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HYDROGEN AS AN ENERGY CARRIER FOR RAILWAY TRACTION

by

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ABSTRACT

Our way-of-life depends on effective transportation: commuting to the work place, travel for business, and cargo shipments around the globe are natural to many of us. Railways are an integral part of the transportation system, enabling the effective and efficient movement of bulk cargo as well as of commuters or intercity travellers.

At a global level, the energy required for railway traction is predominantly provided by diesel, followed by a 30 % share of electricity. Uncertainty about economical diesel supply, and environmental as well as public health concerns about exhaust gases, has promoted the exploration of alternatives. Electrification is a traditional method to evade fuel supply problems and prevent emissions at the point-of-use, but the high capital investment is often uneconomical or unaffordable for private rail companies. Therefore, traction that does not rely on wayside infrastructure for energy supply remains the only choice in many cases.

Hydrogen as a secondary energy, like electricity, can be produced from various feedstocks, including fossil fuels, nuclear power, and renewables. Thus, a reduction or elimination of greenhouse gas emissions is possible. Fuel cells combine hydrogen with oxygen from the ambient air to create electricity and heat while producing pure water as exhaust. No harmful point-of-use emissions, apart from some heat, result and fuel cells are efficient energy conversion devices. Hydrogen is a gas at ambient temperatures and compression or other storage methods are required for utilisation as a fuel. Currently, the cost of the energy conversion systems as well as the more complex storage tanks compared to liquid fuels are drawbacks of hydrogen.

The environmental performance and overall efficiency depend on the on-board energy conversion and the energy supply chain, in the case of railways: diesel or electricity. To evaluate the suitability of hydrogen, a well-to-wheel analysis for the aforementioned energies was conducted. The results, based on the lower heating value of fuels, show that hydrogen

fuel cell traction with hydrogen produced from natural gas has similar efficiencies to electric traction in the UK and in the USA at approximately 25 %, while reducing carbon emissions by 19 % compared to diesel in 2008. Thus, hydrogen yields similar or better results than incumbent systems.

A prototype locomotive, *Hydrogen Pioneer*, was designed, developed, and constructed to demonstrate, together with associated empirical performance tests, whether hydrogen is suitable for railway traction. A relatively high power-plant efficiency of up to 40 % during duty-cycles, and 43 % in the steady-state, was observed, while no technical problems with the hydrogen systems were encountered.

The positive results led to comparative computer simulations for the route Birmingham Moor Street to Stratford-upon-Avon and return. A diesel-electric regional train, which served as a benchmark, a hydrogen-powered vehicle, and a hydrogen-hybrid version were modelled. All the required hydrogen equipment could be accommodated in the respective trains, if 700 bar tanks were employed, and the journey time as well as the range of both hydrogen trains were similar to the diesel version: 94 minutes and 16 hours, respectively. An energy reduction of 34 %, with the hydrogen vehicle, and 55 % with the hydrogen-hybrid train, is achieved compared to the benchmark diesel.

Commercial viability and risks associated with hydrogen as a railway fuel were outside the scope of the work and, therefore, they were not investigated in detail.

Overall, the research provides evidence that hydrogen-powered railway traction is technically possible, reduces energy consumption, has water as exhaust, decreases overall greenhouse gas emissions, and is not dependent on petroleum.

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Exploring railway traction, in particular the application of the energy carrier hydrogen, has been an ambition of the author, and this thesis is the result of the transacted research. Such a project could have not been accomplished without support from several organisations and individuals.

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ABBREVIATIONS

Term	**Explanation / Meaning / Definition**
AC	Alternating Current
BCRRE	Birmingham Centre for Railway Research and Education
CA	California
CER	Community of European Railway and Infrastructure Companies
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct current
DOE	United States Department of Energy
EPA	United States Environmental Protection Agency
EIA	United States Energy Information Administration
FEVE	Ferrocarriles Españoles de Via Estrecha
GTW	Gelenktriebwagen. A type of regional train produced by Stadler
H_2	Hydrogen
H_2O	Water
HHV	Higher Heating Value
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMechE	Institution of Mechanical Engineers
LHV	Lower Heating Value
N_2O	Nitrous oxide
NH_3	Anhydrous ammonia
O_2	Oxygen
ORR	Office of Rail Regulation, Great Britain
PEM	Proton Exchange Membrane
RSSB	Rail Safety and Standards Board, Great Britain
UIC	International Union of Railways. French: Union Internationale des Chemins de fer
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
WTW	Well-to-wheel

1 INTRODUCTION

In early hunter and gatherer societies the group moved along with the food source; for example, if a herd of gazelles changed its whereabouts then the group of people moved along, transporting themselves as well as their belongings. With the appearance of more permanent settlements, the transportation patterns changed: food and other resources were moved from their original location to the settlement for consumption or further processing. Today, food, raw and processed materials, and finished products are still transported around the globe. The movement of goods is complemented by the transportation of people, for example, from home to the work place and back or from home to the supermarket and return.

1.1 Early Land Transport Systems

Since the beginning of society, mankind has been on the search for more effective transportation, which led to the development of carrying devices, such as bags, boxes, and the wheel, which in turn allowed the development of carts and wagons. Further, alternative propulsion sources to move these devices, rather than human beings themselves, have received significant attention and development effort; for example, the use of animals, such as horses on which to ride or pull wagons, or more recently, the use of petroleum products in combustion engines to move cars and trucks.

Railways are a direct consequence of man's desire for effective transportation on land; early examples include: (1) deliberate grooves in roads to reduce friction and guide wagons in ancient Greek and Roman times, and (2) in the Middle Ages, the use of wooden planks as basic rails, to reduce the power and energy required to haul minerals out of mines, enabling children or other untrained persons to move the carts (Schmid, 2010).

The efficient transportation achieved by rail in moving large quantities, passengers or cargo, as started in the mines, exists to this day, and is the main advantage of rail transportation in comparison to the other modes (Hollingsworth & Cook, 1996). This advantage is due to the stiffness of the steel of both the rail and the wheel, which results in the relatively low rolling resistance of the classical railway system. Therefore, the power requirements to achieve motion are reduced, compared to other options, such as vehicles that have rubber tyres and operate on concrete roads or wooden wheels on gravel roads.

At the beginning of the 19th century, the change from human and animal power to steam traction proved successful for railways, but was accompanied by many controversies and fears: that livestock would become infertile, that fruit would rot on the tree, and that grain would fade if a steam locomotive passed by (Hollingsworth & Cook, 1996). However, the clear advantages of steam power to provide more effective transportation, a reduction in operating cost, and shorter travel times prevailed.

1.2 Electric Traction

Electric traction was the next development step for railway propulsion with lasting effect. In 1879 Von Siemens demonstrated an electric locomotive, where power was supplied through a third rail between the running rails, at an exhibition in Berlin, see Figure 1 (Deutsches Museum, 2010). A year later, an electric locomotive powered through the running rails was demonstrated by Edison in New Jersey (Schafer, Welsh,

& Holland, 2001). Their emergent companies “Siemens” and “General Electric” have both been instrumental in initiating change in railway propulsion systems.

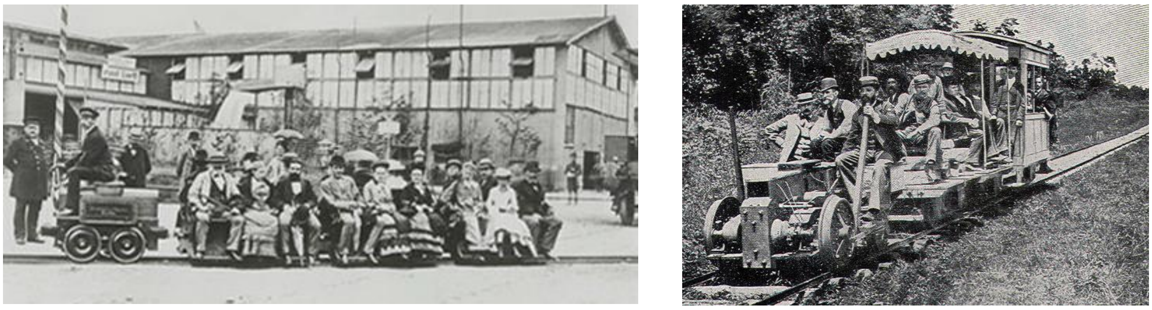


Figure 1: First Successful Electric Trains
Von Siemens on the Left in 1879 (Reproduced from Hollingsworth & Cook, 1996) and Edison on the Right in 1880 (Meadowcroft, 1911)

Within approximately 25 years electric traction proved to be superior to steam traction in speed, power, and ease of operation, while avoiding emissions at the point-of-use. It performed better than steam in every necessary and desirable aspect of train operation (Hollingsworth & Cook, 1996). Nevertheless, no universal electrification boom occurred, owing to the large cost of implementation (Agnew, 1953; Hollingsworth & Cook, 1996; Schafer, et al., 2001). In comparison to steam, electric locomotives were two to three times more expensive (Hollingsworth & Cook, 1996) and required costly wayside infrastructure. In addition, frequently substations, transmission lines, and power stations had to be built by the railway (Agnew, 1953), leading to a four to six times cost increase compared to a steam railway of the same transport capacity (Hollingsworth & Cook, 1996). Additionally, the efficiency of the early electric systems was close to or below that of steam operated systems (Duffy, 2003). Therefore, electrification was limited to applications that could not be operated with steam in a satisfactory manner (Wilcox & Oehler, 1943); the two primary reasons were:

(1) Limited Natural Resources. Railways in countries or regions that did not have their own coal reserves were severely affected by price increases or supply limitations. One reason that the Swiss railways were electrified early on is the Swiss reliance on imported coal, leading to reduced supply during the First World War and consequently high prices, while hydro-power was locally available (Hollingsworth & Cook, 1996; Moser, Jossi, & Pfeiffer, 2009). Dependency on imported coal was also a reason for the early adoption of electric traction in Italy (Hollingsworth & Cook, 1996). The Chicago, Milwaukee, St. Paul & Pacific Railroad electrified part of the route through the Rocky Mountains and Cascade Mountains for several reasons and the main one being: the potential to utilise local hydro-power for train operation rather than transporting coal over long distances to the mountain regions, thereby reducing operating cost (Murray, 2005).

(2) Emissions. Railways that operate in areas where emissions at the point-of-use are particularly undesirable were quick to electrify, for example: Underground railways, such as the City & South London Railway recognised that exhaust emissions from steam locomotives hindered operation in tunnels, because of the required ventilation to ensure the survival of staff and passengers (Duffy, 2003; Hollingsworth & Cook, 1996). On the main line, the same principle applied: In 1895 the Baltimore & Ohio Railroad electrified a section of their main route that was located in a tunnel under Baltimore. The reasons were the intolerable emissions of steam traction and the prohibition of tunnel ventilation shafts (Cunningham, 2010). Also, legislation had a significant influence on electrification, again due to emissions; one example is New York City: In 1903 the city passed a law that prohibited the operation of trains that produce emissions at the point-of-use within city limits, which came into effect in 1908 and is still in place today (Hollingsworth & Cook, 1996). The reasons were (a) concerns about the safety of operation in tunnels, due to several collisions in tunnels where the drivers could not see the signals as a result of emissions, such as smoke, steam and soot, and (b) the perceived general contribution of the railways to the air quality problems in the city (Duffy, 2003; Hollingsworth & Cook, 1996).

In the early 20th century, another less common circumstance that could justify electrification emerged: high density and frequent service (Wilcox & Oehler, 1943), such as railways serving commuter belts. Economies of scale are the reason: The reduced variable cost will, eventually, outweigh the high initial fixed cost that is sunk into the plant, unless the plant cannot support the quantity of traffic necessary to recover the investment through variable cost savings (Begg, Fischer, & Dornbusch, 2005). When the principle is applied to railway electrification then the scenario is as follows: the cost of electrification infrastructure has to be recovered through operational cost savings and capacity increases. One early example of electrification aimed at increasing capacity is that of the New York, New Haven & Hartford Railroad in 1907 (Christmas, 1982). Although, the system's thermodynamic efficiency was lower than that of steam operation (Duffy, 2003), other operational advantages, such as lower maintenance for electric vehicles and the higher availability of the traction equipment outweighed the higher fuel cost as well as the initial outlay for electrification.

In general, large-scale electrification of railway networks does not occur when private business operates the railways (Kerr, 1951), which is due to economic considerations (Schafer, et al., 2001), with one exception: Government funding. All major railway electrification schemes were, or are, financially supported by the respective government (Duffy, 2003; Hollingsworth & Cook, 1996; Schafer, et al., 2001). The primary reason is that long-term macro economic benefits can be realised by the country as a whole but not by an individual company; examples are: reduced emissions, diversification of fuel sources, and investment in times of recession to provide employment (Duffy, 2003; Hollingsworth & Cook, 1996). Naturally, government-owned or previously state-owned railways feature the highest proportion of electrification, and many major projects were initiated after the Second World War when the railways had to be rebuilt due to war damage, and improvements in operations were required to remain competitive with the speed and convenience offered by cars and trucks (Duffy, 2003; Hollingsworth & Cook, 1996; Kerr, 1951; Schafer, et al., 2001; The World Bank Group, 2007; International Union of Railways [UIC] & International Energy Agency [IEA], 2012).

Security of energy supply remains one of the major reasons for electrification. As steam traction was primarily dependent on coal, countries that did not have a domestic supply tended to electrify, as mentioned earlier in the chapter. The same is true in the second half of the 20th century with diesel: countries with domestic supply, such as the USA, employed diesel traction, whereas countries with limited petroleum resources had a tendency towards electrification, as domestic energy sources, such as coal and hydro-power, could be utilised (Kerr, 1951). In addition, the railways in those countries were primarily state-owned, allowing favourable funding conditions for rail electrification. In general, it can be summarised that electrification occurs to solve specific operational problems, such as emissions at the point-of-use; for geo-political reasons of energy security, enabling the utilisation of domestic energy sources; and in some circumstances to increase network capacity and performance.

1.3 Diesel Traction

Steam propulsion was the major form of traction for railways up to the end of the first half of the 20th century, but it was challenged in certain circumstances and areas by electrification, as described, and by diesel traction from the early 1920s, through the desire to reduce operating expenses.

Several steam-powered branch-line passenger services were becoming unprofitable in the first decade of the 20th century (Schafer, et al., 2001; Zimmermann, 2004). The application of gasoline engines, as used in automobiles, was thought to be a solution because single railcars without a locomotive could be operated (Schafer, et al., 2001). Several on-board power transmission systems were tried, including direct-mechanical in the McKeen Motor Cars (Zimmermann, 2004), and electric transmission, as preferred by General Electric (Welsh, 2008). However, the petrol-engine proved to be unreliable and not powerful enough for railway service (Duffy, 2003), and the mechanical transmission of the McKeen railcars was often defective (Zimmermann, 2004). Overall, the efforts to utilise gasoline engines for railway traction were a failure (Duffy, 2003; Zimmermann, 2004). The most successful part of those cars was the use of electrical transmission (Duffy, 2003; Welsh, 2008), and General Electric gained valuable experience that directly influenced their application of diesel-engines for railway traction (Duffy, 2003).

Emissions, particularly in urban rail yards, were and are undesirable, and, combined with the inherent duty-cycle, made the operation of steam switchers expensive for railways and unpopular with the local community (Agnew, 1953). In 1924 the first successful diesel-electric demonstrator locomotive that led to production models was developed (Duffy, 2003; Hollingsworth & Cook, 1996). Initially, five locomotives were constructed (Hollingsworth & Cook, 1996), and sold for rail yard deployment to reduce emissions from 1925 onwards (Agnew, 1953). Of that locomotive class, number 1 000 of the Central Railroad of New Jersey, see Figure 2, was the world's first commercially produced diesel locomotive (Duffy, 2003; Schramm, 2010).

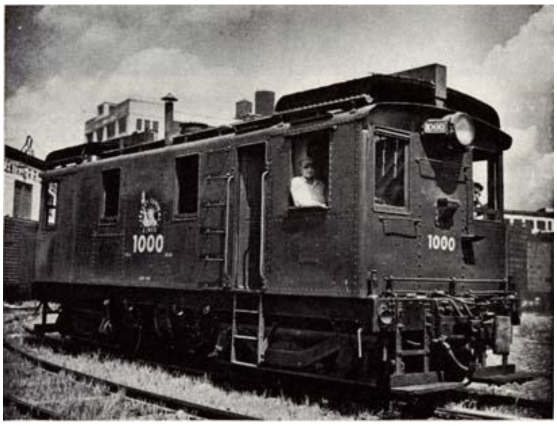


Figure 2: Number 1 000 of the Central Railroad of New Jersey The First Commercially Produced Diesel Locomotive (Schenectady Digital History Archive, 1924)

However, the development of the locomotives was not initiated by the railways but by electric locomotive builder General Electric (Duffy, 2003), which assumed all the commercial development risk. General Electric profited from the experience with gasoline-engine railcars, as mentioned. The company recognised the power limitations of such engines and planned to utilise diesel-engines instead – with success (Duffy, 2003; Schafer, et al., 2001). But the new technology was not adopted quickly, and by 1934 only 100 diesel-electric locomotives operated in switching service in the USA, rising to a market share of about 51 % in 1951 (Agnew, 1953). Further, for many years diesel-electric drive-systems were deemed only suitable for switching applications (Agnew, 1953; Wilcox & Oehler, 1943).

Competitive diesel-designs came to the main line in streamlined train-sets starting in the 1930s (Hollingsworth & Cook, 1996; Zimmermann, 2004). The light-weight design, high speeds, and streamlined appearance aimed to maintain market share in the face of increasing competition from road and air transportation, while reducing operating cost (Hollingsworth & Cook, 1996; Kerr, 1951; Welsh, 2008; Zimmermann, 2004). The "Fliegender Hamburger" and "Pioneer Zephyr" are two prominent examples of streamlined trains.

In 1933 the Fliegender Hamburger or class SVT a new streamlined two-coach train, see Figure 3, demonstrated the suitability of diesel-electric drive systems in multiple unit applications. The technology was very reliable and several other train-sets of the class were constructed, leading to speeds that were the fastest world-wide for about five years (Hollingsworth & Cook, 1996). The war ended the success of these trains, and the German Railway, also, constructed streamlined steam locomotives at the time, which indicates doubts about diesel trains (Hollingsworth & Cook, 1996), maybe due to the limited domestic petroleum reserves.

Figure 3: A Preserved Class SVT "Hamburg" in Leipzig (Bernd, 2007)

The light-weight streamlined three-car multiple unit train, Pioneer Zephyr, had its inaugural journey in the USA in 1934. It almost ended in a technology demonstration disaster, and only the maintenance and repair of equipment while in operation ensured the completion of the trip (Hollingsworth & Cook, 1996), but the record journey time, combined with the stainless-steel streamlined appearance proved a success, see Figure 4. The Pioneer Zephyr was to be more influential on a global scale, because it led its manufacturer to develop main line diesel-electric locomotives, which were sold globally. Subsequently, this ensured the world-wide leadership of General Motors' Electro-Motive Division in the technology for approximately 50 years (Duffy, 2003; Hollingsworth & Cook, 1996).

(Reproduced from Schafer, et al., 2001) (Goldman, 2008)

Figure 4: Left, Pioneer Zephyr in Omaha, NE in 1960; Right, Production Model of the Pioneer Zephyr, Displayed in Chicago's Museum of Science and Industry

Also in 1934, six weeks before the Zephyr, the first "Streamliner," Union Pacific's M-10 000, was presented. The three-car articulated train-set with diesel-electric drive-train employed the same concept as the Zephyr (Welsh, 2008). Designed to be powered by a diesel engine, but first operated with a spark ignition gasoline engine, due to delivery problems of the diesel, the train had the same objective as the Zephyr: increasing passenger appeal though radical new design, that is streamlining, while reducing operating cost (Hollingsworth & Cook, 1996; Welsh, 2008; Zimmermann, 2004). Both trains, see Figure 5, were successful and led to the introduction of subsequent fleets, and both types of trains were powered by drive-systems developed and built by General Motors (Welsh, 2008; Zimmermann, 2004). Thus, the diesel-electric drive system was introduced to the mainline in light-weight train-sets on routes that could not be operated economically otherwise (Agnew, 1953).

Figure 5: Left, Union Pacific's M-10 000 and Right, Burlington's Zephyr Both Diesel-Electric Streamliners (Niedermeyer, 2012)

The train-sets were all special light-weight constructions, the Zephyr being stainless-steel and the M-10 000 made from aluminium, and it was not clear at the time, whether standard, much heavier railway services, passenger and freight, could technically be operated with diesel traction (Schafer, et al., 2001). The power required for the streamliners was significantly lower, at around 600 hp, compared to main line steam hauled passenger trains, which often required 3 600 hp or more (Schafer, et al., 2001).

However, Electro-Motive, which supplied the traction equipment for the trains mentioned above, was determined in promoting diesel-traction to railways and demonstrating the technology's capabilities (Duffy, 2003; Hollingsworth & Cook, 1996; Schafer, et al., 2001). The company assumed significant research and development cost and risk, and ran U.S.-wide demonstrations of trains and locomotives to exhibit the advantages over established steam; and the determination to replace steam with diesel was a major contributor to the technology's success (Duffy, 2003; Hollingsworth & Cook, 1996).

In 1935, Electro-Motive built box-cab twin-unit diesel locomotives, see Figure 6, with combined 3 600 hp, which were intended to demonstrate the suitability of the diesel-electric system to replace standard passenger steam, and the project was successful (Hollingsworth & Cook, 1996; Schafer, et al., 2001).

Figure 6: Electro-Motive Box-Cab Number 511-512
(Reproduced from Schafer, et al., 2001)

The company designed and built the box-cab locomotives at its own expense to demonstrate the technology, without a customer at hand; further the locomotives were not streamlined but intended to exhibit the capabilities of diesel-electric systems (Duffy, 2003; Schafer, et al., 2001). In 1935, a demonstration of the locomotives took place on the Baltimore & Ohio Railroad, which subsequently ordered a single-unit locomotive in the same year (Schafer, et al., 2001). Also in 1935, the Atchison, Topeka & Santa Fe Railway took delivery of a box-cab locomotive to investigate its performance on standard heavy-weight passenger trains (Duffy, 2003; Hollingsworth & Cook, 1996). In both cases the locomotives exceeded the performance and efficiency of the replaced steam (Schafer, et al., 2001).

In 1939, Electro-Motive followed with a traction vehicle intended for freight service, a four-unit locomotive with the number 103, see Figure 7, that operated over 20 different host railways (Duffy, 2003; Hollingsworth & Cook, 1996). Duffy (2003) continues to write that number 103 “is often called ‘the locomotive which did it’ ” (p. 233), in demonstrating that diesel traction can technically replace steam in all areas of railway service.

Figure 7: Electro-Motive Freight Locomotive Number 103 (Reproduced from Drury, 1996)

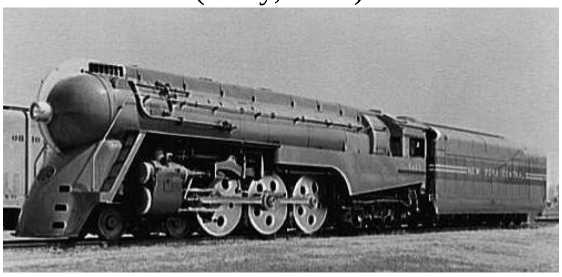
From the beginning of diesel main line passenger service, in train-sets as well as locomotives, marketing for public appeal was an essential part of the strategy, achieved through streamlining as well as colourful locomotive and train design (Hollingsworth & Cook, 1996; Wilcox & Oehler, 1943). One of the famous examples is the "Warbonnet" colour scheme of the Atchison, Topeka & Santa Fe Railway, see Figure 8.

Figure 8: "Warbonnet" Colour Scheme on a Streamlined Santa Fe Locomotive Intended to Attracted Passengers to the Railway, displayed at the California Railroad Museum Courtesy and Copyright Jan Kohler, 2003

Despite the successful demonstrations of diesel traction and the achievements of the train-sets, the generally conservative and risk-averse railway industry often remained steam-power (Schramm, 2010), and the manufacturers often applied the new marketing techniques, streamlining and colours, to their steam trains, see Figure 9. Prominent examples in the U.S. are: The Daylights of the Southern Pacific Railroad, the 20th Century Limited of the New York Central, the Broadway Limited of the Pennsylvania Railroad, the Hiawathas of the Milwaukee Road, or in the UK, the A4 Class by the London and North Eastern Railway (Hollingsworth & Cook, 1996; Schafer, et al., 2001).

(Perry, 1937)

(Jacksich, 2004)



(Gottscho-Schleisner Inc., 1939)

Author's Collection (2012)

Figure 9: Examples of Streamlined Steam Locomotives
Left-Top, Milwaukee Road Hiawatha, Right-Top, Southern Pacific Daylight, Left-Bottom, New York Central Hudson, Right-Bottom, London and North Eastern A4 Class

The reluctance to accept diesel-power was in part due to: (1) the two to three times higher purchasing cost (Churella, 1998), (2) the shorter life expectancy (Churella, 1998; Wilcox & Oehler, 1943), (3) the lower power achieved compared to steam, particularly at high speed, resulting in the necessity of multiple-unit diesel locomotive operation, although the tractive effort at low speeds was higher than steam (Agnew, 1953; Churella, 1998), and (4) the need for new fuelling and maintenance infrastructure (Churella, 1998). All of these shortcomings had to be offset by variable cost savings gained in operations, primarily through lower fuel and maintenance cost, and only when the economic superiority of diesel was well established, railways began to phase-out steam (Agnew, 1953). Or as J. M. Symes, vice-president of operations of the Pennsylvania Railroad, which was the largest railway in the world at the time, put it in 1949:

> [Before and through the Second World War] The economy of the diesel had not sufficiently proven itself to us ... The doubtful 5 or 6 per cent return on the diesel against the other forms of motive power at the beginning of the War moved into a definite return of about 30 per cent at the end of the War, and inasmuch as a large motive power program was required on our railroad to take care of obsolescence and increase operating efficiency, that is when we moved into the diesel field. (As cited in Agnew, 1953, pp. 12-13)

The superior operating characteristics of diesel over steam are primarily due to the electric drive-system (Agnew, 1953; Duffy, 2003). Operation of electric trains would have resulted in the same benefits, but in most cases the high investment cost prevented electrification, as mentioned (Agnew, 1953; Wilcox & Oehler, 1943). Diesel locomotives in North America were marketed as self-propelled electric locomotives (Agnew, 1953; Duffy, 2003; Hollingsworth & Cook, 1996; Schafer, et al., 2001), which provided the benefits of electric operation without expensive wayside infrastructure (Schafer, et al., 2001).

As mentioned, reduction or elimination of emissions at the point-of-use and better operating characteristics were, and are, the primary advantages of electric propulsion, while steam power allowed the operation of trains anywhere on the network without the need for expensive electrification infrastructure (Hollingsworth & Cook, 1996; Schafer, et al., 2001). Diesel-electric traction combines these advantages: autonomous traction with fewer emissions than steam and the superior operating characteristics of electric propulsion. However, the overall power is still limited by the on-board prime-mover.

Autonomous traction refers in this thesis to a method of propulsion that does not rely on a wayside infrastructure for energy supply, in other words electrification. Examples of autonomous traction are steam engines and diesel locomotives.

Other attempts to create the advantages offered by diesel traction failed, examples are: coal burning steam-turbine locomotives and steam-turbine locomotives with generators and electrical drive-systems (Hollingsworth & Cook, 1996). More successful were gas-turbine locomotives; some burning heavy fuel oil, such as Union Pacific's series of locomotives. And indeed, the first experimental Train à Grande Vitesse (TGV) were powered by gas-turbines (Hollingsworth & Cook, 1996). But issues with corrosion of the turbine-blades due to the nature of the fuel and the low efficiency, preventing the use of other fuels in Union Pacific's case, and the oil crisis of the 1970s, coupled with the low turbine efficiency in the TGV's case, prevented the wide-spread adoption of the technology (Hollingsworth & Cook, 1996).

The main problem for all examples of these unsuccessful designs was: (1) economic viability, often caused through low thermal efficiencies that could not be compensated by lower fuel cost, or (2) complex drive-systems that were unreliable and maintenance intensive, or (3) a combination of both, all resulting in extended use of diesel traction or electrification. Electric and diesel traction are, since the mid 20th century, the dominant forms of railway traction, with steam largely confined to heritage railways or tourist attractions.

In summary, a change in railway traction is promoted when the following conditions occur:

1) Concerns about fuel supply
2) Concerns about emissions
3) Desire to reduce operating cost, particularly to remain competitive

Successful traction designs have proven to meet all of these conditions. Electrification or dieselisation was employed to replace steam traction, while the specific technology choice depended on the particular circumstances of the railway system.

1.4 Situation Today

Today, railways are under pressure to decrease their overall emissions, especially carbon (UIC & IEA, 2012). Further, a reduction of other combustion emissions at the point-of-use, such as particulate matter and nitrogen oxides, is required by law in the European Union (European Commission, 1997-2012) and the USA (U.S. Environmental Protection Agency [U.S. EPA], 2012b). Also, concern about the supply of petroleum in the longer-term and economic considerations relating to fuel prices, which affect the operating cost of diesel trains, are currently present in the railway industry. In other words: the above stated three conditions exist today, particularly for diesel propulsion. In addition, audible noise that is emitted from railway vehicles, for example from diesel combustion or cooling fans, has to be reduced and for new trains maximum limits apply.

