	482 kW	158 kW
Prime-mover power	406 kW	495 kW	198 kW
Maximum battery-pack power	-	-	360 kW

The roof of both hydrogen-powered and hybrid-hydrogen train is ideal for installation of 350 bar compressed gas tanks after minor modifications. At the same time power-plant and battery-pack can be installed under the train where originally the diesel engine and transmission system was fitted. The hydrogen tanks installation space was calculated with respect to area available on top of the train roof. Some space under the train was also available for tanks installation, but due to safety reasons it failed to fulfil the risk assessments.

All trains provide an operating range of approximately 20 hours, which requires daily refuelling. In UK currently 16 hours range is normal daily routine [2, 25]. Energy requirements for full return journey are reduced by 44 % with hydrogen powered train and 60% reduced with hydrogen-hybrid train. Reduction of carbon emissions was calculated according to the carbon emissions produced by production of hydrogen by steam reformation of natural gas. The carbon emission for hydrogen-powered train was reduced by 59% and for hydrogen-hybrid reduced by 77% compared to benchmark diesel Sprinter train.

Traction characteristics for all trains were approximately in the same range, however additional power for pure hydrogen powered train was required to compensate for the increase in mass. The hydrogen-hybrid train was limited to 349 kW at the wheels which is same as power at wheels of original benchmark "Sprinter" class 150. The drive system of hydrogen-hybrid train was capable of providing more power than it provides but it will result in higher energy consumption and shorter journey time.

Overall, a promising performance was achieved with both hydrogen powered and hydrogen-hybrid train, in terms of energy consumption and reduced carbon emissions. At the same time maintaining the same services provided by diesel powered "Sprinter" class 150 as discussed in above sections. The concept design undertaken in this study has demonstrated the feasibility of such a vehicle operating on a typical UK sub-urban rail route.

6. Concept Trains Capital Cost

The cost estimation is based on assumption of converting current fleet of 28 train sets of London Midland Service "i-e 14 x 2 –cars Class 150 units". The cost estimation does not include the supplying and installation of hydrogen generating plant and on-depot equipment. The most expensive component in conversion are fuel cells.

Currently a 99 kW fuel cell approximately costs £250k. However, considering the popularity and high demand of clean energy the fuel cell prices will potentially decrease in near future. [33] This supports the business case for using fuel cell vehicles in future. The second most expensive component in conversion is the battery. The cost of a 22.6 kWh lithium ion battery is approximately £15k. Other high-cost items include are Traction motors. IGBT converters and hydrogen storage tanks.

Safety analysis and risk assessments will need to be carried out which will be play a significant role in the initial design costs.

Table 10 and 11 represents the capital cost for both concept hydrogen powered and hybrid-hydrogen powered trains. The data is obtained from research carried out at University of Birmingham and sponsored by Hitachi. The research was carried out on fuel cell electric multiple unit, [33, 34, 35].

Table 10: Summary of Capital Costs for Hydrogen Powered British Class 150

Conversion Cost (Per vehicle)			
Item	**No./Car**	**Cost Each (£)**	**Sub-Total (£)**
Engineering/Design Approval & Project Management	-	-	2,000,000
Conversion Cost	1	60,000	60,000
Fuel Cell	5	250,000	1,250,000
IGBT	1	80,000	80,000
Traction Motor	2	15,000	30,000
Hydrogen Tanks	170	2,000	340,000
Air compressor	1	5,000	5,000
Pipework, Valves & Auxiliaries	1	5,000	5,000
Radiator for Fuel Cells	1	2,000	2,000
Total Conversion Cost (Per Car)			3,772,000
Total Conversion Cost (Per Fleet)			51,616,000

Table 11: Summary of Capital Costs for Hydrogen-Hybrid Powered British Class 150

Conversion Cost (Per vehicle)			
Item	**No./Car**	**Cost Each (£)**	**Sub-Total (£)**
Engineering/Design Approval & Project Management	-	-	2,000,000
Conversion Cost	1	60,000	60,000
Fuel Cell	1	750,000	750,000
Battery	8	15,000	120,000
IGBT	1	80,000	80,000
Traction Motor	2	15,000	30,000
Hydrogen Tanks	120	2,000	240,000
Air compressor	1	5,000	5,000
Pipework, Valves & Auxiliaries	1	5,000	5,000
Radiator for Fuel Cells	1	2,000	2,000
Total Conversion Cost (Per Car)			3,292,000
Total Conversion Cost (Per Fleet)			38,176,000

The conversion costs presented in table 10 and 11 are significantly higher compared to the current fleet of diesel class trains. However, considering the diesel engine maintenance cost after each 20,000 hours and fuel costs for diesel trains, hydrogen fuel cell trains are presumably cheaper in longer run. The modern fuel cell system required minimal overhauling at 20,000 hours life. Due to the strict regulations for carbon emissions by government authorities, the diesel train operators might consider the option of upgrading existing fleets to use renewable energy sources This will make the hydrogen solution more viable over the remaining life of both aging and new trains.

7. Carbon Emissions

Carbon emissions calculations were based on prediction for London Midland fleet of 28 vehicles "i-e 14 x 2 –cars Class 150 units" assuming annual millage of 690,321 miles including weekends according to (2015-2016) time table of London Midland Service. The emissions were analysed for diesel or natural gas from the point at which fuel is delivered to depot.

The annual carbon dioxide emissions estimated by author are shown in table 12 [33].

Table 12: Predicted Carbon Emissions

Vehicle Type	***Energy Source***	***CO2/Fleet (t)***
Class 150 DMU	Diesel	51,856
Class 150 FCMU	Gas Reformation	21,280
Class 150 FCEMU	Gas Reformation	11,928

According to table 12 the annual carbon emission of pure-hydrogen powered train is 21,280 t and hybrid-hydrogen powered train is 11,928 t which is 59% and 77% respectively less than Class 150 diesel version.

8. Conclusion

The British class 150 "Sprinter", a regional, train was simulated over the journey from Birmingham Moor Street station to Stratford-upon-Avon station and return. The results were used as a benchmark for the development of hydrogen-powered train and hydrogen-hybrid train conceptual trains.

All components essential for a hydrogen-drive system can be easily accommodated under the floor of the train where the diesel engine and transmission system was fitted. The 350 bar compressed hydrogen gas storage option will cover 23.18 m^2 area on the top of the train roof while leaving 32.99 m^2 free space. A more detailed study may disclose additional space available for installation of tank inside the coach or separate side-compartment on the train.

Both trains based on hydrogen propulsion system reduce the energy consumption compared to benchmark train "Sprinter" class 150. The pure hydrogen-powered train was reduced by 44 % and hydrogen-hybrid train reduced by 60 % fuel with the help of regenerative braking.

Reduction in carbon emissions were achieved as well. Pure hydrogen-powered train reduced carbon emissions by 59% and hydrogen-hybrid train achieved 77% reduction. Carbon emissions reductions calculation are based on the duty cycle of the complete return journey and LHV of the fuel. It was considered by the author that the hydrogen is exclusively produced by Steam Methane Reforming process without any renewables aids.

The above analysis on the basis of benchmarking, computer simulations and associated evaluations demonstrates that the hydrogen-powered rail vehicles are feasible and hydrogen fuel cell systems can be used specifically on rail vehicles as a primary propulsion system.

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