Railways have responded to these challenges in autonomous traction in two ways: (1) through electrification programmes, particularly in Europe (UIC & IEA, 2012), and

(2) the investigation of innovative alternative propulsion methods for lines that cannot be electrified economically.

In certain areas, such as city centres, the visual impact of electrification infrastructure, see Figure 10, has prompted alternative arrangements, such as ground level electrification, e.g., in Bordeaux, or hybrid vehicles with energy storage, e.g., battery-packs on the trams in Nice, see Figure 11 (Hoffrichter, Silmon, Schmid, Hillmansen, & Roberts, 2013; Moskowitz, 2010). The trams in Nice can operate from overhead electrification infrastructure or, in the non-electrified sections, power is provided from the on-board batteries, therefore, the trams are hybrid vehicles.

Figure 10: Main Line Overhead Electrification Infrastructure in Bordeaux (Author's Collection, 2011)

Operation From Overhead Electrification (Felix Schmid, 2009)

Operation With Energy Provided by the Batteries (Charles Watson, 2009)

Figure 11: Hybrid Tram in Nice
Courtesy and Copyright Felix Schmid and Charles Watson

Also, more market-driven, private railways, for example in the USA, have been pursuing propulsion options that are less capital intensive than electrification, similar to developments in the past. Examples of alternative autonomous traction efforts include:

- Utilisation of bio fuel (Lustig, 2010b)
- Battery-power (Lustig, 2010a)
- The application of natural gas (Canadian National Railway Company, 2012),
- The use of hydrogen (Hoffrichter, Hillmansen, & Roberts, 2010)

For all of these options it has to be demonstrated that they reduce emissions and decrease the dependency on petroleum as well as that they are cost-effective in railway operations. In addition, it must be shown that the option is technically suitable for railway traction. The research conducted and presented in this thesis considers the suitability of hydrogen as an energy carrier for railway traction.

The research hypothesis is stated in the next section, before the scope of the research is defined. Thereafter, a brief description of the methods employed is provided, before the structure of the document is outlined to finish the introduction.

1.5 Research Hypothesis

Alternative options for autonomous railway traction are required, as described above, which is mainly due to: (a) the need to decrease emissions; (b) concerns about diesel fuel supply, both fuel cost as well as security of supply; (c) economic concerns about electrification, particularly for relatively low traffic density lines and for private railways where funding does not allow electrification; and (d) the need to avoid the visual impact of electrification in certain cases. One option is the energy carrier hydrogen, which is the focus of the research presented in this thesis, and the hypothesis is:

Hydrogen is a suitable energy carrier for autonomous railway traction.

To demonstrate that the statement is true, the hypothesis is split into the following elements:

1) Hydrogen production is not dependent on a single primary energy source, especially petroleum.
2) A reduction of overall greenhouse gas emissions compared to diesel traction is achieved, in addition to the avoidance of emissions at the point-of-use.
3) Hydrogen-powered systems are technically suitable for and can be implemented in railway traction vehicles.
4) The performance of such a vehicle is satisfactory for the provision of railway services, and the hydrogen fuel cell system achieves satisfactory duty-cycle efficiencies.
5) A hydrogen-based system can operate a service with similar performance as existing diesel vehicles, while a reduction of energy consumption and emissions is achieved. And the necessary drive-system components can be accommodated within the space available on the train, while not exceeding permissible vehicle mass restrictions.

All of these statements are investigated in the research presented in the thesis. They are directly based on the problems that autonomous railway traction systems face today, and represent technical conditions that have to be met for a feasible design. Further, the set of conditions was derived from the experience of successful, long-lasting railway traction technology changes, which occurred in the past. Economic viability and safety concerns about hydrogen are not included in the hypothesis and the cover of these metrics is limited in the research and subsequently this thesis.

1.6 Thesis Scope

The primary scope of the thesis is to prove the hypothesis and, therefore, is largely based on technical assessments. However, the focus is on system evaluation rather than the technical details of any particular component. The investigation includes hydrogen production and supply with the associated carbon emissions and efficiencies in comparison to electricity and diesel, the application of a hydrogen-powered drive-system in a railway vehicle, the empirical performance evaluation of a hydrogen-powered prototype, and comparative computer simulation of a diesel-electric train and a hydrogen-only vehicle as well as a hydrogen-hybrid train. The primary areas that have not been explored in detail are described hereafter.

1.6.1 Economic Considerations

The hypothesis is aimed at demonstrating the technical suitability of hydrogen as an energy carrier for railway traction. Detailed economic considerations are outside the scope of the research presented; one reason is that, generally, technical feasibility precedes economic feasibility. A cost-effective solution that cannot be physically implemented is not a real solution, whereas a technical option that can be realized is already a solution, for which the economic viability can be assessed. Further, financial feasibility is dependent on many conditions, including local factors, such as the cost of competing options, for example fuel supply and cost of infrastructure, as described above. Also, implementation of a technically-feasible option could be required by law, as demonstrated with the example of the no-steam-trains policy in New York City. Nevertheless, occasional references are made to economic feasibility, which includes aspects like the cost of hydrogen and diesel, as well as the cost of fuel cells. Also, the efficiency achieved by the various traction systems will have a direct effect on the operational cost, for example, a more efficient vehicle requires less fuel to provide the same service and, therefore, fuel costs will be lower.

1.6.2 Risk and Safety

Hydrogen is a gas at ambient conditions and, therefore, requires alternative handling to liquid fuels or electricity. Different safety arrangements are necessary to mitigate the risks associated with the gas, particularly leakage and unintended ignition. The risk and safety analysis that is required for adoption of a railway fuel is outside the scope of this research. However, the safety of hydrogen has been investigated in other transportation industries, such as the automobile business (Markert, Nielsen, Paulsen, & Andersen, 2007; Pasman & Rogers, 2010; Schlapbach, 2009; Swain, 2001). Also, hydrogen has been used in industrial applications for several decades, as described in the Hydrogen Supply Chapter, and associated safety standards exist. In addition, Britain's Rail Safety and Standards Board (RSSB, 2005) evaluated hydrogen safety, were it to be employed as an energy carrier for railway traction. Further, hydrogen-powered railway vehicle prototypes have been tested (Hoffrichter, et al., 2010), and hydrogen-powered mining locomotives are in operation (Miller, Hoffrichter, Hillmansen, & Roberts, 2012). All of the aforementioned cases indicate that the risk associated with hydrogen is manageable and should not prevent implementation in a railway context, although revised and new standards will be necessary. The research presented in the thesis does not cover hydrogen safety in detail but includes some references to particular issues, for example, fire risk in case of a fuel leak and safety relevant properties of hydrogen.

1.7 General Methodology

The methods employed in the research can broadly be split into two categories:
(1) Literature focused, and (2) Experimental.

Literature formed the basis for the introduction, background, hydrogen supply, and well-to-wheel chapters. The first three of these chapters consist primarily of a summary informed by literature, whereas the well-to-wheel chapter employs an existing well-documented method for comparative fuel investigations in the railway sector.

The second part of the thesis, consisting of the Hydrogen Pioneer design, empirical performance evaluation, and vehicle simulation includes some results of a literature study but primarily relies on methods that are specific to the chapter.

Unless the approach is literature-based, the method employed in the chapter is described within its context. The nature of the research required the deployment of various methods, many of which are specific to the work presented in the particular chapter. A description of all the methods utilised in the research under this subheading would lead to redundancy and, in the author's opinion, would reduce the clarity of the argument. Therefore, no further methodology description is provided outside the respective chapters.

1.8 Document Structure

In this section the author outlines the structure of the document. As mentioned, the thesis is split into two parts: the first part is primarily literature-based, while the second part consists of the development of hydrogen-powered railway vehicles and their associated performance.

Chapter One: Introduction

The thesis begins with an introduction where the author briefly reviews the history of railway traction change and the associated drivers, followed by the hypothesis and scope of the research. Further, a short methodology section is included and the thesis structure is outlined.

Chapter Two: Background

In the background chapter the author describes the current reasons that promote a change in transportation fuels, including emissions and resource constraints. Also, the rationale for the application of hydrogen as an alternative fuel is portrayed. The chapter ends with a brief review of hydrogen-powered railway traction unit prototypes.

Chapter Three: Hydrogen Supply

In this chapter the writer describes the existing hydrogen supply chain. Hydrogen production methods, transport and distribution infrastructure, as well as storage options are discussed. Further, the ability of hydrogen to be used as an energy storage medium is illustrated. A reader that is familiar with hydrogen supply may skim through the chapter, as no new findings are presented. However, the section is included to provide a complete stand-alone document so that readers less familiar with the topic do not have to rely on additional reading.

Chapter Four: Well-to-Wheel Analysis

The established railway propulsion energy chains, diesel and electricity, are compared with hydrogen in this chapter. Both carbon emissions and overall efficiencies for the energy supply chain are determined, beginning from the original energy source, such as coal in the ground, to the turning of the railway wheel. The investigation assumes the maximum efficiency that a train might reach, rather than the duty cycle efficiency, which is part of the investigation of following chapters. Further, a large part of the work presented has been published in a journal paper, which is attached in the appendix.

Chapter Five: Prototype Locomotive: Hydrogen Pioneer

The author was a member of the team that designed, constructed, and demonstrated the UK's first hydrogen-powered locomotive. Associated design calculations as well as the general development of the locomotive are described in the chapter.

Chapter Six: Empirical Performance Evaluation

In this chapter the author utilises the Hydrogen Pioneer to conduct a performance evaluation. First, the resistance to motion of the vehicle is determined, which is followed by a series of tests to establish the performance of the locomotive, including vehicle duty-cycle efficiency, operation of the hybrid drive-train, and power-plant efficiency.

Chapter Seven: Concept Design

Computer simulation is employed to create virtual hydrogen-powered vehicles. The diesel-electric train "Gelenktriebwagen (GTW)" with two coaches is used as a benchmark vehicle, which is assumed to be operating over a regional railway route in Britain. The results are utilised to develop two hydrogen-powered vehicles, one of them a hybrid, which are operated over the same route. A comparison between the characteristics of the three vehicles, including journey time, energy consumption, and carbon emissions is provided in the chapter.

Chapter Eight: Conclusion

In the last chapter the author summarises the work and reviews the approach that was employed in the investigation. With a general discussion about hydrogen-powered railway vehicles, including barriers to implementation and further research areas, the writer ends the thesis.

Back Matter

The back matter consists of appendices, which are some the publications of the author during the PhD period, and the list of references.

PART I:
LITERATURE-BASED RESEARCH

2 BACKGROUND

In this chapter the author presents background information to provide the context of the study and the rationale for the utilisation of hydrogen. Further, some hydrogen-powered railway traction prototypes are briefly mentioned. Part of the work that is presented has been published in a journal paper (Hoffrichter, Silmon, Iwnicki, Hillmansen, & Roberts, 2012), see Appendix A, and parts have led to a conference paper publication (Hoffrichter, Hillmansen, & Roberts, 2010), see Appendix B.

2.1 Energy Consumption, Market Share, and Emissions

Transportation of cargo and passengers is an enabler of civilisation (Hibbs, 2003), as already described. The energy consumed for transport activities accounts for approximately 20 % of global primary energy, and transportation on roads has a share of about 75 % of the energy requirement, with the remainder split between air, sea, and rail (IEA, 2012).

In the European Union, 31 % of the energy consumption is due to transportation, of which railways have approximately a 2.5 % share, while accounting for 6 % of passenger travel, and 10 % of cargo movements measured in tonne kilometres (UIC & Community of European Railway and Infrastructure Companies [CER], 2008). In the USA, railways have a 48.3 % share of the freight market, and 0.2 % share of the passenger travel market, measured in tonne kilometres (UIC & IEA, 2012), while accounting for 2.1 % of the 27.8 % transportation share of energy use (S. C. Davis, Diegel, & Boundy, 2012). In Russia, the USA, China, India, and Australia rail has the largest market share of freight transportation measured in tonne kilometres (IEA, 2009).

Thus, railway traffic differs according to geographic region, but all have in common the considerably lower energy consumption compared to transportation on roads and by air. A modal shift from road to rail is encouraged to reduce energy consumption and emissions (IEA, 2009). One possibility to promote modal shift is described next.

In the UK railways have an 8 % share of the freight transport market measured in tonne kilometres (Office of Rail Regulation [ORR], 2011), which is below the share in the European Union, and the share is significantly lower than in the USA. Reasons include the higher flexibility, quicker transfer times, low cost of road transportation (Hoffrichter, et al., 2012), and close proximity to ports. To encourage modal shift from road to rail a decrease in transit times is desirable. However, the mixed-traffic structure of the railways complicates the integration of freight trains, which typically travel slower than passenger trains (Hoffrichter, et al., 2012). Hoffrichter, et al., continue, and propose novel trains, such as four-car multiple units that carry containers, or passenger multiple units that are converted to carry pallets. Both opportunities would create characteristics similar to passenger trains. In a comparative study, the effect on journey time, energy consumption, and emissions has been determined for such new rail vehicles and road transport. The results show that a significant reduction in energy consumption and carbon emissions is achieved while reducing the transit time of rail transportation (Hoffrichter, et al., 2012). Further, rail’s particular competitiveness in transporting large quantities is confirmed. Therefore, a more effective use of energy for a given transport capacity is achievable in the rail mode, and the similar performance of the vehicles to passenger trains allows more flexible path allocation (Hoffrichter, et al., 2012). Thus, it is possible for rail to increase its market share without major investments in additional infrastructure.

The case above outlines the advantage of rail in terms of fuel consumption and environmental performance, compared to road. Below, the fuel sources as well as associate emissions resulting from railway traction are described in more detail.

2.1.1 Energy Sources

Currently, diesel fuel and electricity are the two main energy sources for railway traction (IEA, 2009). Both have their advantages and drawbacks: (1) Electricity has advantages in allowing a generation mix of various energy sources, such as fossil fuels, renewables, and nuclear, while avoiding emissions at the point-of-use. But it requires additional wayside infrastructure, which is usually costly to implement, as mentioned (Hollingsworth & Cook, 1996; Kerr, 1951; Schafer, et al., 2001). (2) Diesel fuel has the benefit of allowing autonomous operation of trains, permitting travel over routes that cannot be electrified or are not electrified economically. Drawbacks are the reliance on one energy source, petroleum (Agnew, 1953; Kerr, 1951), and exhaust emissions at the point-of-use, which are inevitable (UIC & CER, 2008).

The electrification share of railway networks varies according to region, for example: 99.5 % of the network is electrified in Switzerland, (Railway Directory, 2012). By contrast approximately 0.004 % of the largest railway network in the world, which is located in the USA, is electrified (The World Bank Group, 2007). The majority of the electrification in the States is in the North East Corridor, where passenger trains account for a large proportion of operations, and the corridor is owned and operated by the National Railroad Passenger Corporation, also known as Amtrak (Railway Directory, 2012; The World Bank Group, 2007). In Canada 0 % of the network is electrified, VIA Rail, Canadian National, and Canadian Pacific only (The World Bank

Group, 2007). In the European Union 53 % of the railway network is electrified (UIC & IEA, 2012).

Further, electrification infrastructure often requires overhead structures, which have a visual impact on their surroundings. In some cases, such as historic city centres, alternative propulsion systems have been utilised to avoid the impact (Moskowitz, 2010), as mentioned in the introduction. Autonomous traction is, therefore, in many areas the only propulsion choice.

Currently, most autonomous traction vehicles combust diesel fuel in an engine to propel the train, and about 70 % of the global rail energy use is attributed to diesel with the remainder assigned to electricity (IEA, 2009). Figure 12 illustrates the global railway energy use by source. The IEA (2009) continues to describe the largest rail energy users as being the USA and China, which both primarily operate freight trains and hold the largest share in that market, as mentioned, explaining the high energy consumption.

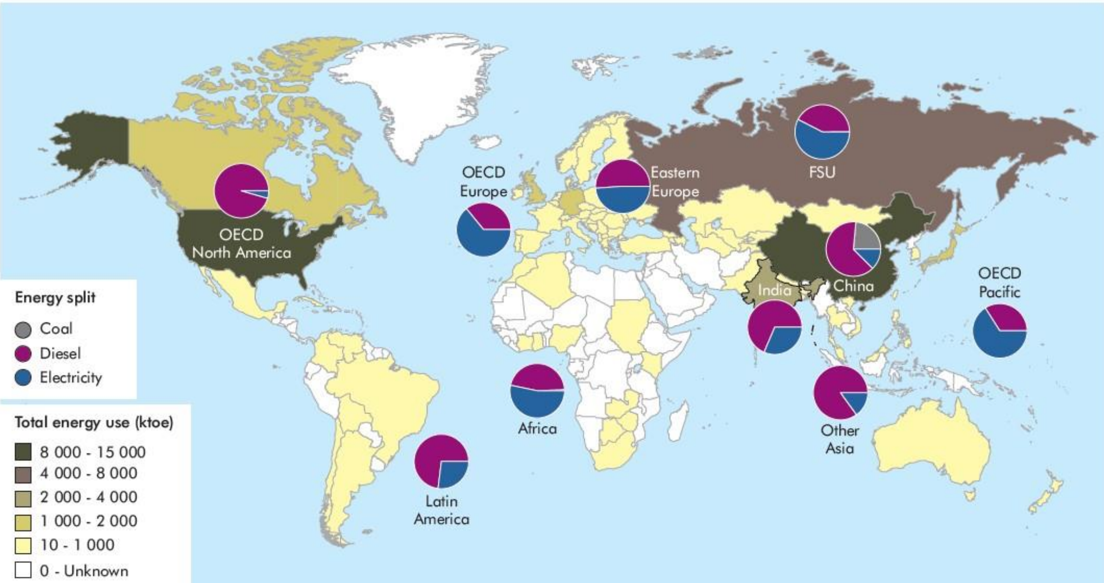


Figure 12: Total Rail Energy Consumption and Energy Sources in 2006 (IEA, 2009)

Diesel, which is refined from petroleum, is a finite energy source. Hubbert (1949) developed a model, based on empirical studies, that describes the extraction rate of petroleum wells. He observed that production from some fossil fuel reserves rise to a peak and thereafter decline, and that the pattern follows approximately a bell shaped curve (Hubbert, 1956). His theory became known as “Peak Oil”. Hubbert (1956), utilising the developed method, predicted the peak oil production for the United States to be in the 1970s, and his predictions were correct (Hirsch, Bezdek, & Wendling, 2005).

Hirsch, et al. (2005) explain that, since the production of an existing well increases, peaks, and declines, new reserves have to be discovered and start production to compensate for the reduced output of the older well, if demand remains stable or grows. Thus, when discovery and production of new reserves somewhere in the world do not meet or exceed the current extraction, the world peak is reached (Hirsch, et al., 2005). When demand exceeds supply rising prices are the result (Begg, et al., 2005). Currently, a significant rise in world-wide petroleum demand is predicted (Hirsch, et al., 2005) and the majority of the increase is due to transport applications (IEA, 2012). A peak in world-wide petroleum production will arise, and the question is about the point in time rather than its occurrence; if unconventional reserves are considered the peak will be delayed.

Diesel prices have been rising over the last decade (S. C. Davis, et al., 2012; U.S. Energy Information Administration [U.S. EIA], 2013) and increases are likely in the future, as described. Further, the majority of known conventional petroleum reserves are in countries that may be described as politically unstable, and supply interruptions are not unimaginable. In addition, unconventional extraction methods are complex and expensive, and only economically viable at high petroleum prices (Hirsch, et al., 2005). However, diesel is the primary fuel for autonomous traction, as mentioned, and therefore, an increase in prices has a direct effect on railways. In addition, fuel is one of the major contributors to railway operating costs. An alternative to diesel that is not petroleum-based is desirable for the aforementioned reasons.

2.1.2 Emissions

Most scientists accept that global temperatures are increasing, which is generally deemed undesirable due to a resulting risk of sea level rise and other threats to humans and natural systems (HM Government, 2011; National Academy of Sciences, 2010). One mechanism that governs the temperature on Earth is the greenhouse effect: sun radiation is reflected by the planet's surface but not completely released into space and, instead, reflected back to the surface by greenhouse gases, preventing or slowing the loss of heat (U.S. EPA, 2012a).

Mann, Bradley, and Hughes (1998) discovered a correlation between the increase of greenhouse gas concentrations in the atmosphere and global temperature rise, which coincides with the start of the industrial revolution and, subsequently, the increased combustion of fossil fuels by humans. Thus, it is believed that the emission of greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (U.S. EPA, 2012a), leads to an increase in global temperature (HM Government, 2008, 2011; National Academy of Sciences, 2010). The greenhouse gas that is primarily associated with the combustion of fossil fuels is carbon dioxide, and the gas is often used as a proxy for all greenhouse gases and has been given the global warming potential of one (Mann, et al., 1998; National Academy of Sciences, 2010; U.S. EPA, 2012a). The global warming potential of the other greenhouse gases is as follows: methane 21, nitrous oxide 301, and fluorinated gases range from 140 to 23 900 (U.S. EPA, 2012a). Fluorinated gases have no natural cause and are only emitted from human-related activities (U.S. EPA, 2012a). The U.S. EPA continues to describe that fluorinated gases are used in cooling equipment, such as air conditioners and fridges; in electricity transmission equipment, for example circuit breakers; and are by-products of the aluminium and semiconductor industry and, therefore, are not directly related to transportation.

Most greenhouse gases are substances that occur naturally on Earth, and a cycle exists that balances their occurrence and, therefore, temperatures (U.S. EPA, 2012a), for example, carbon is captured by green plants and released when the plants decompose or burn in a fire. For the aforementioned reasons it is suspected that a dramatic reduction of greenhouse gas emissions caused by humans is likely to limit temperature rise (National Academy of Sciences, 2010).

Emissions that arise from railway traction can be split into two distinct categories: (1) Emissions at the point-of-use, and (2) overall emissions.

Overall Emissions

Emissions from railways primarily result from the combustion of fossil fuels, such as diesel and coal. For diesel traction the emissions occur at the point-of-use whereas, for electric traction, emissions are released at the fossil fuel power station. Electric traction has the potential of avoiding greenhouse gas emissions, depending on the electricity mix, for example if only renewable sources constitute production (IEA, 2009; UIC & IEA, 2012). More detail is provided in the well-to-wheel chapter. However, today the electricity mix is carbon intensive in many regions and a switch to electricity would not lead to greenhouse gas reductions, compared to petroleum-based fuels (IEA, 2009). Therefore, it is necessary to decarbonise the electricity mix to achieve lower emissions, which can be realised with both an increasing share of renewables and nuclear electricity generation (IEA, 2009). Nevertheless, railways account for less than 1 % of the total global carbon dioxide emissions (UIC & IEA, 2012)

Emissions at the Point-of-Use

Electric trains have very few emissions at the point-of-use (UIC & IEA, 2012); whereas most emissions related to diesel traction occur as a result of fuel combustion on-board the vehicle. Figure 13 illustrates the point-of-use emissions of the same class of locomotive depending on external factors and power demand.

(Andrusia, 2012) (Pierry, 2012) (Starnes, 2012)

Figure 13: Visible Point-of-Use Emissions of GE P42DC Depending on Operating Conditions and Environmental Factors: From Extreme, Left, to Standard Conditions, Right.

The combustion of diesel in an engine leads to the release of several types of emissions, including, heat, carbon dioxide, nitrogen oxides, and particulate matter, and the latter three are damaging to the environment and to humans. For example, particulate matter is suspected to be a cause of cancer (World Health Organization: International Agency for Research on Cancer, 2012), nitrogen oxides are the main cause of smog (Noyan, 2011) and nitrous oxide has 310 times the global warming potential of carbon dioxide, as mentioned. Because of the location where these emissions occur, such as in stations, as well as due to environmental concerns, legislation that requires the reduction of point-of-use emissions from railway traction has been introduced (European Commission, 1997-2012; U.S. EPA, 2012b). For diesel traction to comply, various measures have been taken, including engine modifications, exhaust-gas after-treatments, and filters (Lustig, 2011; McDonnell, 2012b). However, it is not possible to eliminate all emissions, because combustion of a carbon-based fuel takes place on-board. Thus, if stricter regulations supersede current ones, then additional development of combustion engines is needed to comply, or alternative propulsion methods that have fewer or no emissions at the point-of-use must be employed.

Uncertainty about economical fuel supply, as well as rising concerns about emissions at the point-of-use and overall greenhouse gas emissions, as mentioned, is promoting the exploration of alternative fuels for the transportation sector. One of these alternatives is hydrogen. In the next section the author describes the rationale behind the use of hydrogen as an energy carrier, before moving on to a brief section about hydrogen-powered railway traction prototypes.

2.2 Hydrogen as a Transportation Fuel

Hydrogen is the first element in the periodic table, and a carbon-free, colourless, odourless, non-toxic gas (Air Products, 2013; Schlapbach, 2009; U.S. Department of Energy [U.S. DOE], 2008b). Further, hydrogen is the lightest element and 14 times lighter than air, moreover it is not a greenhouse gas and, in case major hydrogen leakage rates were to occur, its secondary contribution to the greenhouse effect is, currently, estimated as negligible, if present at all (Air Products, 2013; Noyan, 2011; Winter, 2009). Also, hydrogen is an abundant element in the universe and on Earth, present in water, hydrocarbons, and all organic matter (Air Products, 2013; U.S. DOE, 2008b). However, hydrogen rarely occurs on its own but is usually part of another substance, such as water and, therefore, has to be separated from the compound to be available in its pure form, which requires energy input (U.S. DOE, 2008b). Thus, hydrogen is a secondary energy, like electricity (Winter, 2009), also referred to as an energy carrier (U.S. DOE, 2010). More detail about hydrogen production is provided in the next chapter and in the well-to-wheel part of the document.

Molecular hydrogen has the highest energy density, on a mass basis, of any chemical, which is desirable in a fuel, but it is a gas at room temperature, thus requiring a large volume, and compression or another technology for storage is necessary (Schlapbach, 2009), see hydrogen supply chapter for more information.

Hydrogen is the only fuel, aside from hydrogen-based ammonia, NH_3, that does not release carbon emissions when utilised for energy generation (Leighty & Holbrook, 2012). Being a secondary energy, like electricity, hydrogen can be generated from many different feedstocks (Winter, 2009) and, consequently, reduces the dependency on petroleum as well as offers the potential to reduce overall greenhouse gas emissions, as described in the hydrogen supply and well-to-wheel chapters in more detail.

2.2.1 Hydrogen Energy Conversion

Hydrogen can be converted into mechanical energy in a combustion engine or to electrical energy in a fuel cell (Schlapbach, 2009). Both options are briefly described hereafter.

Hydrogen Internal Combustion Engine

Combustion of hydrogen in air is possible if a concentration of 4 % to 75 % is reached (Schlapbach, 2009). This allows its utilisation in combustion engines, where it is burned, similar to gasoline (Brinkman, Wang, Weber, & Darlington, 2005; MAN Nutzfahrzeuge AG, 2006).

The product of combustion with air is primarily water but can include nitrogen oxides and small amounts of other emissions, which are due to lubricant combustion in the engine. However, the point-of-use emissions are significantly lower than for carbon-based fuels (Brinkman, et al., 2005), and hydrogen combustion engines have been employed in prototype cars, buses, and vans (Brinkman, et al., 2005; HyFleet:Cute, 2009). Thus could be implemented in railway traction vehicles. The technology has the advantage that it is similar to existing engines and, thus, production could increase quickly.

However, hydrogen storage requirements coupled with an engine efficiency that is similar to that of diesel engines (MAN Nutzfahrzeuge AG, 2006) results in a shorter range: The hydrogen internal combustion engine BMW Hydrogen 7 has a range of 200 km while half the boot space is taken-up by the approximately 8 kg of liquid hydrogen. The on-board gasoline fuel tank of 74 litres extends the range to 700 km (BBC News, 2006).

An alternative to combustion engines is fuel cells, which are more efficient and allow similar ranges to current cars. Hydrogen fuel cells are described in more detail below. In the well-to-wheel chapter both internal combustion engines and fuel cells are assessed for the suitability in railway applications.

Hydrogen Fuel Cell

A fuel cell is an electro-chemical device in which hydrogen is converted into electricity and heat (U.S. DOE, 2011b). Several types of fuel cells exist, such as Proton Exchange Membrane, Solid Oxide, Alkaline, Phosphoric Acid, and Molten Carbonate. Each has its advantages and drawbacks while being appropriate for particular types of application (U.S. DOE, 2011a, 2011b).

Currently, the most suitable fuel cell for transportation applications is the Proton Exchange Membrane technology (U.S. DOE, 2011a). While other fuel cells, especially Alkaline (Grigorovich, 2012) and Solid Oxide (Steinberger-Wilckens & Pour, 2012), could be used in railway traction, only Proton Exchange Membranes are described further, as the scope of the research is on the whole system rather than a single component. Further, the basic function of converting hydrogen to electricity is the same. In a Proton Exchange Membrane, hydrogen and oxygen, usually taken from ambient air, are combined to create electricity and heat, leaving as exhaust pure water; as shown in Figure 14. Schlapbach (2009) explains the process in three stages:

1. Hydrogen enters the cell at the anode side where the hydrogen molecule is split into atoms.
2. An anode catalyst separates the electrons from the atom creating hydrogen ions, which pass to the cathode, whereas the electrons have to move across an electric circuit to arrive at the cathode.
3. Oxygen is directed to the cathode, where it combines with the hydrogen ions and electrons to form water, which then leaves the cell.

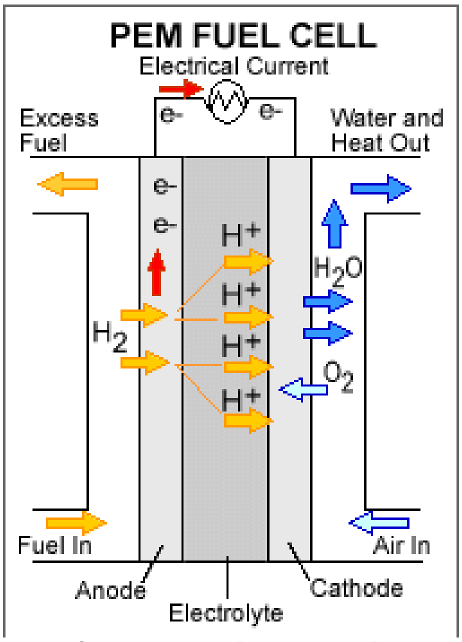


Figure 14: Diagram of a Proton Exchange Membrane (PEM) Fuel Cell (U.S. DOE, 2011b)

Several fuel cells are usually combined in a stack, because a single cell only creates sufficient electricity for very small consumers (U.S. DOE, 2011b), for example, the stack used in Mercedes buses consists of 396 individual fuel cells (Daimler AG, 2009a). Typical stack outputs for transport applications are in the range of 70 kW to 200 kW, and a combination of several stacks creates a higher output if needed (Grigorovich, 2012; HyFleet:Cute, 2009; Mercedes-Benz: EvoBus, 2009; Miller, Hess, Barnes, & Erickson, 2007; Schwarzer, 2012).

Electrical peak efficiencies of Proton Exchange Membranes have reached 58 % to 60 % (Daimler AG, 2009a; U.S. DOE, 2011a), and a stack lifetime of 20 000 hours has been achieved (Fuel Cell Today, 2012), which is deemed long enough to compete with multiple unit diesel engines (RSSB, 2005). Locomotive power-plants should have a lifetime of 30 000 hours to 40 000 hours to compete with diesel engines, according to the RSSB (2005). Fuel cell stacks are expected to reach lives of 30 000 hours to 36 000 hours by 2015 (Ahluwalia, Wang, & Kumar, 2012; Fuel Cell Today, 2012).

Fuel cells are attractive for railway applications as the output is electrical energy and stacks are suitable for a power-plant as the data above indicates. In addition, Proton Exchange Membranes have been utilised in railway traction prototypes, which are described later in the chapter. Currently, the main disadvantage is their higher cost compared to diesel-engines, but the price is decreasing and the fuel cell stack manufacturer Ballard hopes to match the ownership cost of a diesel-hybrid bus in 2014 (Fuel Cell Today, 2012). The company expects a stack cost reduction of 35 % to 40 % by 2015 (Ahluwalia, Wang, et al., 2012). The U.S. DOE (2013) estimates a cost of $47/kW for hydrogen fuel cells in 2012, if mass produced, which is a reduction in cost of approximately 83% since 2002. However, in 2011 the power-plant cost for a U.S. hydrogen fuel cell bus was approximately $1 000 000 or approximately $6 700/kW, which reflects the price for small scale production of fuel cells (Ahluwalia, Wang, et al., 2012).

2.2.2 Hydrogen as a Fuel in the Automotive Sector

The majority of energy used in the transportation sector is attributed to individual personal transportation on roads, primarily cars (IEA, 2009). Further, as mentioned, petroleum-derived products, such as gasoline and diesel, vastly dominate the market with a share of approximately 95 % (IEA, 2009). For the aforementioned reasons of resource limitations and emissions resulting from the combustion of petroleum products, automobile manufacturers have been seeking alternatives; examples are bio-fuels, natural gas, and electric vehicles (IEA, 2009, 2012). Combustion-engine hybrids and gas-powered vehicles are already commercially available, but still depend on fossil fuels and produce emissions at the point-of-use, whereas electric drive-trains do not emit greenhouse gas exhaust at the vehicle (Brinkman, et al., 2005).

Electric Drive-Trains

Electric cars have been produced in various combinations: battery-only, hydrogen fuel cell hybrid, and combustion-engine hybrids, which are commercially available (Brinkman, et al., 2005; McKinsey & Company, 2010). The greatest technical challenge for alternatively-fuelled vehicles is to achieve a range that is similar to existing fossil fuel combustion engine systems (IEA, 2009; Schwarzer, 2012). Figure 15 shows a comparison of energy densities according to mass and volume of on-board storage. All options, except for batteries and hydrogen, are types of hydrocarbons and, therefore, will have emissions at the point-of-use. However, one of the requirements of a new fuel is the avoidance of vehicle exhaust emissions and, therefore, the carbon-releasing alternatives are not further considered.

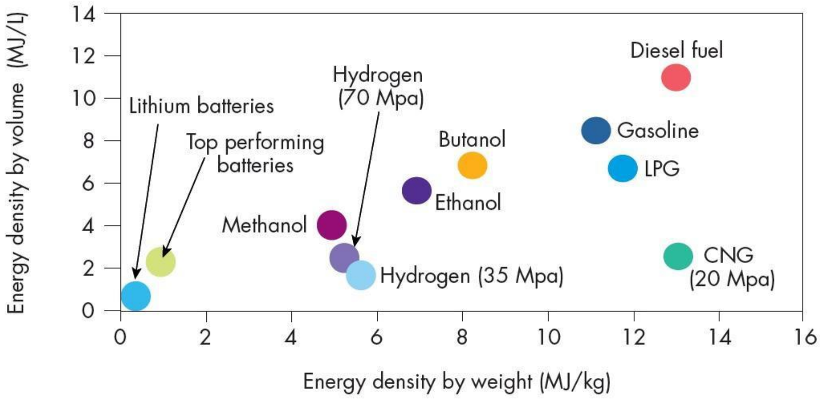


Figure 15: Energy Density of Various On-Board Energy Storage Systems (IEA, 2009)

From Figure 15 it can be seen that none of the alternative fuel storage systems reach the energy density of liquid petroleum-based fuels. Batteries have the lowest densities. Thus, to achieve a similar range to existing vehicles, either more space for the fuel storage has to be allocated, which is difficult in most automobiles, or the efficiency of the drive-system has to improve, or a combination of both.

Battery-Only Vehicles

Currently, most battery-only vehicles have a maximum range of 100 km to 150 km; an exception is the Tesla Model S, which reaches a maximum range of 424 km (IEA, 2009; U.S. DOE & U.S. EPA, 2013). In addition, recharging times for batteries are significantly longer than for liquid or gaseous fuel refilling, typically in the order of several hours (Kendall, 2012; Markel & Simpson, 2006). Therefore, they are primarily suitable for short journeys within urban areas and for driving cycles that allow for the long charging time, e.g., overnight, but are not able to compete with fossil-fuel systems over longer distances.

Hydrogen Fuel Cell Electric Vehicles

The efficiency of a diesel-powered car is around 22 % during the standardised European Driving Cycle (Von Helmolt & Eberle, 2007). Currently, fuel cells can achieve efficiencies of up to 60 %, as mentioned, and during the same driving cycle a fuel cell hydrogen-hybrid car already achieved an efficiency of 36 % in 2007 (Von Helmolt & Eberle, 2007). Thus, the higher efficiency counteracts the energy storage requirement and driving ranges of 380 km to 525 km, depending on the quantity of hydrogen stored, are achieved in the aforementioned driving-cycle, while the storage equipment can be accommodated in a medium-sized car (H2Moves, 2011). Also, a range of approximately 680 km has been achieved with hydrogen fuel cell vehicles (U.S. DOE, 2013).– Compared to present cars, a similar amount of space is available for passengers and luggage in fuel cell vehicles (Daimler AG, 2011; H2Moves, 2011; Hyundai Motor

Europe, 2011). Further, the cars can be refilled in three to four minutes (Daimler AG, 2011; H2Moves, 2011; Hyundai Motor Europe, 2011). Figure 16 shows a selection of hydrogen-powered cars with such characteristics at a demonstration event in Hannover.

Figure 16: Examples of Small-Series Production Hydrogen-Powered Cars (Author's Collection, 2012)

In summary, hydrogen-powered fuel cell cars offer a similar driving range and refuelling time to existing vehicles, while reducing energy consumption and having only water as exhaust. The quantity of water vapour resulting from the use of hydrogen in fuel cell cars is approximately the same as for the current combustion technologies and the impact of water vapour emissions to climate change is negligible (Colella, Jacobson, & Golden, 2005). The reason for the low impact of water vapour is that the emissions occur close to the Earth's surface and the water emissions are several magnitudes lower than naturally occurring water vaporisation (Colella, Jacobson, & Golden, 2005).

For the aforementioned advantages of hydrogen-powered fuel cell cars the majority of automobile manufacturers, including General Motors, Ford, Daimler, BMW, Hyundai, Honda, and Toyota consider electric drive-trains powered by hydrogen fuel cells as the only viable long-term replacement of combustion engine cars (Fuel Cell Today, 2012; Schwarzer, 2012). Further, all of these manufacturers have announced small series commercial production of cars, with the first being available in 2013 from Hyundai, followed by the other manufacturers from 2015 (Fuel Cell Today, 2012).

In addition to cars, several hydrogen-powered buses have been demonstrated in various European cities, including Berlin, Hamburg, Barcelona, Madrid, Amsterdam, and London (HyFleet:Cute, 2009). Bus trials have also taken place in Beijing, Perth, Vancouver, Palm Springs, the San Francisco Bay Area, and several other places around the globe (Ahluwalia, Wang, et al., 2012; HyFleet:Cute, 2009). Many of these buses operated with fuel cells, but some with hydrogen combustion engines (HyFleet:Cute, 2009). All demonstrated that hydrogen can be used in public transit to provide a reliable service (Ahluwalia, Wang, et al., 2012; HyFleet:Cute, 2009). The follow-on project started in 2010, again involving several cities including London, Hamburg, and Oslo, and the aim of the scheme is to fully commercialise hydrogen fuel cell buses by 2015 (Ahluwalia, Wang, et al., 2012). A filling station with a rate of 5 kg per minute was built in Vancouver for hydrogen bus refulling (Ahluwalia, Wang, et al., 2012), allowing to refill a bus with 35 kg hydrogen storage (Mercedes-Benz: EvoBus, 2009) in 3.5 minutes, which is similar to diesel-fueled busses with the same operating range.

Hydrogen Refuelling Stations

Cluster-based local hydrogen refuelling networks are currently under construction in Japan, Germany, California (Fuel Cell Today, 2012), and the UK (Department for Business, Innovation and Skills, 2012), to support the vehicles that are to be introduced in the next few years. These initiatives include government departments, automotive manufacturers, and energy companies, such as Linde, Air Products, Air Liquide, Shell, OMV, Total, Vattenfall, and EnBw, which will build and operate the filling stations (Daimler AG, 2009b; Department for Business, Innovation and Skills, 2012). An example of an in-service hydrogen station that is available to the public is shown in Figure 17.

Figure 17: Hydrogen Filling Station that is Available to the Public at Stuttgart Airport (Author’s Collection, 2013)

Similar filling stations could be implemented for railway refuelling, in the author’s opinion. The amount of investment as well as the confidence that large energy companies and automotive manufacturers place in hydrogen fuel cell technology and the associated infrastructure, suggests that commercialisation in the sector is possible in the medium term.

Hydrogen Safety

Hydrogen is often perceived as a dangerous fuel, which is partly due to the images of the “Hindenburg” airship disaster, but the problem with the Zeppelin was its highly flammable skin (Schlapbach, 2009; Schlapbach & Züttel, 2001). Many hydrogen properties aid safety: non-toxicity, little or no harmful combustion emissions in air, small radiant heat release while burning, and high volatility (Air Products, 2013; Brinkman, et al., 2005; RSSB, 2005; Schlapbach & Züttel, 2001). Thus, the primary risk relates to fire in case a leak occurs. However, because hydrogen is much lighter than air, as mentioned, it dissipates quickly and a minimum concentration of 4 % of hydrogen in the air has to be present to allow combustion, which is four times higher than for gasoline (Schlapbach, 2009). Figure 18 shows video frames that compare hydrogen and gasoline fires in a fuel leak simulation conducted at the University of Miami.

Before ignition

3 seconds: ignition of fuel

1 minute: hydrogen flow decreasing, gasoline burning

1 minute, 30 seconds: hydrogen flow almost finished, gasoline continuous to burn

Figure 18: Video Frames of Fuel Leak Experiment at the University of Miami
The Hydrogen-Powered Vehicle on the Left, Gasoline-Powered Car on the Right (Swain, 2001)

In Figure 18 it can be seen that the hydrogen flame is primarily burning in an upward direction whereas the gasoline fire is affecting the whole car. In addition, the hydrogen combustion ends after approximately 1.5 minutes while the gasoline fire is still burning. Also, emissions can be clearly seen in the gasoline case whereas the hydrogen burns clean. The experiment illustrates the lower fire risk of hydrogen (Schlapbach, 2009). Passengers in the hydrogen car would have survived, whereas persons in the gasoline car would have incurred serious injuries or would have died (Swain, 2001). Swain (2001) further describes that the hydrogen car was undamaged and the gasoline car was severely damaged.

In general, it can be summarised that hydrogen is no more dangerous than conventional fuels (RSSB, 2005), but certain risks associated with the fuel exist and procedures and standards have to be in place to minimise these (Markert, et al., 2007; RSSB, 2005). Hydrogen safety is not discussed further in the thesis as it is outside the scope, and the passage above is included as a brief outline of risks associated with the gas.

All the aforementioned reasons, such as avoidance of emissions at the point-of-use and fuel security, as well as the investments and tendencies in the automotive sector, warrant an investigation into the suitability of hydrogen as a fuel for railway traction, in the author's opinion. In addition, hydrogen-powered railway vehicles could offer an economical alternative to electrification while reducing emissions compared to diesel. A case study conducted for the Toronto area has shown that a conversion of a diesel-operated line to a hydrogen-powered system can be more economical than equivalent electrification, while achieving similar greenhouse gas reductions (Dincer, 2007; Marin, Naterer, & Gabriel, 2010a, 2010b). However, the study relied on assumptions about vehicle efficiencies and traction performance, as no railway traction prototype data were included; both issues are addressed in the course of this thesis.

Some hydrogen-powered railway traction prototypes have been developed and demonstrated, and these are described in the next section.

2.2.3 Hydrogen-Powered Railway Traction Prototypes

The advantages of hydrogen as a fuel, such as few or no emissions at the point-of-use and non-reliance on petroleum, have prompted development of hydrogen-powered vehicles. For railways, hydrogen offers the potential to combine the advantages of diesel and electric traction: autonomous operation without emissions at the point-of-use while enabling the utilisation of a primary energy resources mix, which can lead to a reduction of overall emissions, as shown in the well-to-wheel chapter.

Some hydrogen-powered railway traction prototypes have been developed and demonstrated, including one built at the University of Birmingham, which is described later in the thesis, in detail. Further prototypes are discussed here. Part of the work presented below led to a conference paper, which is attached in Appendix B.

Mining Locomotives

The first hydrogen-powered locomotive was developed by Vehicle Projects Inc: a 17 kW fuel cell power vehicle with metal-hydride storage, which was demonstrated in 2002 (Hoffrichter, et al., 2010; Miller, et al., 2011). The locomotive outperformed the existing battery-powered vehicle in several respects, including power, operating range, and recharge time (Miller, et al., 2012). The locomotive is shown in Figure 19.

Figure 19: World's First Hydrogen-Powered Railway Traction Vehicle (Miller, et al., 2012)

Since 2002, Vehicle Projects has demonstrated a full-scale hydrogen fuel cell traction locomotive, see next subheading, while developing more advanced mining vehicles. In 2012, the company delivered the first of a fleet of five hydrogen-powered railway vehicles to a platinum mine in South Africa (Miller, et al., 2012). The locomotives have a metal-hydride storage system, 17 kW fuel cell power and a lithium-ion battery-pack, which together provide a net peak-power of 45 kW for 10 minutes. One of the locomotives can be seen in Figure 20.

Figure 20: Hydrogen-Hybrid Mining Locomotive
Courtesy and Copyright Vehicle Projects Inc, 2012

The non-polluting characteristics of hydrogen are a critical advantage in enclosed areas such as mines, and the extended range as well as faster refuelling time, compared to battery locomotives, may prove its economic feasibility. Vehicle Projects, also demonstrated a switcher locomotive, which is described in the next section.

Full-Scale Hydrogen-Powered Prototypes

Currently, several full-scale railway traction vehicles have been demonstrated and most are briefly described below. Further, a road-switcher locomotive is currently under construction and is expected to be demonstrated in 2013.

In 2009 a hydrogen-hybrid locomotive, see Figure 21, for switching purposes was demonstrated in Los Angeles (Miller, Hess, Erickson, & Dippo, 2010). The author was able to witness the operation of the locomotive and, therefore, information provided about the trial includes the author's experience.

Figure 21: Vehicle Projects' Hydrogen-Hybrid Switcher Locomotive (Author's Collection, 2009)

Vehicle Projects developed the locomotive on the basis of a Green Goat™ hybrid vehicle and components employed in Mercedes fuel cell buses and the switcher was demonstrated in collaboration with BNSF railway as well as the U.S. military (Miller, Hess, Barnes, et al., 2007). Miller, et al., continue to describe that two fuel cell stacks, each providing a maximum of 125 kW net power-output, provide the average-power during the duty-cycle, while peak-power is provided by lead-acid batteries, enabling a maximum output of 1.5 MW for approximately five minutes. Hydrogen is stored in 14 compressed-gas cylinders at 350 bar, which together hold 70 kg of the gas (Miller, Hess, Barnes, et al., 2007). Figure 22 illustrates the major drive-system components of the locomotive.

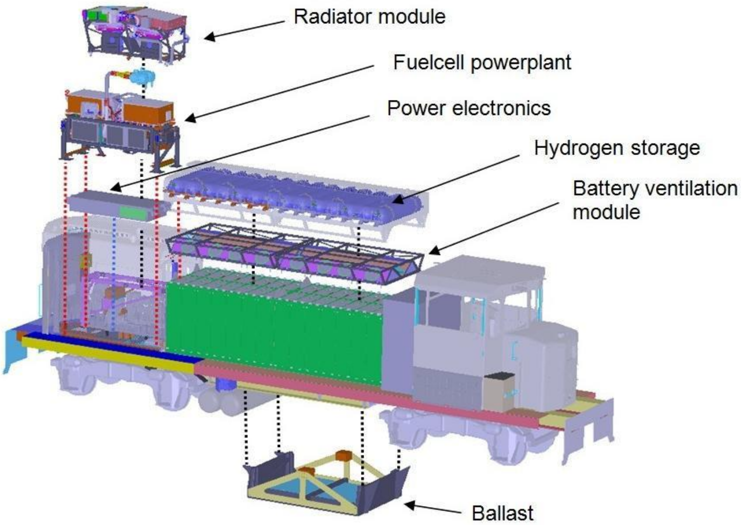


Figure 22: Expanded View of Switcher Locomotive Showing the Major Drive-System Components Courtesy and Copyright Vehicle Projects Inc, 2009

In-service demonstration by BNSF lasted for about three months without major interruptions (Personal communication with Vehicle Projects). The train driver's positive remarks included the quick response and the quiet operation of the locomotive (Personal communication with train driver). Hydrogen was supplied by Air Products in a 200 bar tube trailer and a temporary compressor-pump was utilised to increase the pressure for refuelling of the on-board tanks. The pump and hydrogen trailer are illustrated in Figure 23.

Figure 23: 200 bar Hydrogen Tube Trail and Compressor-Pump (Author's Collection, 2009)

Currently, the switcher is the largest hydrogen fuel cell land vehicle (Miller, et al., 2010) and is, presently, being upgraded to a road-switcher, increasing the fuel cell output to 500 kW and hydrogen storage to 350 kg, in addition to a battery technology change to lithium-ion (Allan, 2012). The road-switcher will be placed in service for demonstration of the technology in 2013.

Passenger prototypes have been constructed in Japan, but never entered service operation. The Railway Technical Research Institute as well as East Japan Railway developed hydrogen-hybrid railcars.

A single railcar was operated by East Japan Railway in 2007 (Kawasaki, Takeda, & Furuta, 2008). Kawasaki, et al., describe that the vehicle had two fuel cell stacks, which provided a combined power output of 130 kW, and lithium-ion batteries that could supplement the power output. In contrast to the switcher locomotive the railcar employed regenerative braking, and 10 kg of hydrogen were stored in 350 bar tanks (Kawasaki, et al., 2008). Further, Kawasaki, et al., report that the train was tested on a commercial line and reached speeds of up to 100 km/h. However, the train never entered commercial service because of a short stack lifetime and fuel cell stack costs remained too high, both being barriers to commercialisation (Kawasaki, et al., 2008).

The Railway Technical Research Institute developed, in several stages, a multiple-unit train, which consisted of two cars in the latest version. All the hydrogen equipment was installed in one car, while the batteries and associated converter were housed in the second (Yamamoto, Hasegawa, Furuya, & Ogawa, 2010). Yamamoto, et al., describe that the train was demonstrated in 2008 and stored 18 kg of hydrogen in 350 bar cylinders, which supplied a 100 kW net power fuel cell stack. Further, the lithium-ion batteries allowed for regenerative braking and provided an additional 360 kW of power. Yamamoto, et al., continue to write that, on the 45 km/h speed limit test track, the vehicle reached the maximum speed, and 100 km/h were possible in the laboratory. For a commercial vehicle, the equipment size would have to be reduced to allow space for passengers and a longer fuel cell stack lifetime is required, according to Yamamoto, et al. (2010). The two-car train is shown in Figure 24.

Figure 24: Railway Technical Research Institute Hydrogen-Powered Train
Courtesy and Copyright Railway Technical Research Institute

Both Japanese trains are demonstrator vehicles that have not been operated in-service. The hydrogen storage tank capacity is significantly lower than in the switcher locomotive case. However, both railcars employ regenerative braking and the principle of a hydrogen-hybrid train was established.

In Europe the first hydrogen-powered railway vehicle is a streetcar, see Figure 25, developed by Ferrocarriles Españoles de Via Estrecha (FEVE) in 2011 (Fuel Cell Today, 2011). The drive-system was integrated into an existing historic streetcar, and has two fuel cell stacks that provide 24 kW as well as lithium-ion batteries with a power of 95 kW, and, in addition, super capacitors (FEVE, 2011; Fuel Cell Today, 2011; Railway Gazette International, 2011). Hydrogen is stored in a cabinet inside the passenger compartment in 12 tanks at 200 bar holding 50 l of the gas, the maximum power is 120 kW, and speeds of 20 km/h to 30 km/h are reached (Fuel Cell Today, 2011; Sopena, 2011). However, the vehicle had not entered commercial service by 2013, to the author’s best knowledge.

Figure 25: FEVE Hydrogen Streetcar
(Railway Gazette International, 2011)

In-service operation of hydrogen-powered streetcars will begin on the Caribbean island of Aruba in 2013 (Englander, 2013). The heritage-style vehicles are powered by fuel cells and lithium batteries, which will allow regenerative braking (Goyjer, 2013). TIG/m, a company based in Los Angeles, CA, designed and manufactures the four streetcars, and the battery-only version has been in operation since December 2012 (Goyjer, 2013; TIG/m Modern Street Railways, 2012). Figure 26 shows the double-decked hydrogen-powered version for Aruba.

Figure 26: Double-Deck Hydrogen-Powered Streetcar for Aruba
Courtesy and Copyright TIG/m, 2013

The choice for hydrogen streetcars was made to support Aruba's goal to become carbon neutral, while avoiding wayside electrification infrastructure (TIG/m Modern Street Railways, 2012).

In summary, hydrogen-powered railway traction has been demonstrated in various service types, ranging from mining to streetcars to a switcher locomotive. Some of the vehicles have been operated in-service, while others were primarily research trains. However, all have in common that hydrogen is utilised in Proton Exchange Membrane fuel cells and stored as a gas, either in metal-hydrides or in compressed storage tanks. The evidence suggests that hydrogen drive-systems are suitable for railway traction, but further analysis is required to establish efficiencies, performance, and overall emissions.

2.3 Summary

Petroleum-derived products are, currently, the main source of energy for the transportation sector. But concerns about the economic availability of petroleum and worries about greenhouse gas emissions have prompted the development of alternatives. The energy carrier hydrogen has been identified by the automotive industry as the only long-term viable solution to these concerns. Hydrogen is abundant and non-toxic, while the combustion product with oxygen is water. Fuel cells, which combine hydrogen with oxygen to create electricity, are more efficient than combustion engines and, therefore, feature lower energy requirements, which aids the accommodation of storage tanks on-board the vehicles. However, the cost of fuel cells is currently high and price reductions are necessary. Also, a longer lifetime is desirable for applications other than cars.

Railways utilise two energy sources at present: electricity and diesel; and the liquid provides the majority of traction fuel on a global scale. Again, concerns about fuel availability, legislation demanding a reduction of point-of-use emissions, and the desire to decrease overall greenhouse gases require alternative propulsion systems for autonomous railway traction. Further, electrification is not economical for all routes and necessitates wayside infrastructure that has a visual impact; both supporting the exploration of alternatives for autonomous traction.

Hydrogen utilised in fuel cells seems a promising option and various railway prototypes have been demonstrated. The largest and most powerful railway-traction demonstrator is a hydrogen-hybrid switcher locomotive with a 250 kW fuel cell stack, which was tested in full service operation for approximately three months in 2009. A locomotive with double the fuel cell power is currently under construction and scheduled to be demonstrated later in 2013.

For any alternative propulsion fuel, it has to be established that reliance on petroleum is reduced and a decrease in emissions is achieved, while ensuring efficient operation of trains. In the next chapter, the author describes hydrogen production pathways and shows that the gas does not rely on petroleum. The chapter thereafter will establish efficiencies and carbon emissions of the incumbent energy systems and hydrogen traction to allow a comparison between them.

3 HYDROGEN SUPPLY

In the previous chapter it was highlighted that hydrogen has the potential to be used as a fuel for transportation services. However, the application of the energy carrier in the sector is not wide-spread at present, but hydrogen is used in other industries. In this chapter, the author first describes the production of hydrogen and its current main applications, followed by a discussion about hydrogen transportation and distribution. Third, on-board and off-board storage technologies are presented before a chapter summary is provided. The conversion efficiencies of the supply chain steps are not determined in the chapter but are treated separately in the next chapter.

3.1 Hydrogen Production

Hydrogen is an abundant element on Earth (Schlapbach & Züttel, 2001) and primarily occurs as a component of other substances, for example, water and hydrocarbons such as oil and coal, but rarely on its own as H_2 (U.S. DOE, 2008b). Therefore, it is necessary to invest energy to free the element from the compound, and thus, hydrogen is an energy carrier, like electricity, rather than an energy source (U.S. DOE, 2008b). In hydrogen production the energy source is often described as feedstock; some feedstocks and processes are shown in Figure 27. The figure does not show all options but only a selection of feedstocks to illustrate the variety of H_2 production possibilities. This is in contrast to conventional liquid fuels, such as gasoline and diesel, where the primary source is petroleum, and further exemplifies the similarity to electrical energy. Hydrogen and electricity as secondary energies have much in common (Winter, 2009) and, in the author's opinion, a comparison to an electric energy system can aid the understanding of the hydrogen supply chain and its role in the energy industry.

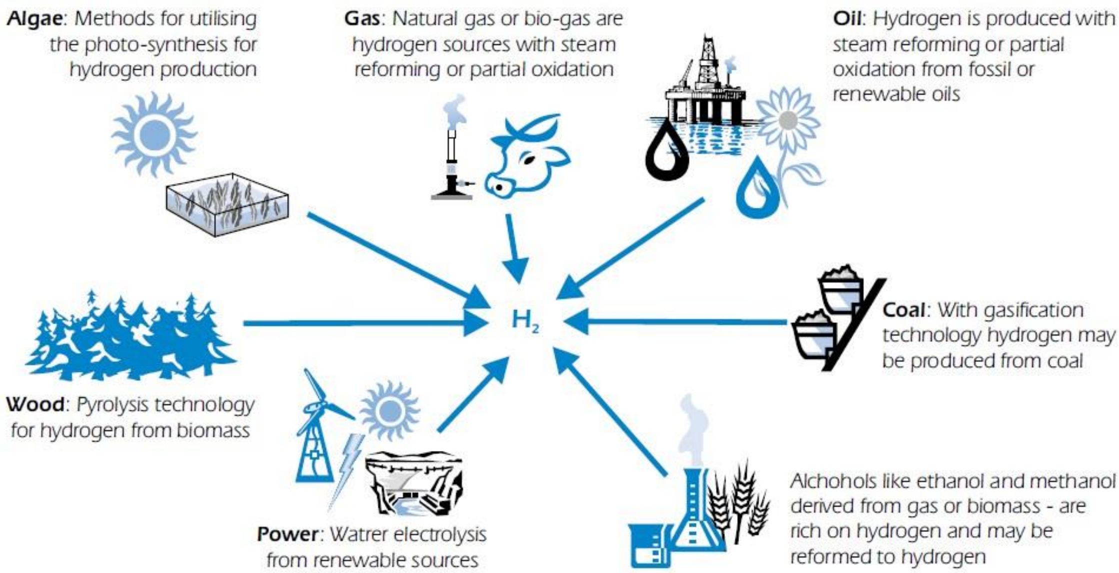


Figure 27: Selection of Hydrogen Feedstocks and Production Processes (IEA, 2006)

Electrolysis of water was the first method of commercially producing pure hydrogen, starting in the 1920s, but H_2 production shifted towards fossil fuel feedstocks in the latter half of the 20^{th} century, which remains the primary method today (IEA, 2006; National Research Council & National Academy of Engineering of the National Academies, 2004). Since the first decade of the current millennium the main feedstock for hydrogen is natural gas (Evers, 2008).

Today, about 50 million tonnes of hydrogen are produced annually (Zakkour & Cook, 2010) as a basis for other chemicals, for use in petroleum refining, or in other process areas, the first two being the most prominent, see Table 1.

Table 1: Hydrogen Production and Usage in 2008
(Zakkour & Cook, 2010)

Hydrogen Production		**Usage of Hydrogen**	
Feedstock	*Share in %*	*Use*	*Share in %*
Natural Gas	48	Ammonia Production	55
Petroleum	30	Petroleum Refining	25
Coal	18	Methanol Production	10
Electrolysis	4	Other	10
Total	100	Total	100

Hydrogen production methods and feedstocks vary, and are primarily determined by economic considerations of the geographical area and the usage of hydrogen (Lee, Yoo, Cha, Lim, & Hur, 2009). For example, in Korea about 50 % of H_2 is made from naphtha, a petroleum product (Lee, et al., 2009), whereas in the USA 95 % of hydrogen is sourced from methane contained in natural gas (U.S. DOE, 2010). A general process flow chart of hydrogen production is presented in Figure 28.

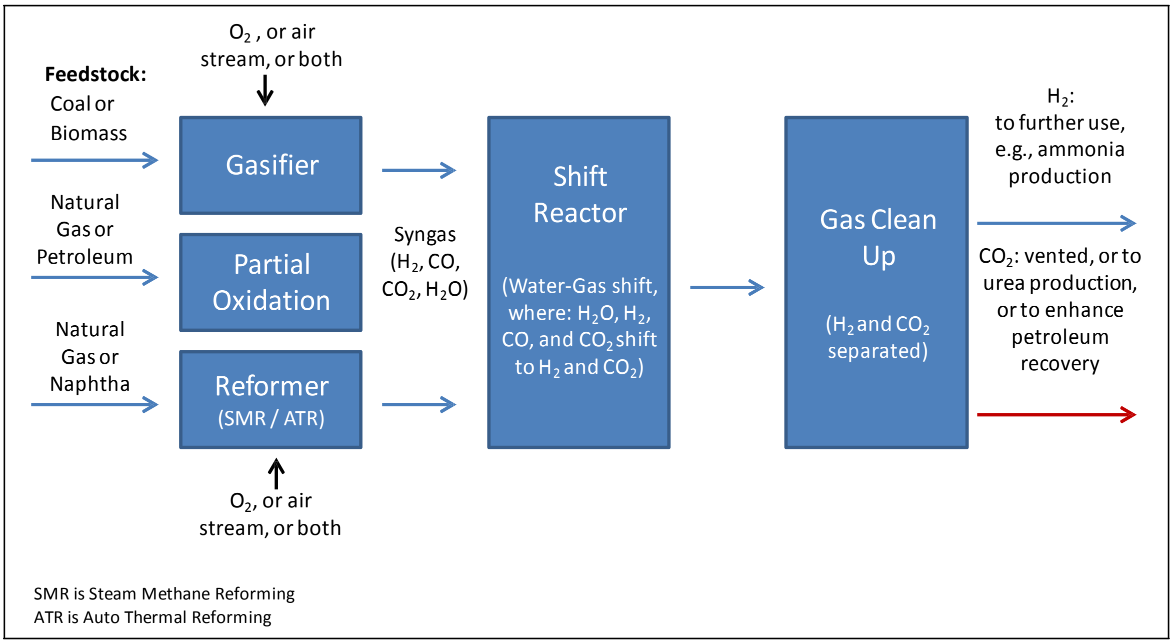


Figure 28: Generalised Process Flow for Hydrogen Production from Fossil Fuels (Zakkour & Cook, 2010)

It can be seen from Table 1 that the majority of hydrogen is used for the production of anhydrous ammonia, NH_3, which, in turn, is mainly employed as a fertiliser (Leighty & Holbrook, 2012; Zakkour & Cook, 2010). The second largest consumers of hydrogen are petroleum refineries, where H_2 is utilised to remove sulphur and nitrogen from petroleum, which is largely driven by regulations that limit the sulphur content in transportation fuels (Intergovernmental Panel on Climate Change, 2005; Zakkour & Cook, 2010). In both sectors the demand for hydrogen is increasing (Intergovernmental Panel on Climate Change, 2005).

The commercial production as well as the usage of hydrogen is, therefore, well understood and industrially implemented, and the same manufacturing methods could be employed for the production of an H_2 based transportation fuel. Some hydrogen production processes are discussed in more detail below, first, the current main feedstock processes and second, methods that are largely based on renewables are described.

3.1.1 Hydrogen Production from Fossil Fuel Feedstock

Steam Reforming

Steam reforming of natural gas or light hydrocarbons is the most popular way to produce hydrogen (Zakkour & Cook, 2010). The largest feedstock, as shown in Table 1, is natural gas, more specifically the methane within it, the process then being called steam methane reforming (SMR), (Intergovernmental Panel on Climate Change, 2005). Figure 29 shows an SMR plant. Another popular feedstock for steam reforming is naphtha, which is reformed from petroleum, and liquefied petroleum gas, both, therefore, falling under the second largest feedstock share (Lee, et al., 2009).

Lee, et al., (2009) show the chemical reactions for the aforementioned steam reforming feedstocks as follows:

SMR	$CH_4+2H_2O=CO_2+4H_2$	(1)
Naphtha steam reforming	$C_nH_{2n}+2nH_2O=nCO_2+3nH_2$	(2)
Liquefied petroleum gas steam reforming	$C_3H_8+6H_2O=3CO_2+10H_2$	(3)

Figure 29: Steam-Methane Reforming Plant
Courtesy and Copyright Air Products, 2012

The general process of hydrogen production through steam reforming is described below (IEA, 2006; Lee, et al., 2009; Zakkour & Cook, 2010): First, impurities in the feedstock are removed, e.g., sulphur. Then the hydrocarbon together with a catalyst, e.g., nickel, is introduced into a reformer to create synthesis gas. The necessary operating temperature of around 800°C to 900°C of this endothermic step is achieved through partial burning of the feedstock. Next, the synthesis gas is cooled, thereby creating high temperature steam of above 700°C, which is then injected into the reformer to crack the C-H bond. Also, the synthesis gas usually contains around 12 % carbon monoxide, which is converted through the exothermic water-gas shift, see below, to hydrogen and carbon dioxide. The last step is the separation of the H_2 and CO_2 gases.

Water-gas shift	$CO+H_2O=CO_2+H_2$	(4)

Partial Oxidation

In the partial oxidation process the fuel, for example, methane, is in part combusted with oxygen to create a synthesis gas that is rich in carbon monoxide and hydrogen (IEA, 2006). The synthesis gas is then converted to hydrogen and CO_2 through the water-gas shift described above (Zakkour & Cook, 2010). The process is exothermic and, therefore, a more compact design is possible compared to steam reforming (IEA, 2006). However, pure oxygen rather than air is required in the process, necessitating energy to separate the oxygen from the air; this is partially offset through the exothermic reaction of the oxidation process (Zakkour & Cook, 2010). Zakkour & Cook continue to write that partial oxidation is typically less efficient than SMR but is adaptable to a wider range of feedstocks.

Auto-thermal reforming

Auto-thermal reforming is a combination of partial oxidation and steam reforming. The overall process creates heat and the produced gases exit the reformer under pressure of up to 100 bar (IEA, 2006; Zakkour & Cook, 2010). Zakkour & Cook describe how partial oxidation provides the heat required for steam reforming in auto-thermal reforming. The created carbon monoxide is converted with the water-gas shift to hydrogen and CO_2 as in the other processes (IEA, 2006). The combination of both processes requires a larger plant, which in turn increases installation and operating costs. Further, the efficiency of auto-thermal reforming is lower than SMR, which is largely due to the energy requirements of the additional plant components (IEA, 2006; Zakkour & Cook, 2010).

Gasification

The gasification of a solid feedstock such as coal is similar to partial oxidation, but with the addition of steam (Zakkour & Cook, 2010); further, the process is endothermic (IEA, 2006). A synthesis gas high in hydrogen and carbon monoxide (CO) is produced and the CO is then converted through the water-gas shift process, described above, to CO_2 and H_2 (IEA, 2006; Zakkour & Cook, 2010). Various gasification processes exist but the most popular are entertained flow systems, as char formation can be reduced compared to other systems (IEA, 2006). The IEA shows the following typical gasification equation:

$$C+H_2O=CO+H_2 \tag{5}$$

Gasification of coal is fully commercialised but more complex than SMR, and the resulting hydrogen is usually more expensive (IEA, 2006).

All the fossil fuel based feedstock processes, including the ones described above, release carbon emissions in the process of hydrogen production, which is also illustrated in Figure 28. Therefore, although no carbon emissions are present at the point-of-use of hydrogen, the whole supply chain has to be considered to evaluate the possible carbon impact of H_2 as a fuel; this is determined in the next chapter. However, it may be easier to store the already-separated carbon at large hydrogen production plants, through carbon capture and storage, than in vehicles, thereby reducing the impact on the climate (Zakkour & Cook, 2010).

3.1.2 Hydrogen Production from Renewable Feedstock

Feedstock Biomass

Biomass in its various forms, ranging from wood over straw to sewage sludge, can be used for hydrogen production (Hornung, 2012; IEA, 2006). Hydrogen from biomass can be produced through gasification as described above (IEA, 2006) or through pyrolysis (Hornung, 2012). The attraction is that hydrogen can be created from waste products, such as sewage, close to large energy demand centres, such as cities. Further, this production method has the potential to remove carbon from the atmosphere and hold it in char and, therefore, may be described as carbon negative (Hornung, 2012). Hornung further explains that prototype plants are currently under construction in many areas, among them in Birmingham, UK, to demonstrate technical and commercial viability of this type of renewable hydrogen production. He suggests that hydrogen from biomass can be produced in 2013 at a cost of £2.40 per kg, with a possibility of cost reduction. In the UK, the equivalent energy contained in diesel, based on the high heating value (HHV, see well-to-wheel chapter) of both fuels (U.S. DOE, 2008a), would cost approximately £2.10 before taxes in the first quarter of 2013 (Fubra, 2013).

Water Electrolysis

Electrolysis of water is another method of hydrogen production (IEA, 2006). In this process an electric current is utilised to split water (U.S. DOE, 2010). The IEA (2006) writes that several types of electrolysers exist, such as proton exchange membrane electrolysers and alkaline electrolysers and, depending on the type, these operate at different temperatures, but all employ the same principle of using electrical energy to separate oxygen and hydrogen from the compound water. The process is, technically, the reverse of the electricity production process through fuel cells.

The required electrical energy can be provided from renewable sources, such as wind, solar, or hydro power plants. In these cases no carbon is released to free the $H_2$and, therefore, this is an attractive possibility to decarbonise transportation fuels (U.S. DOE, 2010). Further, it can offer energy storage for intermittent electrical energy production, which is discussed later in this chapter.

Thermo-chemical Water Splitting

The splitting of water can also be achieved through heat, either directly as water thermolysis or in a two-step thermo-chemical cycle (Xiao, Wu, & Li, 2012). The high temperature requirement of around 3 000°C (IEA, 2006), as well as the separation step of hydrogen and oxygen have prevented the large deployment of water thermolysis, so far (Xiao, et al., 2012). However, the two-step thermo-chemical process is possible now, because lower temperatures, below 927°C to 1727°C, are sufficient and hydrogen separation is easily achievable (Xiao, et al., 2012). In the thermo-chemical cycle a chemical, e.g., zinc, reacts with water to form an oxide, e.g., zinc oxide, and releases hydrogen, then the oxide is returned to its elementary stage, e.g., zinc, through heat (Haseli, Naterer, & Dincer, 2008; Steinfeld & Weimer, 2010; Xiao, et al., 2012). Thereafter, the cycle starts again. The necessary heat can be provided by various sources, such as solar concentration (Steinfeld, 2002) or nuclear power (Dincer, 2007). These processes are attractive because they are carbon free and the in-between step of electricity production can be avoided. However, no commercial hydrogen production plant based on the thermo-chemical process exists to date, although the technical feasibility and the potential for efficiencies of 50 % or higher are firmly established (IEA, 2006).

The processes mentioned above are not exhaustive but are included to illustrate the variety of hydrogen production pathways as well as to show the largest current feedstock sources and H_2 consumers. It is illustrated that hydrogen can be made from many different feedstocks, including various renewable sources and, therefore, diversification of production is possible, which is in contrast to petroleum based fuels, except bio-fuels that can be produced from coal or bio mass. Further, it is outlined that, at present, hydrogen is produced commercially for various applications and that the bulk of feedstocks is, currently, fossil fuel based – the majority being natural gas.

Many of the hydrogen production possibilities described above, particularly SMR and electrolysis, have been built at a scale suitable for refuelling sites (IEA, 2006; National Research Council & National Academy of Engineering of the National Academies, 2004; Perrin, 2007). For example: A small SMR plant at the vehicle refuelling station can be fed by a natural gas pipeline, or an electrolyser is built at the refuelling site. Both have been implemented at filling stations for road vehicles, and on-site generation of hydrogen, in addition to hydrogen delivered from central plants, was employed in a European-wide hydrogen bus demonstration project (HyFleet:Cute, 2009). On-site generation and centralised hydrogen production and delivery to refuelling sites are suitable options for railway vehicle refuelling. The particular method to be employed principally depends on the available infrastructure and economic considerations.

The next section describes the transportation and distribution of H_2 from central large production plants to customers, and the author focuses on the potential of hydrogen as a transportation fuel.

3.2 Hydrogen Transportation and Distribution

The hydrogen production section has shown that the majority of hydrogen is used for industrial processes and, thus, in large quantities. For this reason most hydrogen is transported through pipelines, for the entire distance or in part. If hydrogen is required in quantities that do not justify a pipeline, other methods of transportation are chosen, such as distribution by truck (Gillette & Kolpa, 2008). In this section the author describes the main transportation modes for hydrogen, many of which are closely linked with hydrogen storage, described in more detail in the hydrogen storage section. First, H_2 transportation through pipelines is discussed and, second, the other transportation possibilities are described.

3.2.1 Pipeline

The majority of hydrogen is used within industrial areas, as described above, and the individual sites are often linked with pressurised gas pipeline networks (Gillette & Kolpa, 2008), see Figure 30. Perrin (2007) mentions that pipelines have a share of more than two thirds of the merchant hydrogen transportation market. Pipeline transport of hydrogen has been practiced for a long time, for example since the 1930s in Germany (Winter, 2009).

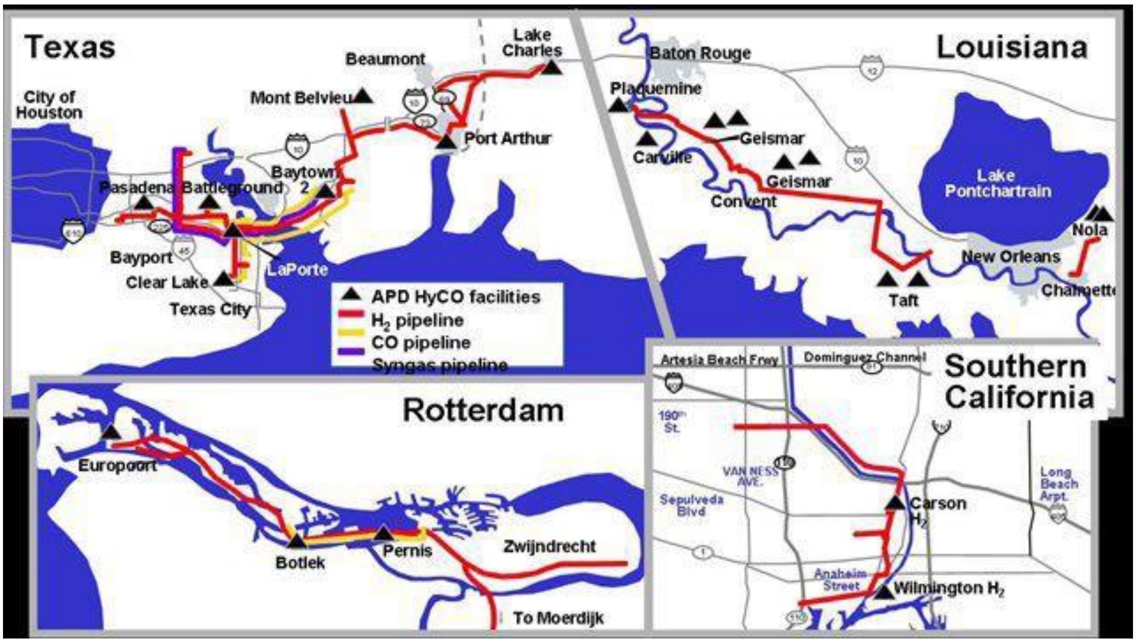
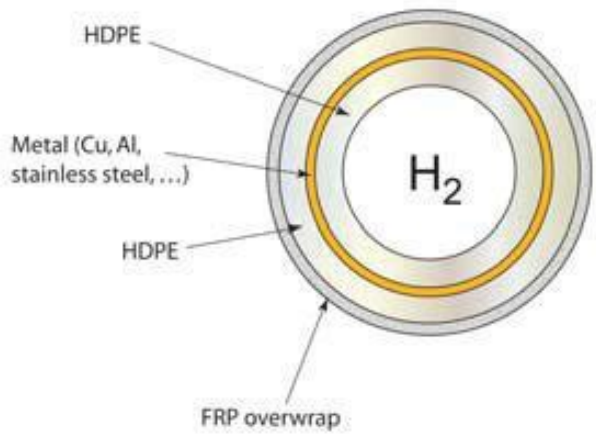


Figure 30: Example of Pipeline Networks in Industrial Areas
Hydrogen pipelines are shown in red (Miller, et al., 2009)

About 16 000 km of hydrogen pipeline exists' globally, but most sections are short; the longest being 400 km from Antwerp to Northern France (Intergovernmental Panel on Climate Change, 2005). However, if a whole distribution network is considered then the largest has a length of 964 km linking France, the Netherlands, and Belgium (Perrin, 2007). Perrin continues to explain that most of the pipelines have a diameter of 100 mm and that the operating pressure is up to 100 bar.

Traditionally, hydrogen pipelines are constructed of steel, but more recently, through the introduction of new materials, composites have become an attractive option but, so far, they have only been used for very short distances within industrial plants (Gillette & Kolpa, 2008). Figure 31 shows an example of a composite pipeline that is made primarily from plastics and a thin metal foil barrier that prevents embrittlement (Leighty & Holbrook, 2012). This type of pipe can be manufactured up to a diameter of one metre and in almost unlimited length.



HDPE is High-density polyethylene
FRP is Fibre-reinforced plastic

Figure 31: Composite Hydrogen Pipeline
(Leighty & Holbrook, 2012)

Gillette and Kolpa (2008) describe that at a given pressure hydrogen has about one-third of the energy density of natural gas, and that hydrogen flows three times as fast as natural gas at the same pipe diameter and pressure. Therefore, hydrogen pipeline sizes and requirements are similar to those of natural gas pipes with the same power rating

Gillette and Kolpa (2008) describe that for long distance transmission compression of the gas is necessary. To ensure that the pressure is sustained compressors are installed along the pipe. The typical spacing of compressors is between 70 km to 160 km for natural gas pipelines (Gillette & Kolpa, 2008). Further, Gillette and Kolpa write that the distances between compressors for hydrogen pipelines would be similar or greater and, therefore, fewer compressors may be needed for hydrogen transmission. Also, the capital cost of pipeline construction for natural gas and hydrogen is similar (Leighty, et al., 2006). In addition, Leighty, et al., suggest that hydrogen pressure-drop pipelines of 100 bar inlet pressure and 30 bar delivery pressure are possible for distances of up to 1 600 km. This could reduce the installation cost for moderate length pipelines compared to traditional compressor based systems.

The energy transportation capacity of pipelines carrying chemical fuels, such as hydrogen or natural gas is significant, see Figure 32. Centralised hydrogen production and distribution to major customers through pipelines, as currently practiced in the petro-chemical industry, could be employed for railway applications. The system would be similar to an electric system: Centralised, secondary energy production, and distribution to railway supply points, such as a sub-stations or refuelling sites. An illustration of the energy transport capacity of a 600 MW standard AC high voltage system and an equivalent hydrogen pipeline is presented in Figure 32.

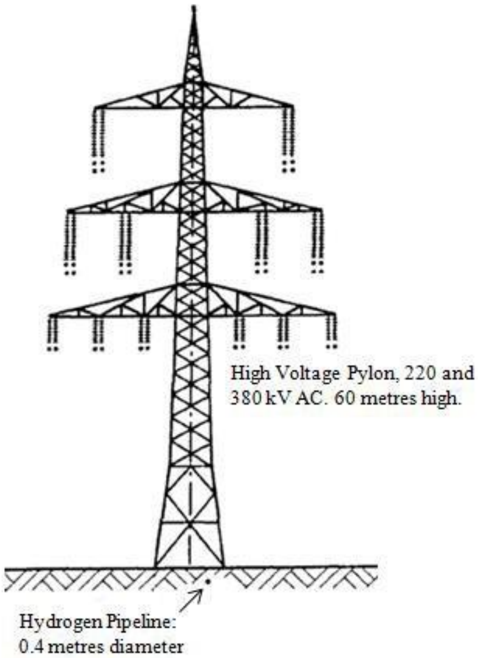


Figure 32: Energy Transport of 600 MW Drawing to Scale (Tetzlaff, 2008)

It can be seen from Figure 32 that the impact of a hydrogen pipeline may be lower than that of an electrical energy transportation system and that underground installation is possible. The distance over which energy is transported in such electricity lines is confined to a few hundred kilometres due to physical limitations and losses (Siemens, 2009). Further, Siemens outlines that for longer distances high voltage direct current lines would be employed. The comparison drawn between the electric and hydrogen systems is valid for short to medium distances, and the practical implementation of both has been demonstrated: high voltage alternating current throughout the world and hydrogen pipelines of up to 400 km in many parts of the world.

Less resistance from the population, particularly in urban areas or areas of natural beauty, may be encountered for underground pipeline construction and operation, compared to overland electricity distribution, so new projects might be implemented more quickly. More radical, scholars suggest the replacement of electricity transmission and distribution with gas based systems, due to the lower impact on the environment and the inherent storage capacity of a gas network (Tetzlaff, 2008). However, that discussion falls outside of the scope of the thesis and the comparison is included to show the similarities between the two energy carriers, electricity and hydrogen.

The following example shall illustrate central hydrogen production capacity, pipeline transportation, and railway refuelling; it is based on the author's research trip to Los Angeles, CA, in 2009:

Vehicle Projects Inc's Hydrogen-Hybrid Switcher locomotive was demonstrated, in collaboration with BNSF railway, in the Los Angeles basin (Los Angeles) in autumn 2009. The hydrogen for the trials was supplied by Air Products, which operates several SMR plants in Los Angeles as well as a hydrogen distribution network, which includes pipelines that serve petroleum refineries, see Figure 30. The hydrogen supplier stated that about 2 % of the current hydrogen production capacity in Los Angeles would allow the fuelling of the 200 switcher locomotives in the visited rail yard, and that a connection to the pipeline network would be possible. Further, at the time, the cost for hydrogen from the pipeline was between \$2 –3 per kg of H_2 (Miller, et al., 2011), while retail diesel costs were \$3 -4 per US gallon, (U.S. EIA, 2013). Thus, hydrogen was available at lower prices compared to diesel on an energy content basis. Today, the price difference would be greater, due to higher diesel prices and the falling cost for hydrogen caused by lower natural gas prices in North America.

The case study example shows that hydrogen production and distribution, as currently employed by the petro-chemical industry, can easily be adapted to the requirements of the railway industry and, further, that in certain areas hydrogen is available at competitive prices.

For the majority of railway refuelling sites, where hydrogen would not be generated on-site, connection by pipeline to hydrogen producers seems the most suitable option. However, in certain cases this might not be possible or economical, especially for demonstration projects or a small fleet. For these cases other distribution methods, which are currently employed to supply smaller quantities of hydrogen to customers (Perrin, 2007), may be more suitable and are discussed below.

3.2.2 Other Transportation and Distribution Options

Hydrogen, like other chemical fuels, can be transported in a storage medium on the road, railways, or boats. In general, transporting hydrogen utilising the various modes is similar, the main difference often being the quantity, for example, a road tanker is similar to, although smaller than, a tank car on the railways, and in the case of marine vessels the carrying capacity is larger. In this section the author describes the transportation and distribution of hydrogen in quantities that do not justify a pipeline, and, rather than describing every transport mode separately, the base situation is the transportation via truck on the road. If there are significant differences when other modes, such as marine or rail are utilised, this is mentioned in the text. The main states in which hydrogen is currently stored to be transported are: (1) in gaseous form and (2) in liquid state.

Transportation of Hydrogen as a Gas

Hydrogen can be stored under pressure in containers, like most gases. These cylinders, varying in pressure, discussed under hydrogen storage in this chapter, can be hauled. Depending on the hydrogen quantity required, the gas tanks have different sizes, ranging from about one metre to truck trailer length, about 16 metres. Pressurised hydrogen is often transported in a 200 bar tube trailer, 200 bar to 480 bar cylinder bundle, or a 500 bar dual-phase tanker (Williamson, 2011). The dual-phase tanker is described in more detail in the liquid section below, as it mainly transports hydrogen as a liquid. The 200 bar tube trailer that can be seen in Figure 33 was employed for the hydrogen switcher locomotive trials described earlier. Often the tube trailer cylinders are manufactured from steel, individual tanks or bundles are made from steel or composites (Perrin, 2007).

Figure 33: Hydrogen Distribution in a 200 bar Tube Trailer (Author’s Collection, 2009)

Cylinder bundles usually consist of several individual gas tanks, a single steel bottle, installed in a hydrogen locomotive, which is described later in the thesis, is shown in Figure 34. Cylinder bundles on a trailer are shown in Figure 35.

Figure 34: 200 bar Compressed Hydrogen Cylinder Installed in a Hydrogen Locomotive Courtesy and Copyright Jonathan Tutcher, 2012

Figure 35: Trailer With Compressed Gas Hydrogen Cylinders in Bundles (Perrin, 2007)

Hydrogen gas trailers have a capacity to carry between 180 kg and 540 kg of H_2, but require an almost 40 t tare load (Perrin, 2007). Transportation on the road as a pressurised gas is, therefore, only suitable for relatively short distances as the energy required to transport the heavy load is significant. Further, if large quantities of hydrogen are required and distribution over the road is desired, then transportation as a liquid is more suitable. On the railway as well as in marine transportation the mass of pressurised storage is less of an issue, due to the more favourable efficiency of these modes.

Transportation of Hydrogen as a Liquid

Hydrogen can be transported in its liquid state. Low temperatures of -253°C are required for hydrogen to stay in this state necessitating a super-insulated container (IEA, 2006). Further, the IEA describes that a significant amount of energy, about 30 % to 40 %, is lost in the liquefaction of hydrogen. The effect on the overall supply chain efficiency is considered in the well-to-wheel chapter later in the thesis. However, the advantage of liquid hydrogen is its larger energy density per unit of volume compared to compressed hydrogen: A super-insulated liquid hydrogen truck can transport up to 3750 kg of H_2, more than six times the quantity of a compressed gas trailer (Perrin, 2007); therefore, allowing fewer deliveries and enabling transportation over longer distances. The transportation via rail or ship of the super-insulated containers is similar to over-the-road movements and again requires less energy for a given distance as already described in the previous section.

Most of the hydrogen stored on-board vehicles has been in pressurised cylinders, as described in the previous chapter and, therefore, the conversion from liquid to gas form is necessary; a process that can take place at the filling station or, in the case of a dual-phase tanker, on the vehicle (Ahluwalia, Wang, et al., 2012). Air Products' dual-phase tanker delivering hydrogen to a filling station is shown in Figure 36. The tanker stores hydrogen primarily as a liquid but the refilling of fuelling stations is possible as a gas or liquid. The vaporisation of the liquid hydrogen takes place on-board the tanker.

Figure 36: Dual-Phase Tanker Delivering Hydrogen Gas to a Filling Station (Williamson, 2011)

The distribution of hydrogen is well-established and the main method employed is transportation in pressurised gaseous form through pipelines. Lower demand customers are usually supplied through tankers, either with liquid or pressurised hydrogen. All delivery options are suitable for railway fuelling applications, but the energy needs of fuelling a fleet of vehicles over the long term favours a pipeline connection, in the author's opinion. For demonstration projects suitable delivery arrangements are as a pressurised gas, as was the case for the Vehicle Projects trials in Los Angeles, or for a longer trial as a liquid. The next section describes hydrogen storage methods with a focus on on-board tanks.

3.3 Hydrogen Storage

Hydrogen can be stored in a variety of states, and the method employed is usually dependent on the quantity of storage required. In this section, the main storage options for hydrogen are described, with a focus on on-board storage for vehicles. The storage of hydrogen as a compound, such as ammonia, NH_3, that requires reformation to pure hydrogen is not covered because the emphasis of the research is on pure hydrogen, as already outlined in the introduction.

3.3.1 Storage as a Compressed Gas

Hydrogen is always produced as gas, as shown in the hydrogen productions section and, therefore, storage in its gaseous form is an obvious choice. However, the low volumetric density of hydrogen at atmospheric pressure requires compression to achieve acceptable tank sizes. Common pressures are 200 bar, 350 bar, and 700 bar (IEA, 2006; Williamson, 2011). In general, the move is towards higher pressures and 700 bar is currently favoured by the automotive industry due to the large quantity of hydrogen that can be stored (Bakker, 2010). However, at these high pressures hydrogen is outside the ideal gas region and a rise of pressure from 350 bar to 700 bar increases the energy content in the tank by 55 %, rather than 100 % (Hansen, Sato, & Yan, 2010). Hansen et al., continue to mention that 10 % additional energy is required for 700 bar compression compared to 350 bar, because most of the energy is used at lower pressures.

Hydrogen tanks are traditionally manufactured from steel and, for lower pressures, up to 200 bar, it is still the most common cylinder material (Winter, 2009), see Figure 34 and hydrogen transportation section, but composite tanks are becoming more common, especially for on-board storage, due to their lower mass (IEA, 2006). An illustration of a typical composite tank designed for on-board usage is shown in Figure 37.

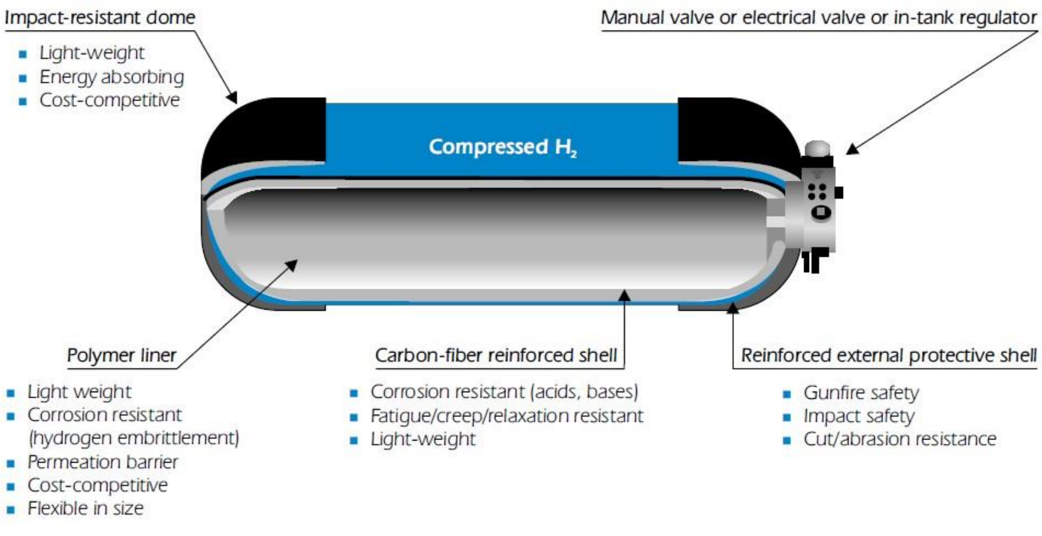


Figure 37: Schematic of a Typical Compressed Hydrogen Gas Composite Tank (IEA, 2006)

Hydrogen storage as a compressed gas is appealing because the state of the element does not have to change: production as a gas released at a pressure, transportation in a pressurised pipeline, and on-board storage as a gas. However, the delivery pressure of a pipeline or most over-the-road transportation options are lower than the tank pressure and, therefore, additional compression at the filling station is necessary (Kampitsch, 2012; Wang, 2003). The effect on the efficiency of the supply chain is presented in the well-to-wheel chapter. The energy density of a 700 bar compressed hydrogen storage tank is high compared to batteries, as shown in Table 2. Currently, the only commercialised technology for on-board storage of hydrogen is compressed gas (Kunze & Kircher, 2012).

Table 2: Comparison of 700 bar Compressed Hydrogen Storage with Batteries (Von Helmolt & Eberle, 2007)

	Hydrogen in 700 bar tank	Lead-Acid Battery	Nickel-metal hydride battery)	Lithium-Ion Battery
Specific Energy (Wh/kg)	1 600	35	70	120
Energy Density (Wh/l)	770	70	140	150
Mass of Storage System (kg)	125	2 860	1 430	830
Volume of Storage System (l)	260	1 430	710	670
Estimated Cost at volume production (USD)*	3 600	15 000	30 000	40 000

*Excludes fuel cell system

However, the energy density per volume is still low compared to other hydrogen storage options, such as liquid storage. For railway applications the required volume may be less of an issue than for automobiles, because of the available spaces; this is particularly true for power-cars and locomotives. A more detailed feasibility evaluation is provided later in the thesis.

3.3.2 Storage as a Liquid

Hydrogen becomes a liquid at a cryogenic temperature of -253°C (IEA, 2006). Handling any material at such temperatures presents challenges and super-insulated tanks are necessary. The main advantage of storing hydrogen as a liquid is the reduced volume required, compared to compressed storage options (Perrin, 2007), which is of particular interest for vehicle applications where space is scarce. Liquid hydrogen storage has been employed in demonstrator automotive applications, particularly by BMW, where the liquid hydrogen was utilised in a combustion engine (Kunze & Kircher, 2012; Schlapbach & Züttel, 2001). An on-board storage tank that holds liquid hydrogen is shown in Figure 38.

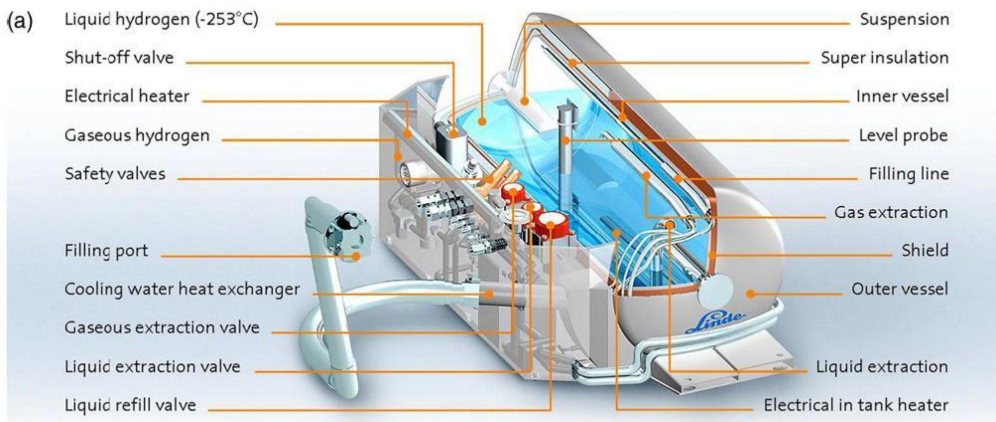


Figure 38: Liquid Hydrogen Tank for On-Board Storage (Von Helmolt & Eberle, 2007)

Hydrogen must be vented from liquid storage tanks due to the boil-off effect. This exists because heat from the surroundings leaks into the tank and causes the liquid hydrogen to vaporise, which results in a pressure increase in the vessel. Therefore, to prevent damage to the tank, the pressurised hydrogen is vented (Ahluwalia, Hua, & Peng, 2012; Von Helmolt & Eberle, 2007; Züttel, 2003).

The high energy requirements to liquefy hydrogen, together with the boil-off rates, have prevented this technology from wide-spread adoption (IEA, 2006; Züttel, 2003) and have led to the development of cryo-compressed storage (Ahluwalia, Hua, et al., 2012; Kampitsch, 2012). Storage of hydrogen as a liquid for railway applications is in principle possible (Miller, Hess, & Barnes, 2007), but the issues described above make this solution less attractive than competing storage technologies.

3.3.3 Cryo-Compressed Storage

The compressed storage of hydrogen at cryogenic temperatures combines liquid and pressurised storage and, therefore, a pressure tank that can withstand the low temperatures is needed (Aceves, et al., 2010). An example of a cryo-compressed tank is BMW’s vessel: 7.8 kg of hydrogen stored at a tank mass of 145 kg and in a space of 235 l (Kunze & Kircher, 2012), see Figure 39 for an illustration.

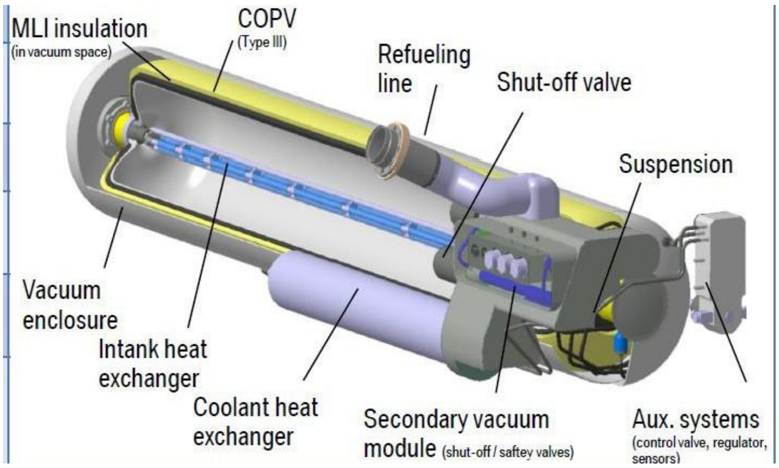


Figure 39: Cryo-Compressed Tank as Used by BMV (Kunze & Kircher, 2012)

Aceves, et al. (2010) write that cryo-compressed systems weigh less and are more compact than 350 bar or 700 bar systems at ambient temperature for the same storage quantity of hydrogen. Cryo-compressed tanks and associated filling stations are currently in the development phase (Kampitsch, 2012) and many inadequacies of liquid storage, such as boil-off, are being overcome (Ahluwalia, Hua, et al., 2012). Kampitsch (2012) mentions that the energy requirements for hydrogen liquefaction and subsequent use in cryo-compressed on-board cylinders are almost the same as the inefficiencies that occur in compressed gas distribution and compression for on-board use. In railway vehicles cryo-compressed storage could be implemented in a similar manner to automobiles. The reduced volume requirements make the option an attractive choice and the implementation decision of the technology is most likely determined on economic considerations.

3.3.4 Storage in Solids

Hydrogen interacts, can be absorbed, and bonds with other materials or elements for storage purposes, and volumetric densities that are higher than liquid hydrogen can be achieved (Ott, Simpson, & Klebanoff, 2012). There are many different materials that have the potential to be used for hydrogen storage (Ahluwalia, Hua, et al., 2012). However, most are still in the research phase (IEA, 2006; Kunze & Kircher, 2012).

Promising materials for hydrogen storage can be grouped into four categories (Yang, Sudik, Wolverton, & Siegel, 2010, p. 659): “(1) conventional metal hydrides, (2) complex hydrides, (3) sorbents, and (4) chemical hydrides.” The same source continues to explain that conventional metal hydrides store hydrogen through the reaction with a metal or metal alloy to form a metal hydride, and these have received the largest research effort. Complex hydrides are “ionic hydrogen-containing compounds which are composed of metal cations ... and hydrogen-containing ‘complex’ anions such as borohydrides (BH_4^-), alanates (AlH_4^-) and amides (NH_2^-)” (Yang, et al., 2010, p. 660). Sorbents are carbon and other high surface materials such as metal oxide frameworks (IEA, 2006). Chemical hydrides are compounds that appear in solid or liquid form and prominent examples are ammonia borane and sodium borohydride (Yang, et al., 2010). Also, Yang et al., mention that chemical hydrides are meant for single-use, meaning that the by- product left after the reaction has to be removed from the tank for off-board processing.

All hydride technologies require cooling when filled and heating when discharging hydrogen (IEA, 2006). In general, hydrides offer high density hydrogen storage but at the cost of a considerable mass, which makes them less suitable for light vehicles, such as cars (Harris, 2012; Züttel, 2003). The various hydride materials and the associated hydrogen storage reactions are not further discussed in the thesis, as the focus is on the application of hydrogen as a fuel, and hydrides function solely as an option for storage. They are primarily treated as a material within a tank, with specific dimensions and mass, which can receive and release hydrogen.

The heat exchange necessary during charging and discharging has implications for filling times and the maximum of five minutes for car refuelling remains a challenge for hydride storage (IEA, 2006; Kunze & Kircher, 2012). Despite all of these challenges hydrides may be used for on-board storage of hydrogen in railway vehicles and, indeed, the first hydrogen-powered locomotive in 2002 had a metal hydride tank (Miller, et al., 2009). Other vehicles followed (Miller, et al., 2012), including the locomotive developed at the University of Birmingham, which can operate with hydride or compressed gas storage, as described later in the thesis.

The high mass of hydrides and the longer refuelling time may be less of an issue for railway applications than for automobiles, but the type of railway vehicle, its design, and the service it operates will have a significant impact on that decision; for example, relatively small mining locomotives can be heavy, whereas multiple units should be light. Also, hydrides have a perceived safety advantage, as high pressures can be avoided and the hydrogen release rate is limited, should a leak occur. For the safety conscious railway industry these advantages may outweigh the drawbacks of hydrides in certain applications.

3.3.5 Comparison of On-Board Storage Technologies

The main on-board storage technologies described above have their respective advantages and disadvantages, and the main considerations for the tank systems are mass and volume (Ahluwalia, Hua, et al., 2012). Figure 40 shows the mass and volume of various storage system options that hold 6 kg of hydrogen.

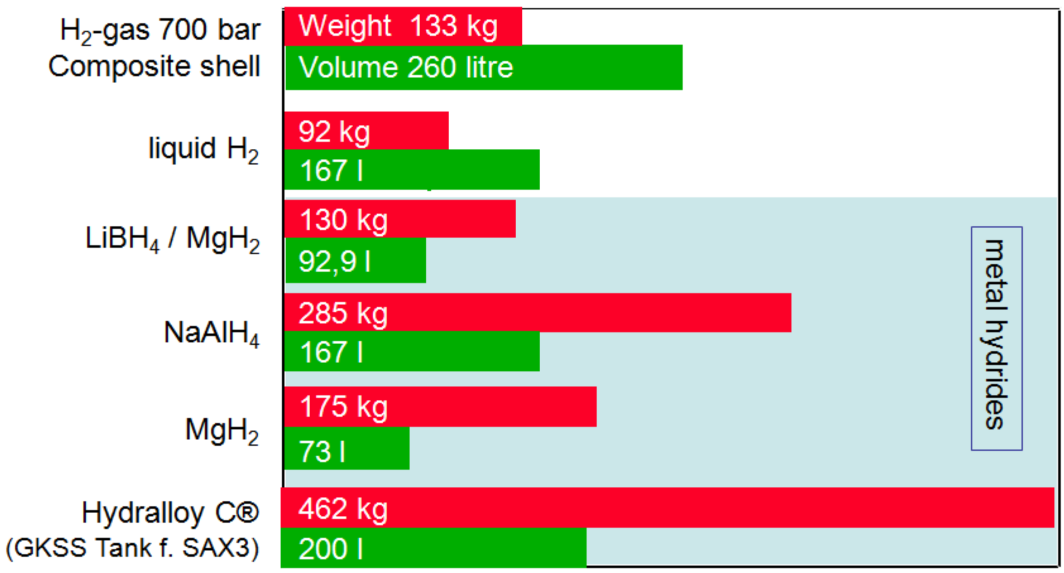


Figure 40: Comparison of Volume and Mass Required to Store 6 kg of Hydrogen (Steinberger-Wilckens & Pour, 2012)

Figure 40 illustrates the high mass of hydride systems and the large volume for compressed storage. Further, the mass and volume advantages of liquid storage are apparent. However, none of the hydrogen storage options are close to the convenient energy storage in traditional petroleum based fuels on a tank system volume and mass basis, and metal hydrides cannot meet the refuelling time either. Currently, the only commercialised option is that of compressed hydrogen tanks (Kunze & Kircher, 2012). The storage option that is closest in performance to traditional fuel tanks is cryo-compressed, very similar to liquid storage in Figure 40, and commercialisation is expected within the next few years (Kampitsch, 2012).

All on-board storage systems can be employed as off-board storage, for example, compressed gas cylinders in a gas storage area. If large quantities have to be stored at a single point, such as for space shuttle refilling, then the liquid option seems to be the preferred choice (Kampitsch, 2012; Schlapbach & Züttel, 2001; Winter, 2009). In cases where the storage location is not determined by the customer, other options for storage are available, such as the pipeline system itself (Müller, Geng, Völkl, & Arlt, 2012; Tetzlaff, 2008) or underground storage in caverns.

3.3.6 Large-Scale Storage in Caverns

Energy storage in large quantities is presently undertaken in tanks for liquid fuels, in underground caverns for natural gas, and in pumped-hydro stations for electricity (Andrews & Shabani, 2012; Müller, et al., 2012). Hydrogen can be stored underground in caverns in a similar way to natural gas (Ozarslan, 2012) and this type of hydrogen storage has been practiced in the UK and the USA by the petro-chemical industry for decades (Andrews & Shabani, 2012; Leighty, 2008). An illustration of such an underground compressed hydrogen storage facility is presented in Figure 41.

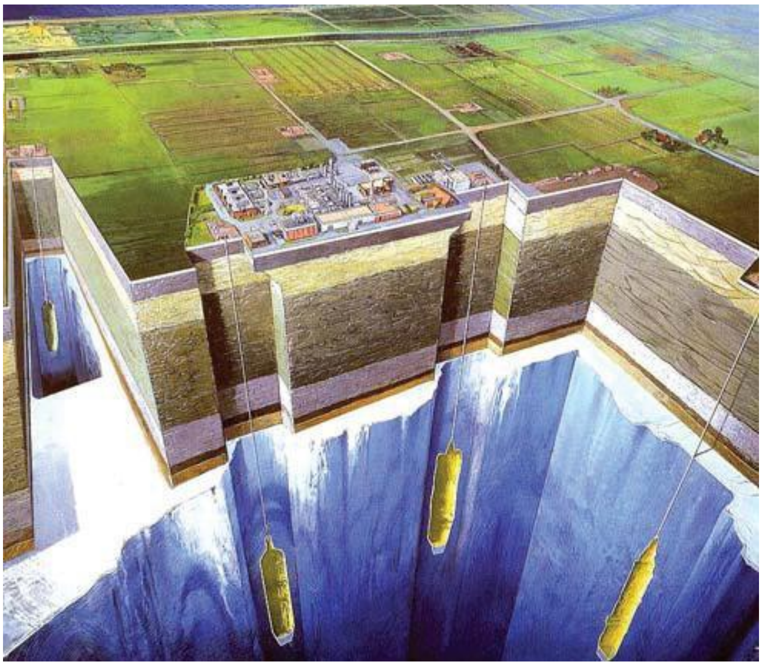


Figure 41: Illustration of Underground Compressed Gas Hydrogen Storage (Leighty & Holbrook, 2012)

Additional storage facilities are planned in several countries, such as Germany (Andrews & Shabani, 2012), primarily to store hydrogen generated through wind power. A wind-power to hydrogen plant for energy storage was opened in Germany in 2011, and one of the project partners was German Railways, recognising the importance of large-scale energy storage from renewables to enable dispatchable electricity for distribution to railway operations (Deutsche Bahn AG, 2011). The author suggests that the produced hydrogen could be directly used as a fuel in autonomous railway vehicles, which would improve the carbon footprint of these, as demonstrated in the well-to-wheel chapter. Hydrogen from this plant is already available as a fuel for road vehicles (Deutsche Bahn AG, 2011), so the step to autonomous rail vehicle refuelling is not large.

Hydrogen as an Energy Storage Medium

Underground hydrogen energy storage capacity is significant and exceeds the underground storage capability for compressed air and pumped-hydro (Müller, et al., 2012). Large-scale storage of energy is indispensible if sizeable contributions of renewable power generation, such as wind and solar, are to be employed and dispatchable electricity is needed (Andrews & Shabani, 2012). Hydrogen is the only large-scale capable energy carrier, except for hydrogen-based ammonia, which can store energy over long periods of time, such as months and years, while allowing the instant conversion to electricity and, therefore, making the power of renewable energy sources dispatchable (Andrews & Shabani, 2012; Leighty, 2008; Müller, et al., 2012; Ozarslan, 2012). Therefore, generation of hydrogen from renewables will increase and additional underground storage facilities are likely to be constructed. The hydrogen that has been produced and stored can also be used to fuel railway vehicles directly, rather than being converted to electricity on-site and thereafter transmitted via the electric grid.

3.4 Summary

Hydrogen is an abundant element on Earth but normally occurs in compounds such as water, and, therefore energy has to be invested to create pure hydrogen. In many respects hydrogen is similar to electricity, which is also a secondary energy.

The majority of hydrogen is produced through the steam reforming of natural gas, and the other main sources are petroleum and coal. H_2 is always created as a gas. Green hydrogen can be created from many renewable sources: Biomass, Water-Electrolysis of renewable energy sources such as wind and solar, and thermolysis of water through a heat source. The primary consumers of hydrogen are the fertilizer industry to create ammonia and the petro-chemical industry for use in petroleum refining. The vast majority of hydrogen is transported in pressurised pipelines, often linking production sites to large consumers such as refineries. Otherwise, hydrogen can be transported in storage vessels: as pressurised gas or as a liquid, generally in truck trailers.

Small-scale storage options, for on-board use, include: pressurised gas in cylinders; liquid hydrogen at cryogenic temperatures; cryo-compressed hydrogen in which a pressurised tank is cooled to cryogenic temperatures, therefore being a combination of afore mentioned options; and storage in solids, such as metal hydrides.

Liquid on-board storage has largely been superseded by cryo-compressed storage, where many of the disadvantages of liquid storage have been overcome. The highest volumetric and gravimetric densities are currently achieved with this storage option. However, the energy required to liquefy hydrogen has a negative impact on the supply chain efficiency.

In principle all on-board storage options are suitable for railway vehicles, and compressed gas as well as hydride storage has been demonstrated.

Hydrogen production, transportation, and storage are well established for industrial customers, and hydrogen as a fuel source for transportation is becoming more popular. The established industrial supply chain could be adapted for railway refuelling sites and competitive prices for the infrastructure can be expected, owing to the mature competitive industrial merchant hydrogen market that includes several large suppliers, such as Air Products, Linde, and Air Liquide, which are able to provide standardised supply solutions. Also, the on-board storage technologies currently used in the automotive sector are technically suitable for railway use.

However, if hydrogen is to be used as a railway fuel a more detailed study about appropriate supply and storage has to be conducted, which will also depend on the amount of vehicles to be refuelled. For a demonstration project, delivery as compressed gas, as already practiced for rail demonstrators, or as a liquid are conceivable; whereas for longer term use delivery as a liquid or a pipeline connection may be preferred.

In evaluating the feasibility of hydrogen as a railway fuel it is necessary to establish the efficiency of the supply chain as well as the carbon impact, otherwise no meaningful comparison to the established technologies, electric- and diesel-traction, can be drawn. The supply chain efficiency, the vehicle efficiency, and the carbon emissions associated with diesel- and electric- traction as well as various hydrogen options for railway traction are determined in the next chapter.

4 WELL-TO-WHEEL ANALYSIS

In this chapter, a well-to-wheel analysis for railway traction vehicles and their energy supply chain is conducted. It is an expanded version of the studies that resulted in the paper, published in *Transportation Research Part D: Transport and Environment*, that is attached in Appendix C, for which the author was the primary contributor as well as the lead author. In the first part of the chapter the author explains the well-to-wheel (WTW) method and sets the study boundaries. Then, the vehicle efficiency for the studied propulsion systems is determined. In the third part, the well-to-tank parameters for electricity, diesel, and hydrogen supply in the year 2008 are determined. The fourth part combines the vehicle efficiency and the supply chain efficiency to compute the WTW efficiencies for the various systems.. The fifth part focuses on renewable energy WTW parameters for the energy carriers hydrogen and electricity. In the final part a summary is provided.

4.1 Method and Boundaries

A WTW analysis is an approach that considers the energy consumption and greenhouse gas emissions associated with entire production pathways and drive train systems. A WTW analysis includes the energy use and greenhouse gas emissions that occur at every stage of the process, from the original source (well) to the energy delivery at the wheels (wheel) (Wang, 2002). It is usually split into two stages: (1) The well-to-tank or fuel cycle stage, and (2) the tank-to-wheel or vehicle efficiency stage (TIAX LLC, 2007). This split is useful as the same type of fuel may be utilised to power vehicles with different drive-systems. In the conducted analysis, the WTW computations for fossil-fuel based fuels start with one kWh at the wheels of the vehicle and are calculated backwards through the supply chain up to fossil fuel recovery; this system has been chosen to incorporate the various emissions that result from the combustion of fossil fuels.

The renewables calculations start at the original source (well) with 100 %, for example, the solar radiation available on given area disposed perpendicular to the rays is set as 100 %.Efficiencies are computed forward through the supply chain resulting in an efficiency value that is lower than 100 %. This approach is chosen to ensure a consistent representation of the efficiency values for both fossil fuels and renewables. In the renewables case the energy values did not have to be presented in absolute numbers, such as kWh, as no carbon emissions associated with the energy conversion takes place and, hence, the relative losses in percent provide the data required.

The boundary for primary energy is, therefore, different for renewables and fossil fuels: The conversion efficiency from solar energy, through photosynthesis to form biomass and, consequently, fossil fuels, such as coal and oil, is not included, whereas for renewables one accounts for the conversion efficiency, for example, from solar to electricity or wind to electricity or water flow to electricity. This approach is consistent with other studies (A. Evans, Strezov, & Evans, 2010b), and the author is of the opinion that including photosynthesis in a WTW analysis is not useful in accounting for resource depletion, as fossil fuels are already formed. Other studies choose to account for this in setting the electricity output of renewables as 100 % (Brinkman, et al., 2005; L-B-Systemtechnik GmbH, 2002), so the boundary is the same as for fossil fuels. However, in WTW studies it is usual to set different boundaries for primary energy (Brinkman, et al., 2005), and the author chose for the conducted analysis to treat fossil fuels in the same way as natural resources like wind and solar energy. This choice is rooted in practicality as "...high levels of waste associated with an inefficient process are unsustainable" (A. Evans, et al., 2010b, p. 5), and the resource requirements for renewables, such as land take are real, whereas it is unusual to set land aside specifically to create petroleum or mineral coal, given the very long timeframe for their creation.

Two economic regions, the UK and the US, and the specific case of California are considered in this study and have been chosen for the following reasons: The UK, for the relatively low share of railway electrification compared to other EU member states, and the USA, due to the reliance on autonomous traction and the low likelihood of large-scale railway electrification. California was included due to the stringent emission standards and the high contribution of renewable energy sources in the electricity mix.

4.1.1 Heating Values

A chemical fuel has commonly two heating values associated with its enthalpy and free-energy values: (1) The higher heating value (HHV) and (2) the lower heating value (LHV).

The HHV assumes that all substances are brought back to the original temperature after combustion, usually 25°C, and includes in particular the condensation of all vapours, such as water. Therefore, the latent heat of the vaporisation of water is included in the HHV (U.S. DOE, 2008a).

The LHV assumes that water is in its vapour state after the combustion of the fuel, and that no latent heat of vaporisation of water is included in the heating value, therefore, the energy to vaporise water is not recovered as heat (Wang, 1999a). Thus, a higher value is obtained for HHV because the heat of condensation of the water contributes to the net enthalpy.

The LHV approach is commonly used for WTW analyses and is recommended by Wang (1999a), the UK Department for Environment, Food and Rural Affairs, as well as the UK Department of Energy and Climate Change (AEA, 2009). However, calculations in LHV can occasionally lead to efficiencies above 100 %, for example, to 105 % for some condensing boilers, which is physically impossible (Bossel, 2003). This is not the case when the HHV is used. The HHV is consistent with the laws of thermodynamics and presents efficiencies in physically correct numbers. For this reason calculations and results have also been presented in HHV. The conversion between the two heating values has been carried out on the basis that the quantity of fuel (mass, volume) does not change. Heating values are only relevant for chemical energy carriers or fuels and not for electricity or mechanical conversions.

In contrast to heat engines, the natural form of energy to consider for electrochemical power devices, such as fuel cells, is the Gibbs free energy, ΔG. This is true because both the change in enthalpy ΔH and the change in entropy ΔS of an electrochemical reaction can be driving forces of the device. Most heat engines, such as combustion engines, cannot be driven by ΔS, so their efficiency stays the same regardless of using ΔG or ΔH. Free energy, enthalpy, and entropy are related by the Gibbs equation:

(6)

Where G is Gibbs free energy, H is enthalpy, T is the absolute temperature at which the reaction occurs, and S is entropy.

This notwithstanding, because most of the data in the literature are in terms of enthalpy, the energy calculations in this document are based on the change in enthalpy, ΔH. As indicated by the Gibbs equation above, ΔG can be calculated from ΔH if the entropy is known or can be estimated.

Table 3 shows the LHV and HHV for various fuels, and the corresponding CO_2 emissions. The original emission data is given in LHV and has been converted to HHV.

The emission from a nuclear power-plant is high-level radioactive waste and the quantity has been taken as 0.01 g per kWh (Department of Energy and Climate Change 2008a), but it has not been possible to associate a relevant environmental impact with the nuclear waste.

In all cases of energy conversion heat is produced as part of the process, which could be considered an emission. It is often not fully recoverable, as described with the heating values. Heat has to be managed to prevent damage of equipment and frequently cooling mechanisms are employed in energy conversion plants, for example, cooling towers at power-plants or radiators in combustion engine vehicles. For railways the management of the heat created from traction equipment can be problematic, for example, in long enclosed spaces such as underground networks. However, in this study the management of heat is not specifically considered but included in the auxiliary value of the traction equipment when the vehicle efficiency is determined.

Table 3: LHV and HHV of Fuels and Their CO_2 Content

Fuel	LHV (MJ/kg)[b]	HHV (MJ/kg)[b]	HHV/ LHV	LHV/ HHV	LHV CO_2 (kg/kWh)[c]	HHV CO_2 (kg/kWh)
Gaseous Fuels at 0°C (32°F) and 1 atm						
Natural Gas	47.141	52.225	1.108	0.903	0.203	0.183
Hydrogen	120.21	142.18	1.183	0.845	0	0
Liquid Fuels						
Crude Oil[a]	42.686	45.543	1.067	0.937	0.279	0.261
Diesel	42.791	45.766	1.07	0.935	0.263	0.246
Liquid Hydrogen	120.07	141.8	1.181	0.847	0	0
Residual Oil[a]	39.466	42.21	1.07	0.935	0.279	0.261
Solid Fuels						
Coal (wet basis)	22.732	23.968	1.054	0.948	0.326	0.309

[a]Emissions based on fuel oil
[b]U.S. DOE (2008a)
[c]AEA (2009)

In Table 3, the ratio between the HHV and the LHV and vice versa is included to show the factors that were applied to convert from one heating value to the other. The reason is that the data presented in the literature is not consistent and conversions were required to present the well-to-wheel efficiency, corresponding emissions, and associated supply chain using both heating values.

4.1.2 Assumptions

The method, and consequently the results in the conducted WTW analysis are based on the following assumptions:

- Carbon Dioxide (CO_2) emissions and high-level nuclear waste are considered emissions - any other greenhouse gas emissions are not considered.
- The CO_2 content of the fuels is based on UK data. It has been assumed that all regions use the same fuel types.
- The efficiencies of UK electricity generation power-plants have been used for the US and California.
- The well-to-tank diesel fuel cycle and the well-to-tank natural gas-based hydrogen cycle are based on American data and have been used for the UK.
- The calculations are based on inputs from various years. It is assumed that these figures are still representative. Innovation and improvements may have increased efficiencies and a reduction in emissions is achieved. But the efficiencies of large plants, such as power-plants and refineries, do not tend to change significantly over a few years horizon.
- Regenerative braking is not considered, because currently it is not utilised widely, except when the railway network is electrified. And the analysis is aimed at comparing autonomous traction options and wayside energy supply reliant options However, regenerative braking could be included in the analysis by adjusting the vehicle efficiency.
- The vehicle efficiency for diesel and electric traction has been calculated using standard values obtained from literature. The Internal Combustion Engine (ICE), diesel and hydrogen, is assumed to work at its highest efficiency.

- The hydrogen fuel cell power-plant efficiency is based on operational tests of a hydrogen-hybrid switcher locomotive during trials in Los Angeles.
- The renewable mix in California is determined with the assumption that the efficiencies for biomass and geothermal power are based on the LHV.
- Electrical transmission losses in the power grid are based on the UK and have been used for the US and California.

4.2 Vehicle Efficiency

In this section the vehicle efficiency is calculated and in the next section the fuel-cycle efficiency is determined.

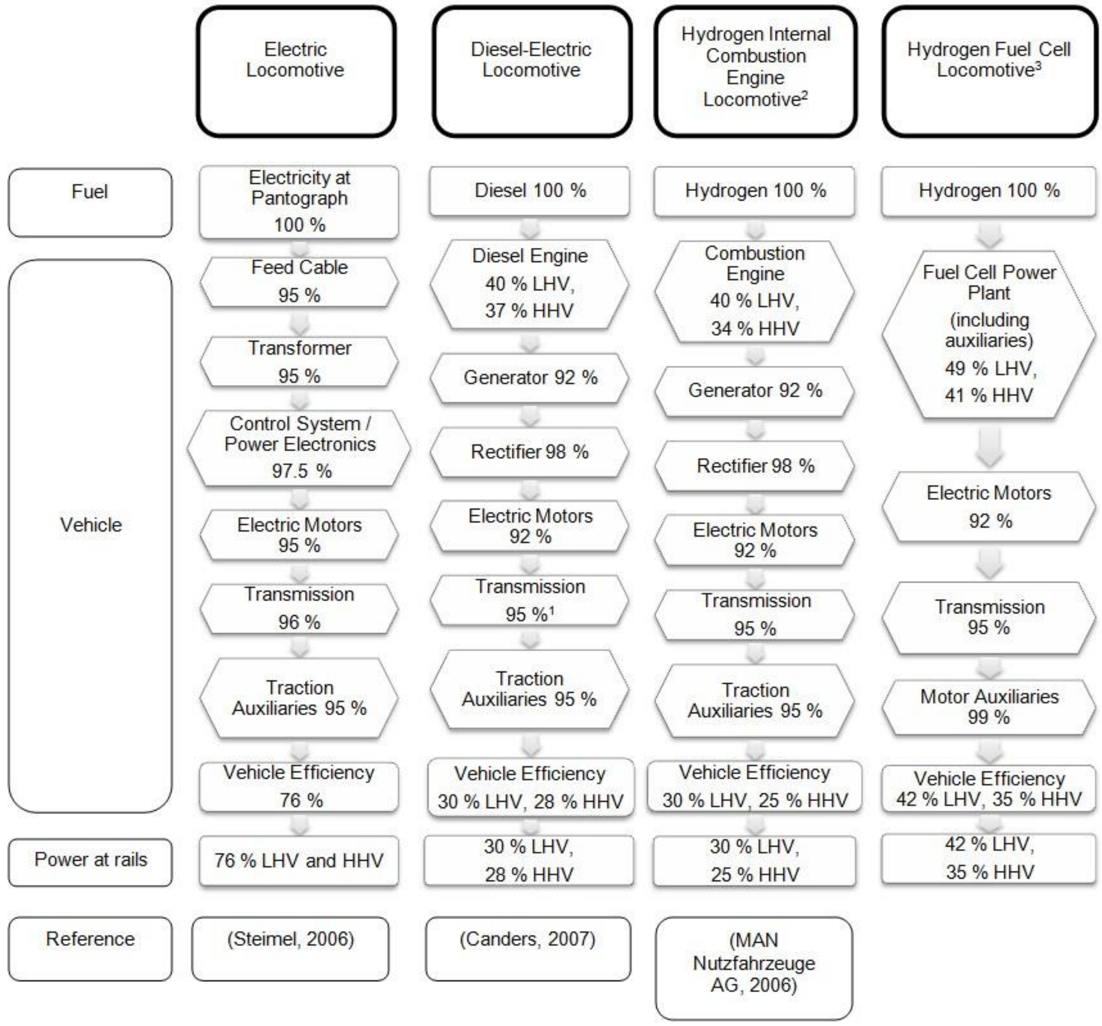
The vehicle efficiency of a traction unit is determined by how the energy that enters the vehicle is converted into traction work. The electric traction efficiency is based on an electric locomotive that is fed from a catenary line while diesel traction is based on a diesel-electric locomotive.

Hydrogen can either be burned in an ICE or used in a fuel cell, as mentioned. All existing railway traction prototypes use Proton Exchange Membrane fuel cells. Therefore, fuel cell traction employs fuel cell stacks as the vehicle's power-plant. Below are the vehicle efficiencies for both types.

The fuel cell power-plant efficiency has been established by test runs of the hydrogen switcher (shunter) of Vehicle Projects Inc (Miller, et al., 2010). This locomotive does not use regenerative braking, like electric and diesel traction in this analysis, and has been chosen for that reason. The efficiency has been established in full service operation over a period of several months. Its power-plant efficiency is 49 % LHV and 41 % HHV. Based on Gibbs free energy, the respective power-plant efficiencies are 51 % and 50 %. Japanese test runs of hydrogen-powered railcars that use regenerative braking have shown similar power-plant efficiencies of approximately 50 % LHV (Yamamoto, et al., 2010). However, these tests were not conducted during in-service operation but on a test track that is less than 1 km long. For this reason, the power-plant efficiency of the American locomotive has been chosen for this study.

MAN builds hydrogen ICEs for buses, which principally work like an Otto engine, with a maximum efficiency of 40 % LHV (MAN Nutzfahrzeuge AG, 2006). For the hydrogen combustion engine locomotive a similar drive system to the diesel-electric locomotive is assumed and the only change is the substitution of the diesel engine by a hydrogen engine while the rest of the drive system is not altered. Figure 42 shows the efficiencies for various forms of traction. Traction auxiliaries are assumed to consume 5 % of the energy available (Steimel, 2006) and include, for example, cooling equipment and compressors, therefore, a factor of 95 % has been applied to compute the vehicle efficiency in Figure 42.

All the vehicle efficiencies are based on the maximum efficiency that a traction system might reach, rather than the duty cycle efficiency, which can be substantially lower (UIC, 2003). In addition, the efficiencies present typical values for existing traction equipment. Higher efficiencies for particular components, for example, fuel cells, as mentioned (Daimler AG, 2009a; Schwarzer, 2012), or the whole drive-system have been achieved in specific trains (J. Evans, 2010; UIC, 2003).



Notes:

[1]Canders (2007) does not consider auxiliaries; the auxiliary value from Steimel (2006) of 95 % has been added.

[2]The Hydrogen ICE Locomotive does not exist. MAN produced hydrogen internal combustion engines for buses. In this comparison this engine substituted the diesel engine.

[3]For the fuel cell locomotive, only the fuel cell power-plant efficiency was determined. It is built from a diesel-electric locomotive, therefore, the efficiency chain from a diesel has been used. Auxiliaries, such as ventilation and cooling of the fuel cell stack, are already included in the power-plant efficiency, so the auxiliary value at the end of the chain is motor-specific and accounts, for example, for traction motor cooling.

Figure 42: Vehicle Efficiencies

The main conversion loss of energy occurs in the transfer from chemical energy into a different form. The vehicle efficiency of the electric locomotive is high in comparison, as the conversion from chemical to electrical energy already occurred at the electricity generation plants. The high efficiency of the fuel cell can directly be seen in the energy efficiency of the fuel cell locomotive. The lower efficiencies in the combustion engine cases are due to the inherent conversion steps: chemical energy to thermal energy to mechanical energy and last to electrical energy, whereas in a fuel cell there is only one stage: chemical to electrical energy (National Fuel Cell Research Center, 2009).

4.3 Well-to-Tank Analysis

The other main part of WTW analysis is to establish the losses from the original energy source (well) to the tank of the vehicle.

4.3.1 Recovery and Transport

All fossil fuels have to be recovered, extracted, and transported to a processing plant. The efficiencies for this first step are given in Table 4. Renewable sources such as solar, wind, and hydro do not have to be extracted and transported to the plant as the plant is located at the source and, therefore, the efficiencies for renewables are assumed to be 100 %.

Table 4: Recovery and Transport Efficiencies

Source	**Efficiency in %**		**Reference**
	LHV	HHV*	
Coal	99	99	(Wang, 1999a)
Uranium	95	95	(Wang, 1999a), this includes enrichment
Natural Gas	95	95	(Wang, 2003)
Petroleum	96	96	(Wang, 2003)

*The HHV has been calculated from the LHV values and the difference, between both, for each fuel is less than 1 %; when the figures are rounded no difference is present.

4.3.2 Emissions

The burning of fossil fuels releases emissions. One of the major greenhouse gases is CO_2, as mentioned. Nuclear power-plants produce radioactive waste, which has to be safely stored and is considered to be damaging to the environment, and is therefore shown in this analysis as an emission. The CO_2 emissions for each fuel and the high-level radioactive waste are shown in Table 3.

4.3.3 Electric System

The electric railway power system has several energy conversion stages. First the fuel, for example, coal has to be recovered, then it is transported to the power-plant, where it is converted into electricity. This electricity is then transmitted using the national grid, and as the last step, the electricity is conducted via the railway electrification infrastructure to the traction units' collection point.

Generation Efficiency

Most countries have a mix of electricity generation plants. Depending on source used, the generation plants emit CO_2 emissions, generate radioactive waste, or need specific geographical features, such as a river.

The electric power generation splits for the UK, the USA, and California in the year 2008 are shown in Table 5. The efficiency figures have been calculated from the data presented in the DUKES 5.6 (Department of Energy and Climate Change, 2008b). The energy efficiency for renewables has been assumed to be 35 %, which is based on wind turbines (A. Evans, et al., 2010b; Muyeen, Tamura, & Murata, 2008). The hydro efficiency is assumed to be 90 % (E.ON AG, 2010). Efficiencies have been assumed to be the same for all areas, with the exception of the renewable mix for California, which is shown in Table 6. In general, load factors of the various power-plants have not been considered, for example, a solar energy plant does not convert energy at night, and only the efficiency of the conversion process is included. The reason is that load factors depend on various factors, such as fuel availability or geographic region. The efficiency does not change dramatically when the plant is in operation, except for the case of solar energy plants, which are treated separately in the renewables section of the chapter.

Table 5: Electricity Generation Mix 2008

Area	**Source**	**Share in %**	**Efficiency in %**		
			LHV	**HHV**	
United Kingdom	Renewables	3[a]	35[b]	35[b]	
	Hydro	1[a]	90[c]	90[c]	
	Nuclear	14[a]	34	34[a]	
	Natural gas	47[a]	51	46[a]	
	Coal	34[a]	36	34[a]	
	Other	1[a]	24	22[a]	
	Total	100	~ 41	~ 39	Weighted Mean See Table 11
United States	Renewables	3[d]	35[b]	35[b]	
	Hydro	6[d]	90[c]	90[c]	
	Nuclear	20[d]	34	34[a]	
	Natural gas	21[d]	51	46[a]	
	Coal	48[d]	36	34[a]	
	Other	2[d]	24	22[a]	
	Total	100	~ 39	~ 37	Weighted Mean See Table 12
California	Renewables	10[e]	31	31	See Table 6
	Hydro	11[e]	90[c]	90[c]	
	Nuclear	15[e]	34	34[a]	
	Natural gas	46[e]	51	46[a]	
	Coal	18[e]	36	34[a]	
	Total	100	~ 44	~ 41	Weighted Mean See Table 13

[a]Department of Energy and Climate Change (2008b)
[b]A. Evans, et al. (2010b) and (Muyeen, et al., 2008)
[c]E.ON AG (2010)
[d]U.S. EIA (2008)
[e]Nyberg (2008)

Table 6: California Renewables 2008

Source	Share in %[a]	Efficiency in %		Weighted Efficiency in %	
		LHV	HHV	LHV	HHV
Biomass	20	27[b]	24[b]	5.4	4.8
Geothermal	42	13.5	13.5[c]	5.67	5.67
Small scale hydro	13	90	90[d]	11.7	11.7
Solar	2	20	20[e]	0.4	0.4
Wind	23	35	35[f]	8.05	8.05
Total	100			~ 31	~ 31

[a]Nyberg (2008)
[b]A. Evans, Strezov, and Evans (2010a). The authors of the paper do not state if the efficiencies are based on the LHV or the HHV, it is assumed that the LHV was used.
[c]Barbier (2002)
[d]E.ON AG (2010)
[e]Seitz (2010)
[f]A. Evans, et al. (2010b) and Muyeen, et al. (2008)

Electrical Transmission

The public power transmission system in the UK delivers about 93 % of the electricity generated from power-plants to the public power outlet, in the railways case public supply substations (Department of Energy and Climate Change, 2008c).

The railway transmission system losses are between 5 % and 10 % (UIC & CER, 2008), therefore, an efficiency of 92.5 % is used for the railways electricity transmission system.

4.3.4 Diesel

The fuel cycle efficiency for diesel fuel is presented in this section. The figures are based on American calculations and the same figures have been used for European efficiencies. Further, it is assumed that the figures have not significantly changed since their publication. The diesel efficiency chain up to the tank is presented in Table 7.

Table 7: Diesel Well-to-Tank Efficiency

Stage	Efficiency in %		Reference
	LHV	**HHV**[2]	
Petroleum in the ground	100	100	
Recovery and transport	96	96	(Wang, 2003)
Refining to diesel	90	90	(Wang, 2008)
Transport and Storage of diesel[1]	99.5	99.5	(Wang, 2003)
Total	85.5	85.5	

[1]Assumed to be the same as for petrol
[2]The HHV efficiencies have been calculated from the LHV efficiencies

4.3.5 Hydrogen

The well-to-tank chains for hydrogen, distributed as a gas or as a liquid, are shown in Table 8 and Table 9. The original source for hydrogen production in these calculations is natural gas because, currently, most of the hydrogen produced is derived from natural gas, as mentioned in the hydrogen supply chapter. The hydrogen is assumed to be produced in central plants and then distributed to the filling stations. Further, it is assumed that the figures have not significantly changed since their publication. Other production pathways for hydrogen are discussed later in this section.

Table 8: Hydrogen Gas Well-to-Tank Efficiency

Stage	Efficiency in %		Reference
	LHV	**HHV**[2]	
Natural Gas in the ground	100	100	-
Recovery and transport of Natural Gas	95	95	(Wang, 2003)
Reforming to hydrogen at a Central Plant to hydrogen gas (H_2)	71.5	76	
Transport via Pipeline	96	96	
Compression at refuelling station[1]	89.5	89.5	
Total	58	62	

[1]Based on a natural gas compressor. An electric compressor has an efficiency of 95 %
[2]The HHV efficiencies have been calculated from the LHV efficiencies

Table 9: Liquefied Hydrogen Well-to-Tank Efficiency

Stage	Efficiency in %		Reference
	LHV	HHV[1]	
Natural gas in the ground	100	100	-
Recovery and transport of natural gas	95	95	(Wang, 2003)
Reforming to hydrogen at a Central Plant to hydrogen gas (H_2)	71.5	76	
Liquefaction	71	71	
Transport	98.9	98.9	
Total	48	51	

[1]The HHV efficiencies have been calculated from the LHV efficiencies

4.4 Well-to-Wheel

The combination of the well-to-tank and the vehicle efficiency parameters allows the calculation of the WTW efficiency. First, the calculations for electric, diesel, and hydrogen traction are shown; this is followed by Figure 43 and Figure 44, which present the comparison of the three systems. In the third part, the analysis for renewables is presented.

4.4.1 Electric System

It is assumed that the vehicle efficiencies and the transmissions systems have the same efficiency in each region. The energy required from generation for each region is therefore the same, namely, 1.53 kWh, which is calculated in Table 10.

Table 10: Energy Required From Generation

Stage	Efficiency %	Energy Required kWh
Energy at Wheels		1
Vehicle Efficiency	76	1.316
Transmission Railway Network	92.5	1.422
Transmission National Grid	93	1.53
Energy needed from generation		**1.53**

The recovery and transport of uranium for nuclear, coal, and other energy sources releases CO_2, and diesel emissions have been included for these fuels as it is assumed that the resources are mainly transported with modes that burn diesel for propulsion, such as ships and rail. Natural gas is assumed to be mainly transported by pipeline and, therefore, the corresponding CO_2 emissions have been included in recovery and transport.

Table 11, Table 12, and Table 13 show the WTW efficiencies for electric traction in the areas UK, USA and California. The efficiency calculations start with one kWh at the wheels, further all considered emissions are calculated in the tables.

Table 11: UK Electric Traction, Overall Efficiency, and CO_2 Emissions (2008)

LHV

	Generation						Recovery and Transport (R&T)				Overall				
	Part of Production %[1]	Part of Production kWh	Efficiency (LHV)[1] %	Energy Generation kWh	CO_2 Factor (LHV)[2] kg/kWh	CO_2 Generation kg	R&T (LHV)[3] %	R&T Energy kWh	CO_2 Factor (LHV)[4] kg/kWh	CO_2 R&T kg	Overall Energy kWh	Overall CO_2 kg	Radio-active Waste[2] g/kWh	Overall Radio-active Waste g	Overall Efficiency (LHV) %
Renewables	3	0.046	35	0.131	0	0	100	0	0	0	0.131	0			
Hydro	1	0.015	90	0.017	0	0	100	0	0	0	0.017	0			
Nuclear	14	0.214	34	0.63	0	0	95	0.033	0.263	0.009	0.663	0.009	0.01	0.0063	
Natural Gas	47	0.719	51	1.41	0.203	0.286	95	0.074	0.203	0.015	1.484	0.301			
Coal	34	0.52	36	1.445	0.326	0.471	99	0.015	0.263	0.004	1.46	0.475			
Other	1	0.015	24	0.064	0.279	0.018	96	0.003	0.263	0.001	0.067	0.019			
Total	**100**	**1.53**[5]	**41.4**	**3.697**		**0.775**		**0.125**		**0.028**	**3.822**	**0.804**		**0.0063**	**26**

HHV

	Generation						Recovery and Transport (R&T)				Overall				
	Part of Production %[1]	Part of Production kWh	Efficiency (HHV)[1] %	Energy Generation kWh	CO_2 Factor (HHV)[2] kg/kWh	CO_2 Generation kg	R&T (HHV)[3] %	R&T Energy kWh	CO_2 Factor (HHV)[4] kg/kWh	CO_2 R&T kg	Overall Energy kWh	Overall CO_2 kg	Radio-active Waste[2] g/kWh	Overall Radio-active Waste g	Overall Efficiency (HHV) %
Renewables	3	0.046	35	0.131	0	0	100	0	0	0	0.131	0			
Hydro	1	0.015	90	0.017	0	0	100	0	0	0	0.017	0			
Nuclear	14	0.214	34	0.63	0	0	95	0.033	0.246	0.008	0.663	0.008	0.01	0.0063	
Natural Gas	47	0.719	46	1.563	0.183	0.286	95	0.082	0.183	0.015	1.645	0.301			
Coal	34	0.52	34	1.53	0.309	0.473	99	0.015	0.246	0.004	1.545	0.477			
Other	1	0.015	22	0.07	0.261	0.018	96	0.003	0.246	0.001	0.073	0.019			
Total	**100**	**1.53**[5]	**38.8**	**3.941**		**0.777**		**0.133**		**0.028**	**4.074**	**0.805**		**0.0063**	**25**

[1]See Table 5
[2]See Table 3
[3]See Table 4
[4]See Electric System
[5]See Table 10

Table 12: USA Electric Traction, Overall Efficiency, and CO_2 Emissions (2008)

LHV

	Generation						Recovery and Transport (R&T)				Overall				
	Part of Production %[1]	Part of Production kWh	Efficiency (LHV)[1] %	Energy Generation kWh	CO_2 Factor (LHV)[2] kg/kWh	CO_2 Generation kg	R&T (LHV)[3] %	R&T Energy kWh	CO_2 Factor (LHV)[4] kg/kWh	CO_2 R&T kg	Overall Energy kWh	Overall CO_2 kg	Radio-active Waste[2] g/kWh	Overall Radio-active Waste g	Overall Efficiency (LHV) %
Renewables	3	0.046	35	0.131	0	0	100	0	0	0	0.131	0			
Hydro	6	0.092	90	0.102	0	0	100	0	0	0	0.102	0			
Nuclear	20	0.306	34	0.9	0	0	95	0.047	0.263	0.012	0.947	0.012	0.01	0.009	
Natural Gas	21	0.321	51	0.63	0.203	0.128	95	0.033	0.203	0.007	0.663	0.135			
Coal	48	0.734	36	2.04	0.326	0.665	99	0.021	0.263	0.006	2.061	0.671			
Other	2	0.031	24	0.128	0.279	0.036	96	0.005	0.263	0.001	0.133	0.037			
Total	**100**	**1.53[5]**	**38.9**	**3.931**		**0.829**		**0.106**		**0.026**	**4.037**	**0.855**		**0.009**	**25**

HHV

	Generation						Recovery and Transport (R&T)				Overall				
	Part of Production %[1]	Part of Production kWh	Efficiency (HHV)[1] %	Energy Generation kWh	CO_2 Factor (HHV)[2] kg/kWh	CO_2 Generation kg	R&T (HHV)[3] %	R&T Energy kWh	CO_2 Factor (HHV)[4] kg/kWh	CO_2 R&T kg	Overall Energy kWh	Overall CO_2 kg	Radio-active Waste[2] g/kWh	Overall Radio-active Waste g	Overall Efficiency (HHV) %
Renewables	3	0.046	35	0.131	0	0	100	0	0	0	0.131	0			
Hydro	6	0.092	90	0.102	0	0	100	0	0	0	0.102	0			
Nuclear	20	0.306	34	0.9	0	0	95	0.047	0.246	0.012	0.947	0.012	0.01	0.009	
Natural Gas	21	0.321	46	0.698	0.183	0.128	95	0.037	0.183	0.007	0.735	0.135			
Coal	48	0.734	34	2.16	0.309	0.667	99	0.022	0.246	0.005	2.182	0.672			
Other	2	0.031	22	0.139	0.261	0.036	96	0.006	0.246	0.001	0.145	0.037			
Total	**100**	**1.53[5]**	**37**	**4.13**		**0.831**		**0.112**		**0.025**	**4.242**	**0.856**		**0.009**	**24**

[1]See Table 5
[2]See Table 3
[3]See Table 4
[4]See Electric System
[5]See Table 10

Table 13: California Electric Traction, Overall Efficiency, and CO_2 Emissions (2008)

LHV

	Generation						Recovery and Transport (R&T)				Overall				
	Part of Production %[1]	**Part of Production kWh**	**Efficiency (LHV)[1] %**	**Energy Generation kWh**	**CO_2 Factor (LHV)[2] kg/kWh**	**CO_2 Generation kg**	**R&T (LHV)[3] %**	**R&T Energy kWh**	**CO_2 Factor (LHV)[4] kg/kWh**	**CO_2 R&T kg**	**Overall Energy kWh**	**Overall CO_2 kg**	**Radio-active Waste[2] g/kWh**	**Overall Radio-active Waste g**	**Overall Efficiency (LHV) %**
Renewables	10	0.153	31	0.494	0	0	100	0	0	0	0.494	0			
Hydro	11	0.168	90	0.187	0	0	100	0	0	0	0.187	0			
Nuclear	15	0.23	34	0.675	0	0	95	0.036	0.263	0.009	0.711	0.009	0.01	0.0068	
Natural Gas	46	0.704	51	1.38	0.203	0.28	95	0.073	0.203	0.015	1.453	0.295			
Coal	18	0.275	36	0.765	0.326	0.249	99	0.008	0.263	0.002	0.773	0.251			
Total	**100**	**1.53[5]**	**43.7**	**3.501**		**0.529**		**0.117**		**0.026**	**3.618**	**0.555**		**0.0068**	**28**

HHV

	Generation						Recovery and Transport (R&T)				Overall				
	Part of Production %[1]	**Part of Production kWh**	**Efficiency (HHV)[1] %**	**Energy Generation kWh**	**CO_2 Factor (HHV)[2] kg/kWh**	**CO_2 Generation kg**	**R&T (HHV)[3] %**	**R&T Energy kWh**	**CO_2 Factor (HHV)[4] kg/kWh**	**CO_2 R&T kg**	**Overall Energy kWh**	**Overall CO_2 kg**	**Radio-active Waste[2] g/kWh**	**Overall Radio-active Waste g**	**Overall Efficiency (HHV) %**
Renewables	10	0.153	31	0.494	0	0	100	0	0	0	0.494	0			
Hydro	11	0.168	90	0.187	0	0	100	0	0	0	0.187	0			
Nuclear	15	0.23	34	0.675	0	0	95	0.036	0.246	0.009	0.711	0.009	0.01	0.0068	
Natural Gas	46	0.704	46	1.53	0.183	0.28	95	0.081	0.183	0.015	1.611	0.295			
Coal	18	0.275	34	0.81	0.309	0.25	99	0.008	0.246	0.002	0.818	0.252			
Total	**100**	**1.53[5]**	**41.4**	**3.696**		**0.53**		**0.125**		**0.026**	**3.821**	**0.556**		**0.0068**	**26**

[1]See Table 5
[2]See Table 3
[3]See Table 4
[4]See Electric System
[5]See Table 10

4.4.2 Diesel System

The WTW efficiency for diesel traction, starting with one kWh at the wheels, including CO_2 emissions, is shown in Table 14.

Table 14: Diesel Traction Efficiency and CO_2 Emissions in 2008

LHV

Stage	**Efficiency (LHV) %**	**Energy Required kWh**	**CO_2 kg/kWh**	**Overall CO_2 kg**
Energy at Wheels		1		
Vehicle Efficiency[1]	30	3.333		
Transport and Storage[2]	99.5	3.35		
Refinery[2]	90	3.722		
Recovery and transport[2]	96	3.877	0.263	1.02
Total	**26**	**3.877**		**1.02**

HHV

Stage	**Efficiency (HHV) %**	**Energy Required kWh**	**CO_2 kg/kWh**	**Overall CO_2 kg**
Energy at Wheels		1		
Vehicle Efficiency[1]	28	3.571		
Transport and Storage[2]	99.5	3.589		
Refinery[2]	90	3.988		
Recovery and transport[2]	96	4.154	0.246	1.02
Total	**24**	**4.145**		**1.02**

[1]See Figure 42
[2]See Table 7

4.4.3 Hydrogen System

Table 15 and Table 16 display the WTW efficiency and CO_2 emissions for gaseous hydrogen traction, starting with one kWh at the wheels. The same parameters are used in Table 17 and Table 18 for liquid hydrogen.

Table 15: Gaseous Hydrogen, Fuel Cell, ICE, Overall Efficiency, and CO_2 Emissions (LHV)

LHV, FUEL CELL

Stage	Efficiency (LHV) %	Energy Required kWh	CO_2 kg/kWh	Overall CO_2 kg
Energy at Wheels		1		
Vehicle Efficiency[1]	42	2.381		
Plant to Tank[2]	86	2.769		
Hydrogen Generation[2]	71.5	3.873		
Recovery and transport of Natural Gas[2]	95	4.077	0.203	0.828
Total	**25**	**4.077**		**0.828**

LHV, ICE

Stage	Efficiency (LHV) %	Energy Required kWh	CO_2 kg/kWh	Overall CO_2 kg
Energy at Wheels		1		
Vehicle Efficiency[1]	30	3.333		
Plant to Tank[2]	86	3.876		
Hydrogen Generation[2]	71.5	5.421		
Recovery and transport of Natural Gas[2]	95	5.706	0.203	1.158
Total	**18**	**5.706**		**1.158**

[1]See Figure 42
[2]See Table 8

Table 16: Gaseous Hydrogen, Fuel Cell, ICE, Overall Efficiency, and CO_2 Emissions (HHV)

HHV, FUEL CELL

Stage	**Efficiency (HHV) %**	**Energy Required kWh**	**CO_2 kg/kWh**	**Overall CO_2 kg**
Energy at Wheels		1		
Vehicle Efficiency[1]	35	2.857		
Plant to Tank[2]	86	3.322		
Hydrogen Generation[2]	76.3	4.354		
Recovery and transport of Natural Gas[2]	95	4.583	0.183	0.839
Total	**22**	**4.583**		**0.839**

HHV, ICE

Stage	**Efficiency (HHV) %**	**Energy Required kWh**	**CO_2 kg/kWh**	**Overall CO_2 kg**
Energy at Wheels		1		
Vehicle Efficiency[1]	25	4		
Plant to Tank[2]	86	4.651		
Hydrogen Generation[2]	76.3	6.096		
Recovery and transport of Natural Gas[2]	95	6.417	0.183	1.174
Total	**16**	**6.417**		**1.174**

[1]See Figure 42
[2]See Table 8

Table 17: Liquid Hydrogen, Overall Efficiency, and CO_2 Emissions (LHV)

LHV, FUEL CELL

Stage	Efficiency (LHV) %	Energy Required kWh	CO_2 kg/kWh	Overall CO_2 kg
Energy at Wheels		1		
Vehicle Efficiency[1]	42	2.381		
Plant to Tank[2]	70.2	3.392		
Hydrogen Generation[2]	71.5	4.744		
Recovery and transport of Natural Gas[2]	95	4.994	0.203	1.014
Total	**20**	**4.994**		**1.014**

LHV, ICE

Stage	Efficiency (LHV) %	Energy Required kWh	CO_2 kg/kWh	Overall CO_2 kg
Energy at Wheels		1		
Vehicle Efficiency[1]	30	3.333		
Plant to Tank[2]	70.2	4.748		
Hydrogen Generation[2]	71.5	6.641		
Recovery and transport of Natural Gas[2]	95	6.991	0.203	1.419
Total	**14**	**6.991**		**1.419**

[1]See Figure 42
[2]See Table 9

Table 18: Liquid Hydrogen, Overall Efficiency, and CO_2 Emissions (HHV)

HHV, FUEL CELL

Stage	**Efficiency (HHV) %**	**Energy Required kWh**	**CO_2 kg/kWh**	**Overall CO_2 kg**
Energy at Wheels		1		
Vehicle Efficiency[1]	35	2.857		
Plant to Tank[2]	70.2	4.07		
Hydrogen Generation[2]	76.3	5.334		
Recovery and transport of Natural Gas[2]	95	5.615	0.183	1.028
Total	**18**	**5.615**		**1.028**

HHV, ICE

Stage	**Efficiency (HHV) %**	**Energy Required kWh**	**CO_2 kg/kWh**	**Overall CO_2 kg**
Energy at Wheels		1		
Vehicle Efficiency[1]	25	4		
Plant to Tank[2]	70.2	5.698		
Hydrogen Generation[2]	76.3	7.468		
Recovery and transport of Natural Gas[2]	95	7.861	0.183	1.439
Total	**13**	**7.861**		**1.439**

[1]See Figure 42
[2]See Table 9

4.4.4 Results and Discussion of the Present System

Figure 43 shows the comparison of all three considered traction types, where the calculations are based on the LHV. Figure 44 shows the comparison based on the HHV.

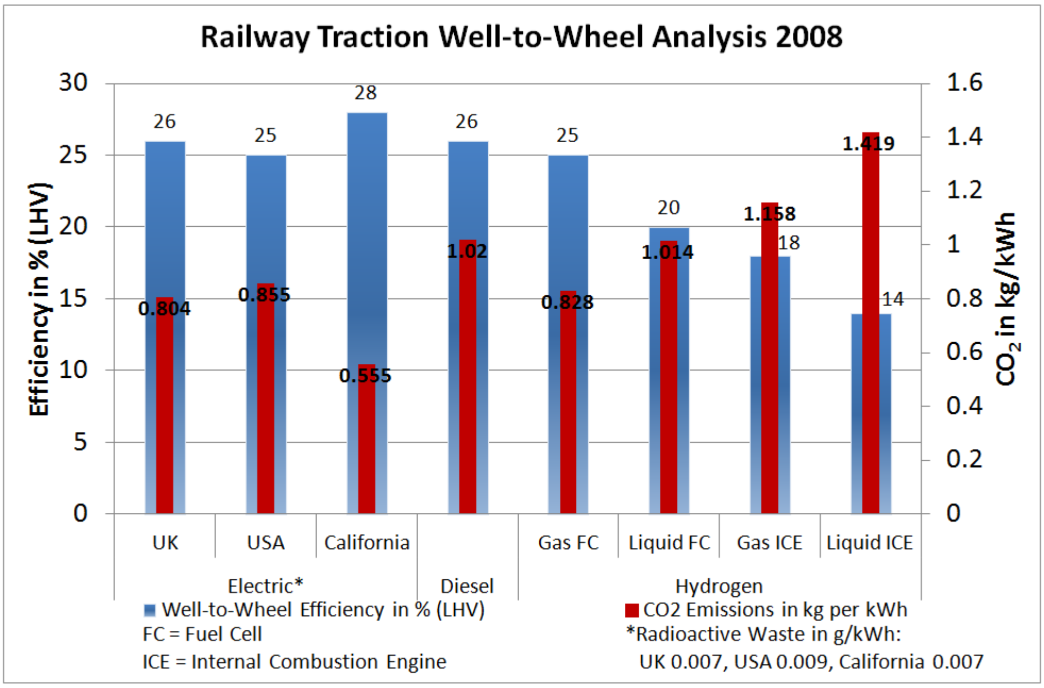


Figure 43: LHV Well-to-Wheel Analysis Results

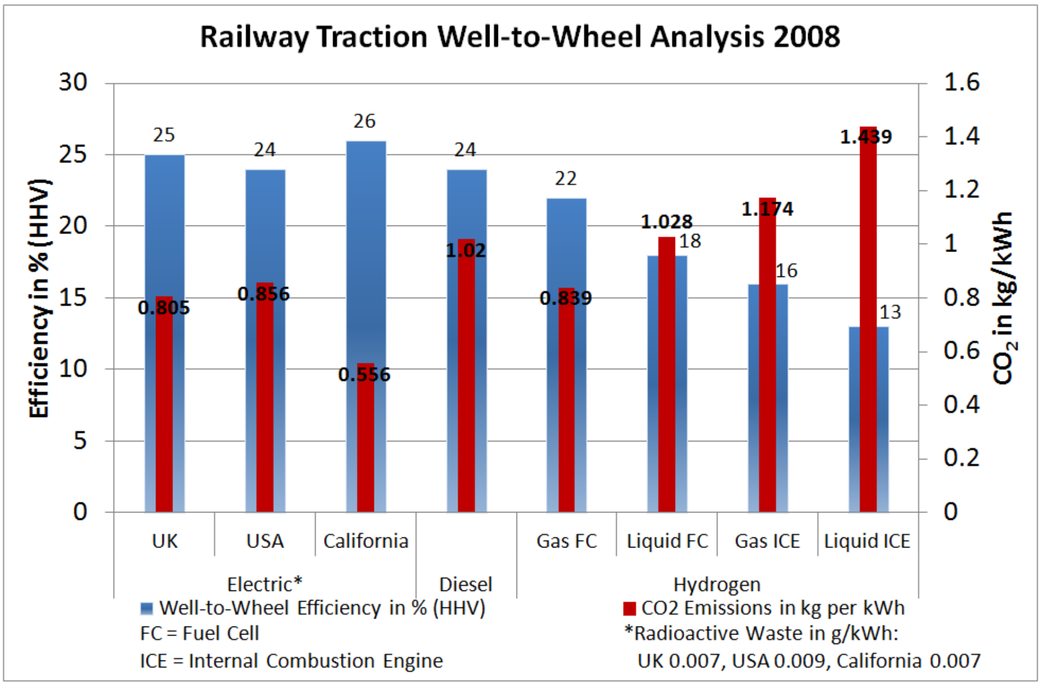


Figure 44: HHV Well-to-Wheel Analysis Results

The WTW efficiencies range from 14 % to 28 % (LHV), and 13 % to 26 % (HHV). The 14 % and 13 % are for liquid hydrogen in an ICE and the 28 % and 26 % are achieved in California's electric system. The second highest WTW value is 26 % LHV achieved with diesel traction, and 25 % HHV is achieved with the UK electric system. The high efficiencies in California are due to the large contribution of natural gas and hydro generation.

The CO_2 emissions range from 0.555 kg/kWh to 1.419 kg/kWh (LHV), and 0.556 kg/kWh to 1.439 kg/kWh (HHV). The lowest CO_2 value of 0.555 kg/kWh (LHV), and 0.556 kg/kWh (HHV), is again achieved in California, due to the substantial contribution of low- and non-carbon sources for the electricity generation: large scale hydro, other renewables, nuclear and natural gas. The second lowest value of 0.804 kg/kWh (LHV), and 0.805 kg/kWh (HHV), is achieved in the UK electric system. The high contribution of non- and low-carbon sources, nuclear and natural gas, are the reason for this.

The comparison of diesel and hydrogen gas in a fuel cell shows that the WTW efficiency of diesel traction is higher, but hydrogen traction would result in lower emissions. The use of ΔG for the efficiency calculations would lead to higher efficiencies and lower emissions of the hydrogen system, especially on the HHV basis and, therefore, this comparison would be more favourable towards hydrogen traction.

The high carbon content of a fuel is not necessarily offset by high efficiency, as shown with diesel traction. The highest efficiency and lowest emissions can be achieved with electrification, if the electricity is produced with non- and low-carbon sources, such as hydro, wind, solar, nuclear, and natural gas.

If diesel traction is substituted with fuel cell vehicles using hydrogen gas, a reduction of about 19 % LHV and 18 % HHV in CO_2 emissions is achieved. Hydrogen gas in a fuel cell vehicle yields a reduction in CO_2 of about 3 % LHV and 2 % HHV compared to the US electric system. The carbon reduction would be, therefore, greatest in the US should the existing diesel fleet be replaced by hydrogen gas fuel cell vehicles. In the UK the CO_2 emission of hydrogen gas fuel cell traction is about 3 % LHV and 4 % HHV higher than the electric system. In California the CO_2 emission of gaseous hydrogen in fuel cell traction would be about 30 %, LHV and HHV, higher than those of an electrified railway network.

It should be recognised in the comparison of the present system that all the hydrogen is produced via steam methane reforming, whereas the electricity generation mix, in all areas, includes renewable- and non-carbon sources.

The development of more efficient fuel cells and improvements in the hydrogen supply chain, for example the use of pressure drop pipelines, will increase the WTW efficiencies and lower the emissions of hydrogen traction.

4.4.5 Renewable Sources

The desire to become more independent from fossil fuels and to lower CO_2 emissions calls for renewable sources. Wind, hydro, and solar sources are considered in this study. The energy carriers can, therefore, be either hydrogen or electricity. Fuels produced from biomass are a renewable source as well, but will release CO_2 emissions when burned. The released CO_2 will be captured by new plants. It may, therefore, be argued that bio-fuels are carbon neutral. However, in this study they are not considered, as one of the objectives of a future fuel source is minimal emission of greenhouse gases, especially at the point-of-use.

First, the three renewables are shown individually, then a comparison diagram is provided, which is followed by a general discussion.

Hydro Power

Water flow can be used to generate electricity and such plants have an efficiency of about 90 % (E.ON AG, 2010). These plants present an opportunity to produce hydrogen from water and electricity through electrolysis. In this study an electrolyser is assumed to have an efficiency of 71.5 % LHV, 84.6 % HHV (Wang, 2002), although new high-pressure electrolysers may reach much higher efficiencies of up to 76 % LHV, 90 % HHV, (Wang, 2002). Applying the calculations presented earlier in this analysis, the WTW efficiencies for gaseous hydrogen and electricity are presented in Table 19.

Table 19: Energy Delivery Comparison for Electricity and Hydrogen Produced From Hydro Power

Electricity		**Hydrogen (Gas)**		
Stage	**Efficiency in %**	**Stage**	**Efficiency in %**	
			LHV	**HHV**
Water	100	Water	100	100
Hydro Power Plant[1]	90	Hydro Power Plant[1]	90	90
National Grid[2]	93	Electrolysis[4]	71.5	84.6
Transmission Railway Network[2]	92.5	Plant to Tank[5]	86	86
Vehicle[3]	76	Vehicle[3]	42	35
Total	**59**	**Total**	**23**	**23**

[1]E.ON AG (2010)
[2]See Electrical Transmission
[3]See Figure 42
[4]Wang (2002)
[5]See Table 8

It can be seen that the losses of the electric system are significantly lower than losses in the hydrogen system. However, the available areas to build new hydro-power-plants are limited and, therefore, this source of power may not be suitable for further electrification plans of railways in many countries.

Wind Power

The efficiencies of wind turbines vary significantly and are dependent on the specific design. In this study, as already mentioned earlier, an efficiency of 35 % has been selected (A. Evans, et al., 2010b; Muyeen, et al., 2008). Table 20 shows the comparison between an electric system and hydrogen gas.

Table 20: Energy Delivery Comparison for Electricity and Hydrogen Produced From Wind

Electricity		**Hydrogen (Gas)**		
Stage	**Efficiency in %**	**Stage**	**Efficiency in %**	
			LHV	**HHV**
Wind	100	Wind	100	100
Wind Turbine[1]	35	Wind Turbine[1]	35	35
National Grid[1]	93	Electrolysis[4]	71.5	84.6
Transmission Railway Network[1]	92.5	Plant to Tank[5]	86	86
Vehicle[3]	76	Vehicle[2]	42	35
Total	**23**	**Total**	**9**	**9**

[1]Muyeen, et al. (2008) and A. Evans, et al. (2010b)
[2]See Electrical Transmission
[3]See Figure 42
[4]Wang (2002)
[5]See Table 8

In this case, the efficiency of the electric system is more than twice as high as that of hydrogen. However, a key issue with wind power is that wind does not necessarily occur when electricity is needed; therefore, a storage medium is required to achieve dependable output.

The current electricity production system has base-load power-plants, such as nuclear power stations and coal-fired power stations, which cannot react quickly to a change in demand. At low demand times, such as at night, the power production of these plants exceeds the demand. The generated electric energy is then often stored in pumped hydro-plants, to be released at peak demand times. This concept can be utilised to balance the unpredictable power production from renewable sources, such as wind and solar. However, the available locations for pumped hydro-plants are limited. Hydrogen as a storage medium is for this reason very useful, and is already utilised to make wind power more dependable (Aklil, 2010).

The relatively unpredictable production of electricity through wind turbines, as well as the inflexibility of present electricity generation, can lead to electricity prices below zero, which happens frequently (Woitas, 2009). For this reason, hydrogen production to stabilise the power generation from wind turbines becomes increasingly important (Meibom & Karlsson, 2010). The use of hydrogen as a storage medium reduces the need for backup power-plants, usually gas-fired, to stabilise the grid in case the power output of wind parks is lower than expected.

Hydrogen has the additional advantage that it can be sold as a valuable product in its own right, for example as a feedstock for the petro-chemical industry or as a transportation fuel. Further, it is usually produced when electricity production exceeds demand, like pumped hydro-storage plants, when electricity is cheap. The use of hydrogen as a railway traction fuel is, feasible and, therefore, the lower overall efficiency is less of a concern.

Solar Power

The main energy source that enables life on Earth is the sun. The energy return on a given piece of land is highest, when the solar energy is directly converted into the required energy, for example solar to electricity (Bossel, 2008). About 0.1 % of available land (circa 500 km x 500 km) could provide the solar energy required by all people, if a 20 % energy conversion factor from solar to electricity is applied (Meier & Steinfeld, 2002).

An efficiency of 31.25 % from solar energy to electricity has been achieved on a much brighter than usual day (Sandia Corporation, 2008); note that this was on a single day in 2008, and is by far not usual. The plant does not have any storage capacity. The largest solar power-plants are achieving a year-round efficiency of about 15 % and a maximum efficiency of 28 %. Located in Spain, they can produce the full amount of electricity for a period of 7.5 h without solar radiation (Solar Millennium AG, 2008). However, there are sunnier areas around the globe, such as the Sahara, Nevada, and Arizona and, therefore, the year-round efficiency of solar power-plant has been increased to 20 %. The problem with solar power is similar to that of wind, as the sky is not equally bright every day and the sun does not shine at night. Therefore, no electricity is produced, and a storage medium is required to cover the fluctuations and provide dependable and uninterrupted energy output. The storage of solar energy and energy output over long periods of time, when the sun does not shine is still a problem.

Further, the sunny areas of the world are often not where people live, so the generated electricity has to be transported over unavoidably long distances, such as 1000 km and above. The transport of electricity over such distances leads to significant losses if alternating current (AC) transmission is utilised (Siemens, 2009). Therefore, it is now usual to use high voltage direct current (HVDC) transmission lines to minimise losses. For HVDC lines a loss of about 3.5 % per 1000 km occurs (Siemens, 2009), and losses for conversion from and to AC at each end are around 1.5 % (Grad, 2008). The HVDC systems are connected at each end with the standard AC power distribution system, as not many substations can be incorporated in the HVDC system. Table 21 shows the overall efficiencies for electricity generated by a solar power-plant with transmission over a distance of 3 000 km, which is about the length from sunny California to Chicago.

Table 21: Electric Traction Powered by Solar Energy Including Transmission over 3 000 km

Stage	**%**	**Efficiency in %**
Sun		100
Power Plant[1]		20
HVDC[1]		
Conversion	98.5	
Transmission	89.5	
Conversion	98.5	
Total HVDC		86.8
National Grid[2]		93
Transmission Railway Network[2]		92.5
Vehicle[3]		76
Total		**11**

[1]See Solar Power
[2]See Electrical Transmission
[3]See Figure 42

Hydrogen can be produced directly with solar energy using a two-step thermo-chemical process, as mentioned (Steinfeld & Weimer, 2010). The conversion efficiency of such a two-step plant, from solar radiation to hydrogen, is about 42 % HHV, however, it is expected that this can be raised to 57 % HHV in the near future (Steinfeld & Weimer, 2010).

Pipeline transportation of hydrogen has been selected due to the long distances to be covered and pumps are installed approximately 160 km (100 miles) apart, which is typical, as mentioned. Per pump, the efficiency is lowered by 1.5 % (Liu, 2003). For 3000 km this yields about 29 %. Pipelines with pressure drops over various distances up to about 1600 km have been suggested, not requiring pumps and therefore having an efficiency of 100 %, (Leighty, et al., 2006), if the energy lost in the pressure difference is not considered. However the energy for compression is accounted for at the pipeline inlet and the outlet.

To overcome oceans, for example from Canada to Europe, pipelines may not be cost effective and practical. However, in general pipelines could be built under the sea, such as under the Mediterranean from the Sahara to southern Europe. Nevertheless, liquid distribution by ship is likely to be adopted to overcome oceans. This distribution mode has an efficiency of 96.9 % (Wang, 2003). The figure is given for liquid hydrogen transport from outside North America to the US over a distance of 8 000 km (Wang, 1999b) and, therefore, for every 1 000 km the efficiency is lowered by about 0.4 %.

Long distance overland transportation of liquid hydrogen is assumed to have a similar efficiency to ocean tankers, as it is likely that it would be transported by train or inland waterways. For a distance of 3 000 km, this type of hydrogen transport would be 98.8 % efficient. Table 22 shows the overall efficiencies for hydrogen as a gas and a liquid, created by the thermo-chemical process and transported over a distance of 3 000 km to a rail vehicle refuelling area.

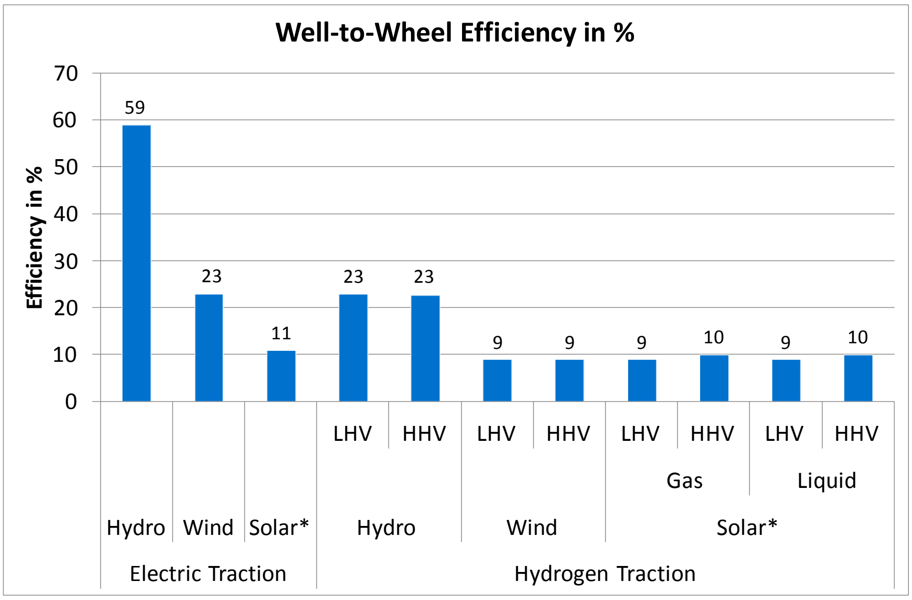
Table 22: Hydrogen Traction Powered by Solar Energy Delivered over a Distance of 3 000 km

Efficiency in % (LHV)			**Efficiency in % (HHV)**		
Stage	**Hydrogen Gas**	**Hydrogen Liquid**	**Stage**	**Hydrogen Gas**	**Hydrogen Liquid**
Sun	100	100	Sun	100	100
Transport and Storage of Water[1]	99.5	99.5	Transport and Storage of Water[1]	99.5	99.5
Power Plant[2]	35.5	35.5	Power Plant[2]	42	42
Liquefaction[3]	-	71	Liquefaction[3]	-	71
Transport[2]	71	98.8	Transport[2]	71	98.8
Compression[4]	89.5	-	Compression[4]	89.5	-
Vehicle[5]	42	42	Vehicle[5]	35	35
Total	**9**	**10**	**Total**	**9**	**10**

[1]Assumed to be as efficient as petrol distribution, it is further assumed that this is sea water and that with the excess heat of the thermo-chemical process it is converted into fresh water, therefore not affecting the efficiency of hydrogen production or the amount of fresh water available.
[2]See Solar Power
[3]See Table 9
[4]See Table 8
[5]See Figure 42

4.4.6 Results and Discussion for Renewables

For the conducted analysis, the geographic location of the power-plants for both electric and hydrogen production pathways has been assumed to be identical. Figure 45 illustrates the results for all considered renewables.



*The efficiency accounts for an energy delivery over a distance of 3 000 km

Figure 45: Well-to-Wheel Analysis for Various Renewables

The WTW efficiency for transmitting energy over a distance of 3 000 km is: 11 % for the electric system, 9 % for gaseous hydrogen, and 10 % for hydrogen as a liquid.

The electric and liquid hydrogen distribution systems achieve the same efficiency between 5 000 km and 7 100 km. For transportation distances longer than 7 100 km, on a WTW basis, energy carried as liquid hydrogen becomes more efficient than electric energy transmission.

Additional calculations have shown that the distribution of hydrogen as a liquid yields a higher efficiency than gaseous transportation, if long distance transport of 2 500 km and above is required. Additionally, larger quantities of hydrogen can be carried in a vessel, requiring fewer tankers, which can lead to more economical transportation. Hydrogen transportation as a liquid is equally possible by other modes, such as rail, requiring fewer transport units for the same quantity of hydrogen carried compared with compressed gas.

However, substantially more energy is required to produce liquid hydrogen, as described earlier in the chapter, then gaseous hydrogen. Liquid hydrogen is produced by the liquefaction of compressed hydrogen, and the liquefaction process is more energy intensive than the compression of hydrogen, as shown in Table 22 above. For this reason the most efficient mode of hydrogen distribution is transport of gaseous hydrogen through pipelines for short and medium distances. At 2 500 km the WTW efficiency for gaseous hydrogen distribution by pipeline and liquid hydrogen distribution is the same, at 10 %. For distances of 1 600 km or less, utilising pressure drop pipelines, which have an efficiency of 100 % (energy lost due to the pressure drop not being considered), hydrogen gas has a WTW efficiency of 13 % and the electric system a WTW efficiency of 12 %.

Comparing electric and hydrogen traction powered by solar energy show similar WTW efficiencies. The ability to store hydrogen is an advantage and assists in overcoming the problem of less sunny times and nights, and additionally, offers flexibility in reaching several markets.

4.5 Summary

The studies show that a high WTW efficiency reduces the amount of energy needed from the original source and that a reduction in overall emissions is possible.

However, the case of diesel traction demonstrates that a high WTW efficiency does not automatically lead to lower emissions, as the high carbon content of the fuel is not offset through the high efficiency.

Hydrogen as an energy carrier to provide power for railway vehicles is a suitable solution on an efficiency and emission basis. The WTW efficiency is similar to electric and diesel systems, but the CO_2 emissions are lower than for diesel traction. The relatively high losses in producing hydrogen through electrolysis lower overall efficiency. Thus, should only be used if the main objective is electricity storage or an uninterrupted power supply is needed, otherwise more efficient methods of hydrogen production can be utilised.

The WTW efficiency of solar to electricity or solar to hydrogen are similar. For a distance of 7 100 km or above, from original source to the consumer, the WTW efficiency of liquid hydrogen distribution is the highest. However, the liquefaction of hydrogen is energy intensive and should be avoided when the transportation distance is short. In regions where large amounts of hydro-power are available and the distances are short, electrification may be the preferred choice. However, the large initial investment for electrification may prohibit future schemes, especially over long distances. Hydrogen can provide a sustainable alternative.

In cases where electricity is largely produced from high-carbon fuels, such as coal, a reduction of CO_2 can be achieved through the use of hydrogen, even if hydrogen is produced from natural gas; the USA case shows a reduction of 3 % in carbon emissions. CO_2 can be further reduced with the contribution of hydrogen produced from renewables.

Compared to diesel traction, CO_2 emissions are reduced by about 19 % (LHV) if hydrogen gas is produced from steam methane reforming and used in a fuel cell vehicle. In the studied regions CO_2 savings could be achieved if diesel trains were substituted with hydrogen-powered trains while electrification would also lead to lower CO_2 emissions.

The study demonstrates that hydrogen is a suitable energy carrier for railway vehicles on an efficiency and emission basis. These vehicles offer a reduction in emissions and the WTW efficiencies are similar to electric and diesel traction. In the author’s opinion, these results are encouraging and justify more detailed investigation into the engineering of hydrogen-powered railway vehicles. The design, construction, and performance of a hydrogen-powered narrow gauge railway vehicle, and the concept design for standard gauge hydrogen-powered railway vehicles are considered in the course of this thesis. The next chapter describes the UK’s first hydrogen-powered locomotive: the Hydrogen Pioneer.

PART II:
HYDROGEN-POWERED RAILWAY VEHICLE DEVELOPMENT

5 PROTOTYPE LOCOMOTIVE: HYDROGEN PIONEER

In the previous chapter it was demonstrated that hydrogen-powered railway vehicles are a feasible option from an environmental and efficiency perspective. However, as described earlier in this document, only a few prototypes exist, and up to summer 2012, no prototype vehicle had been built in Britain, except for an approximately 1:76, OO gauge model, in 2009 (May & Whitter, 2009). In this chapter the author describes the design, construction, and demonstration of Britain's first hydrogen-powered locomotive, called *Hydrogen Pioneer*. First, the motivation to construct such a vehicle is given, next is a description of the design. Thereafter, the performance during the competition that motivated its construction is shown, and finally a summary is provided.

Figure 46: Hydrogen-Hybrid Locomotive Hydrogen Pioneer (Author's Collection, 2012)

5.1 Motivation to Construct a Locomotive

The Institution of Mechanical Engineers (IMechE) wishes to encourage young engineers to take an interest in railways. For this purpose, the IMechE organised a so-called *Railway Challenge*, which is planned to be an annual event. The inaugural Railway Challenge took place on July 1, 2012. Teams that participated in the competition had to design, construct, and demonstrate a railway locomotive that was to operate on 10.25 inch track. The competition comprised several challenges and the engineering-based ones were: A ride comfort challenge, an energy storage challenge, and a traction challenge.

The Birmingham Centre of Railway Research and Education (BCRRE) at the University of Birmingham entered the Railway Challenge with a multidisciplinary team consisting of researchers from: the School of Chemical Engineering, the School of Metallurgy and Materials, and BCRRE. The faculty advisor of the team, Stuart Hillmansen, entered the Railway Challenge on behalf of BCRRE and asked Mr. Stephen Kent and the author for their participation. The team was then created based on individuals' motivation to participate and on the expertise that individuals would contribute to the team. The design and construction of the various components of the locomotive, such as the mechanical design, the control and electrical design, and the power-plant and hydrogen supply design, were assigned to small groups of team members, who were responsible for their respective areas. On a regular basis the whole team met to report on progress and to ensure that the various component systems would work well together.

Figure 47: Hydrogen Pioneer and Development Team
Not all members are shown
Courtesy and Copyright Charles Watson, 2012

The author's main responsibilities in the team were: systems engineering, particularly requirements extraction; documentation, including report preparation and safety analysis; and concept design of the drive-train system. He was also involved in the hydrogen-related designs, such as storage options and power-plant procurement. Further, he procured the track for the initial tests at the university.

5.2 Design of the Hydrogen Pioneer Locomotive

In this section the author describes the concept design and the design of the various sub-systems of the locomotive.

5.2.1 Concept Design

From an early stage it was clear that the founding members of the team did not want to design a fossil fuel-dependent locomotive and, given the author's research, the possibility of a hydrogen-powered vehicle was conceived. In principle it was possible that the main requirements of the Railway Challenge could be met with a hydrogen-based power-plant design. When the founders proposed the hydrogen-powered locomotive concept to the balance of the team, it was accepted universally.

The requirement of regenerative braking capability and the response time, as well as the energy output of the power-plant, led to a hybrid design, where batteries are utilised as energy storage devices. The batteries were sized to meet the peak power demand and to enable the capture of regenerated electrical energy. Given that the power output of the power-plant is DC, that batteries operate with DC current, and that low voltage DC motors and controllers were available, a DC drive-train was chosen. The power-plant consisted of a fuel cell stack and DC to DC converter and is describe in more detail later in this chapter. The conceptual design of the drive-train is shown in Figure 48.

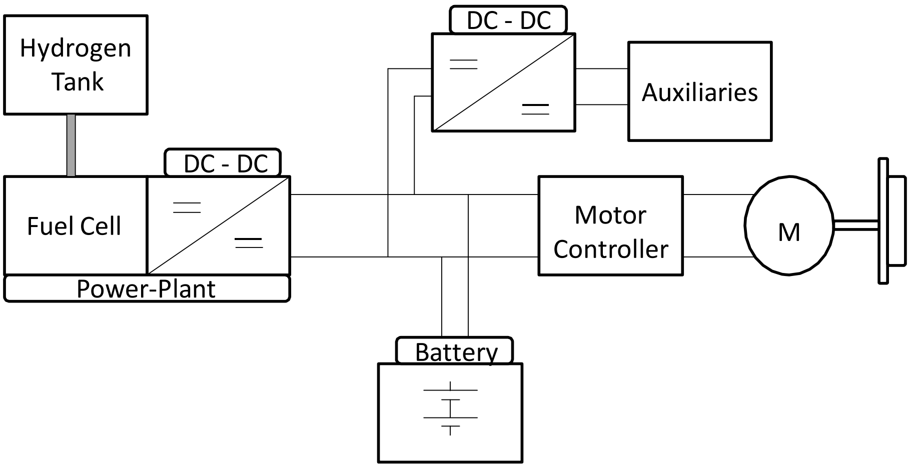
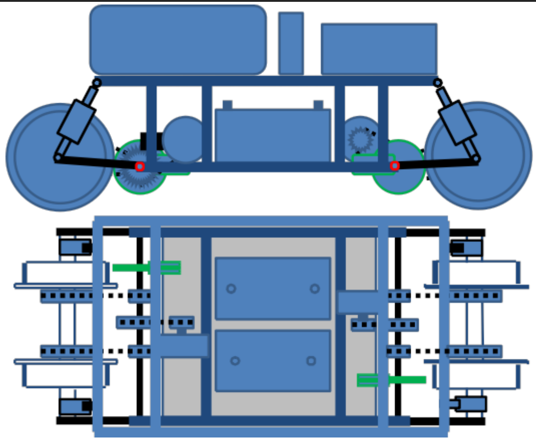


Figure 48: Concept Design of Hydrogen Pioneer's Drive-Train

The mechanical team developed a short wheelbase frame to accommodate the main components of the drive-train. Originally, this was a double-deck design, with the heavy batteries and electrical motors on the lower deck, and the lighter power-plant, as well as the hydrogen storage on the top deck. Figure 49 shows the mechanical and structural first concept of the Hydrogen Pioneer. The basic parameters of the locomotive are shown in Table 23.



Frame = square section extruded aluminium, connectors with hinged ends used for radial arms
Drive = chain drive direct to wheels via intermediate shaft and wheel-mounted gear sprocket
Brakes = 24 V electrically-operated disc brakes (shown in green)
Coupler = attached to top frame (not shown)
Suspension = 4 x rear shocks from full suspension mountain bike
Batteries = sit in a well in-between the cross members on the lower level of the frame

Figure 49: Original Mechanical Concept Design of the Hydrogen Pioneer (Hoffrichter, Reed, & Kent, 2012)

The next sections describe the design of the three main sub-systems of the locomotive: (1) the mechanical system, (2) the control and electrical system, and (3) the hydrogen-related system.

Table 23: Basic Parameters of the Hydrogen Pioneer (Hoffrichter, Reed, et al., 2012)

Parameter	Value
Number of Traction Motors	2
Number of driven wheels	4
Number of driven wheelsets	2
Locomotive Mass without tank in kg	270
Total Locomotive Mass (m_L), including hydride tank in kg, see below	320

5.2.2 Mechanical System

Frame

The structural frame of the Hydrogen Pioneer is constructed with extruded aluminium elements, which form the beams and posts. In contrast to the conceptual design, the final design and construction has three decks rather than two. The deck planes are made from a heavy-duty steel plate, where they were required. On the bottom deck the batteries, electric motors, and mechanical drive-train are mounted. The middle deck provides space for hydrogen storage and is not enclosed to ensure ventilation in case of a leak. The storage tank is installed in the middle deck to lower the centre of gravity, while ensuring a separation from the traction equipment, which reduces the risk of ignition should a leak occur. Up to three metal-hydride tanks can be installed in this deck. The top deck provides space for the power-plant, hydrogen flow regulators, and the control electronics. Figure 50 shows the three-deck frame of the locomotive. The three-deck design allows the separation of the hydrogen-related components, particularly the storage tank, from the high voltage, high current equipment, which reduces the risk of ignition in case of a hydrogen leak.

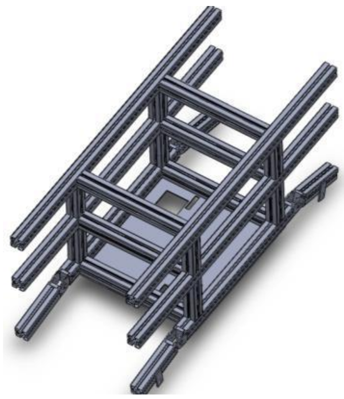


Figure 50: Three-Deck Frame of the Hydrogen Pioneer (Hoffrichter, Reed, et al., 2012)

The frame is clad with clear plastic sheets, which protect the components from the weather and allow viewing of the internal components. The sheets are attached to the structural frame with nuts and bolts.

The locomotive is a non-bogie two-axle vehicle with four independently attached wheels. Four air springs are each connected to a wheel through a cantilever system, and can be tuned to suit the track characteristics. The vertical load from the wheels is carried through the suspension to the main beams on the middle deck. From the two main beams, one on each side of the vehicle, the bottom deck is hung, and the top deck is supported through posts. Further, the load is transmitted sideways in the middle deck to support the hydrogen tank. The suspension and load distribution can be seen in Figure 51.

Figure 51: Air Suspension of the Hydrogen Pioneer (Author's Collection, 2012)

The vehicle is 640 mm wide, taking advantage of the maximum permissible loading gauge of the Stapleford Miniature Railway, where the Railway Challenge took place. The width allows easy access to all components for maintenance and repairs, and additionally provides flexibility in case components have to be relocated.

Mechanical Drive-Train and Motors

The locomotive has two traction motors; one motor drives the front wheels of the locomotive, and the other, the back. The traction motor transmits the torque through sprockets and a duplex chain to a lay shaft, which distributes the traction force to each wheel with sprockets and simplex chains, see Figure 52 and Figure 53.

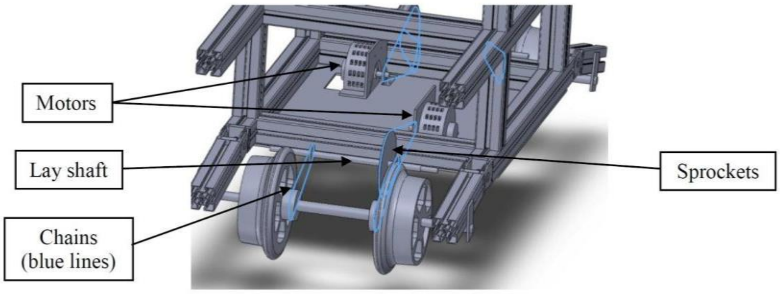


Figure 52: Mechanical Drive-Train Design
(Hoffrichter, Reed, et al., 2012)

Figure 53: Mechanical Drive-Train of the Locomotive
(Author's Collection, 2012)

The lay shaft design enables a high gearing ratio that fulfils the requirements of the locomotive, and facilitates constant chain tension regardless of suspension movement. The duplex chain, between the motor and lay shaft, has been chosen to minimise wear on the relatively small sprocket on the motor.

The two wheels are independently attached on a fixed axle and are driven from the common lay shaft. This system allows simple wheelset construction and is adaptable to different track gauges and, therefore, increases operational flexibility for demonstrations of the Hydrogen Pioneer. Additionally, it enables the possibility of independently driven wheels to increase curving performance in future projects.

The motor selection was based on the requirements of the Railway Challenge, particularly the operating speed and the acceleration capability. The design calculations for the motor selection, the maximum speed, acceleration, and tractive effort of the locomotive are provided in Table 24.

Table 24: Design Calculations to Determine Torque, Acceleration, Maximum Speed, and Tractive Effort
(Hoffrichter, Reed, et al., 2012)

Parameter	Value	Unit	Symbol or Formula
(I)TRACTION MOTOR TORQUE			
Maximum current	*75*	A	I_{max}
No Load current[1]	*6*	A	$I_{no\ load}$
Torque Constant[1]	*0.063*	Nm/A	k
Motor torque	**4.354**	**Nm**	$T_{motor}=(I_{max}-I_{no\ load})*k$
(II) MAXIMUM ACCELERATION ON LEVEL TRACK			
Motor torque[2]	4.354	Nm	T_{motor}(see above)
Number of motors per wheelset	*1*		No
Gearing ratio	*9.2*		GR
Estimated Efficiency of the mechanical drive-train	*95*	%	E_{mech}
Torque on each wheelset	38.05	Nm	$T_{wheelset}=T*No*GR*E_{mech}$
Radius of the wheelset	*0.1*	m	r
Force at the wheel-rail interface per wheelset	380.5	N	$F_{wheelset}=T_{wheelset}/r$
Total driving force	**761.1**	**N**	$Fl_{oco}=F_{wheelset}*2$
Trailing load for traction challenge	*600*	kg	m_{trail}
Mass of locomotive	*320*	kg	m_{loco}
Total load	920	kg	$m_{total}=m_{loco}+m_{trail}$
Maximum acceleration[2]	**0.827**	**m/s²**	$a=F_{loco}/m_{total}$
(III) ADHESION CALCULATIONS			
Total driving force	761.1	N	see II, F_{loco}
Vertical load	3139	N	$F_{vertical}=m_{loco}*9.81$
Required coefficient of friction to avoid wheel slip	**0.24**		$\mu=F_{loco}/F_{vertical}$
Estimated, likely, wheel/rail adhesion at Railway Challenge	0.23		μ_{est}
Is wheel spin likely?	yes		
(IV) MAXIMUM SPEED			
Maximum motor voltage	*36*	V	$V_{motor\ max}$
Motor speed constant	*138*	rpm/V	$\omega_{motor\ constant}$
Maximum motor rotation speed[1]	4968	rpm	$\omega_{motor\ max}=V_{motor\ max} * \omega_{motor\ constant}$
Maximum wheelset rotation	540	rpm	$\omega_{wheelset\ max}=\omega_{motor\ max}/GR$
Wheel circumference	0.628	m	$Ø=2\pi r$
Maximum linear speed	339.1	m/min	$v= Ø*\omega_{wheelset\ max}$
Maximum linear speed	5.652	m/s	v/60
Maximum linear speed	**20.35**	**km/h**	(v/60)*3.6
(V) TRACTIVE EFFORT			
Starting tractive effort limited by likely adhesion	**722**	**N**	$F_{TEstart}=m_L*9.81* \mu_{est}$

Italics=input values
[1]Based on Lynch Motor Company LEM130-95
[2]Assuming that the wheels do not slip

Braking System

The Hydrogen Pioneer features two independent braking systems: (1) Dynamic braking and (2) Mechanical braking.

The dynamic braking system is designed to provide the service braking deceleration of up to 1.3 m/s^2. During braking the motors act as generators and the resulting electrical energy is stored in batteries. Therefore, the design meets the requirement for regenerative braking and has the potential to reduce overall energy consumption.

The mechanical braking system has two applications: (a) it provides the parking brake to ensure the vehicle does not move when stationary for long periods of time, such as during maintenance and repair tasks, and (b) it is used as an emergency brake.

The requirements mandated that an independent emergency brake had to be provided on the vehicle and the mechanical braking system ensured that this requirement was met. In emergency mode this brake brings the locomotive and its trailing load to a halt. The mechanical braking system is used commercially on track inspection trolleys and rated for 2 000 kg loads, which is beyond the designed traction capabilities of the locomotive.

5.2.3 Control- and Electrical System

The electrical system is illustrated in Figure 48, with the components: (1) Fuel cell power-plant, (2) four calcium-based lead-acid batteries, (3) a motor controller, and (4) two permanent-magnet traction motors. The electrical drive circuit operates at 48 V DC to minimise losses and traction currents. Each traction motor provides 2.2 kW continuous power and both together provide 8.7 Nm torque; they are managed by a common motor controller. The four batteries are capable of storing 4.3 kWh of electrical energy, each operating at 12 V and 90 Ah. They are either charged during regenerative braking or from the power-plant in dwell- or idle time and during operation. Further, the power-plant charges the batteries to a level of a maximum of 70 % state-of-charge, to allow enough spare capacity to capture the energy generated when braking. Also, the batteries provide the peak power to the motors, such as during acceleration or when ascending gradients. The control computer operates at 24 V, which is the same as the emergency brake loop; other auxiliaries, for example the instrumentation sensor, operate at 12 V.

Control Computer

The main control unit of the locomotive is a National Instruments Compact Rio real-time computer. It consolidates the inputs from the various sensors and is the on-board unit that executes the driver's commands. The unit monitors the power-plant and batteries, manages the motor controller and the power-flow direction, which reverse during regenerative braking, and collects performance data. It has Wi-Fi capabilities and allows radio control of the locomotive, which is its normal control mode. In case the wireless connection is lost, the locomotive comes to a safe stop. Further, the Compact Rio operates as a safety system and, in case of an emergency detected by the sensors or activation of the emergency stop button, stops the locomotive and transfers the system into a safe state through a shut-down of the power-plant.

All the driver inputs to the tablet computer are received by the control unit and the appropriate responses of the locomotive are ensured, for example, acceleration up to a selected top speed. The installed control system hardware can be seen in Figure 54.

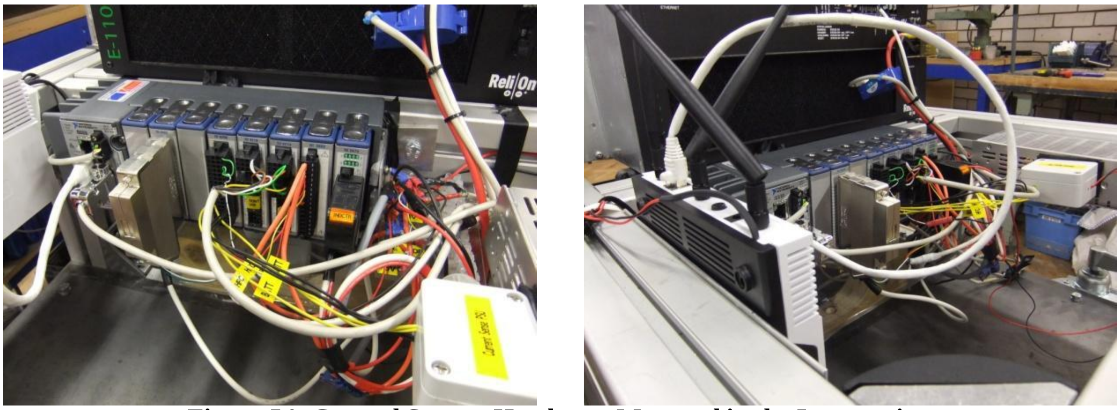


Figure 54: Control System Hardware Mounted in the Locomotive (Author's Collection, 2012)

Control Software

The control software for the Compact Rio is written in National Instruments *LabView*. The programme has two major loops: (1) A high priority safety loop, which monitors the safe operation boundaries of the main components and intervenes, if a component operates outside of the boundary, and (2) A control loop. This loop receives commands from the driver, communicates the status of the locomotive back to the tablet computer, and provides the general control of the locomotive, for example, it sends serial commands to the motor controller.

Tablet Computer

The driver communicates with the Hydrogen Pioneer through an Acer Aspire touch screen tablet computer, see Figure 55.

Figure 55: Touch-Screen Tablet Computer that Provides the Driver Interface (Author's Collection, 2012)

The driver human-computer interaction interface is also written in LabView. The intuitive interface allows the driver to select the travel direction of the locomotive, operating speed, and the selection of other control inputs. Further, it displays information about the status of the locomotive, such as the current speed. A picture of the virtual control panel is shown in Figure 56.

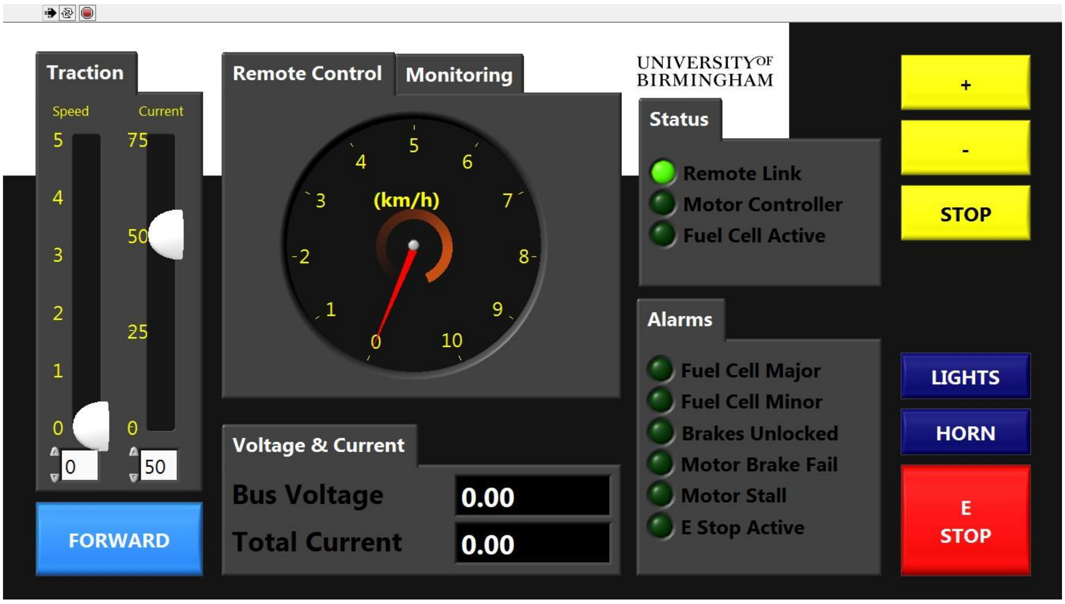


Figure 56: Driver Interface to Control the Locomotive
Courtesy and Copyright Jon Tutcher, 2012

5.2.4 Hydrogen System

The hydrogen system consists of three main parts: (1) The hydrogen storage tank, (2) gas pipe work and gas-supply panel, and (3) the fuel cell power-plant. The hydrogen system components are located on the middle- and the top deck, as illustrated in Figure 57.

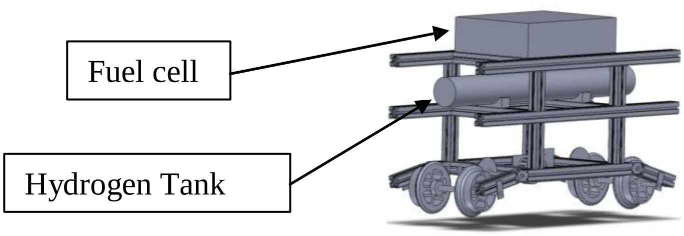


Figure 57: Position of Fuel Cell Power-Plant and Hydrogen Storage Unit
(Hoffrichter, Reed, et al., 2012)

The electrical energy output of the power-plant, and the minimum quantity of hydrogen that had to be stored, was determined on the basis of the Railway Challenge requirements. One of those requirements stated that the locomotive must be able to haul a load of 400 kg on a gradient of 5 % for three hours; this was the toughest requirement for average power and energy storage and, therefore, the design calculations were based on it. The associated design calculations are shown in Table 25. The power-plant was oversized for reasons of caution and the hydrogen tank that was available to the team held more hydrogen than required, so the locomotive components exceeded the minimum, as determined by the design calculations. More detail about the three main hydrogen system components is given below.

Table 25: Design Calculation to Determine the Fuel Cell Rating and Hydrogen Storage (Hoffrichter, Reed, et al., 2012)

Parameter	Value	Unit	Symbol or Formula
Trailing Load[1]	*400*	kg	m_T
Operation time[1]	*3*	h	t
Speed[1] *(km/h)*	*5*	km/h	v
Distance covered	15	km	s=t*v
Gradient[1]	*5*	%	
(I) ENERGY REQUIREMENTS AT WHEELS			
Ascent	750	m	s_A=s*Gradient*1000
Total mass for fuel storage challenge	720	kg	$m_{total}=m_L$(see Table 23) + m_T
Energy required at wheels	5297400	J	$E=9.81*s_A*m_{Total}$
Energy required at wheels	**1.472**	**kWh**	E_{Wheels}=E/3600000
(II) ENERGY- AND POWER REQUIREMENT FROM FUEL CELL			
<u>Electrical Drive-Train Efficiency Estimation</u>			
1. Control System Efficiency	90	%	CSE
2. Battery Conversion Efficiency	75	%	BCE
3. Motor Efficiency[2]	80	%	ME
Overall Efficiency	54	%	OE=CSE*BCE*ME
Energy required from the fuel cell	**2.725**	**kWh**	$E_{Fuel\ Cell}=E_{Wheels}/OE$
Rating of the required fuel cell	**0.908**	**kW**	$=E_{Fuel\ Cell}/t$
(III) HYDROGEN STORAGE REQUIREMENT			
Energy required from the fuel cell	2.725	kWh	see II
Hydrogen volume required for one kWh electrical energy output[3]	*625*	l/kWh	$H_{2required}$
Total Hydrogen Volume required	1703	l	$H_{2Total}=E_{Fuel\ Cell}/H_{2required}$
Density of Hydrogen	*0.09*	g/l	density
Mass of Hydrogen required	**153.1**	**g**	$m_{H2}=H_{2Total}$/density
(IV) VEHICLE RANGE, OPERATED ON HYDROGEN ONLY			
Maximum quantity of hydrogen stored in metal-hydride tank	500	g	$H_{2Quantity}$
Total electrical energy available from fuel cell using full tank capacity	8.899	kWh	$E_{Total\ Elec}=H_{2Quantity}*E_{Fuel\ Cell}/m_{H2}$
Locomotive range on 5 % gradient	**9.8**	**h**	$=E_{Total\ Elec}*t/E_{Fuel\ Cell}$

Italics=input values
[1]Given requirements in the Railway Challenge specifications
[2]Based on Lynch Motor Company LEM130
[3]Given by fuel cell power-plant manufacturer

Hydrogen Storage Tank

The middle deck of the locomotive is designed to hold the hydrogen storage tank or tanks, see Figure 58, and the middle deck was chosen to ensure a low centre of gravity of the locomotive. Further, it is an open deck to allow ventilation in the unlikely event of a hydrogen leak, as mentioned earlier in the chapter. The Hydrogen Pioneer can be operated with different types of storage tanks, as long as hydrogen purity of 99.9 % is assured and the hydrogen is supplied as a gas at less than 300 bar pressure. The design, therefore, allows for a variety of hydrogen storage solutions.

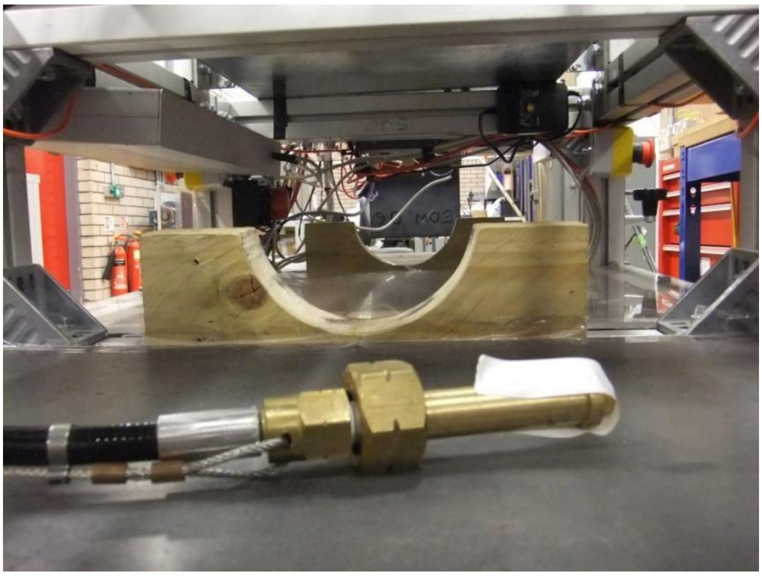


Figure 58: Middle Deck: It Provides Ventilated Space for the Hydrogen Tank (Author's Collection, 2012)

Metal-Hydride Tank

The original concept design envisaged the use of a compressed hydrogen tank on the higher of the two decks. However, during the design process the team recognised that a metal-hydride storage tank offered several benefits for the demonstration at the Railway Challenge. The first advantage is that the tank could be filled with hydrogen at the university and transported with the locomotive to the event, rather than compressed hydrogen having to be delivered to the competition site. Second, lower operating pressures, compared to compressed hydrogen, reduced the risk and hazards and, therefore, the associated risk assessment for high pressure could be avoided. Third, the Metallurgy and Materials group owns several metal-hydride tanks and was willing to lend one to the team. One of the team members is part of that group and his responsibilities entailed the hydrogen supply system. The installed metal-hydride tank, in the middle deck of the locomotive, can be seen in Figure 59.

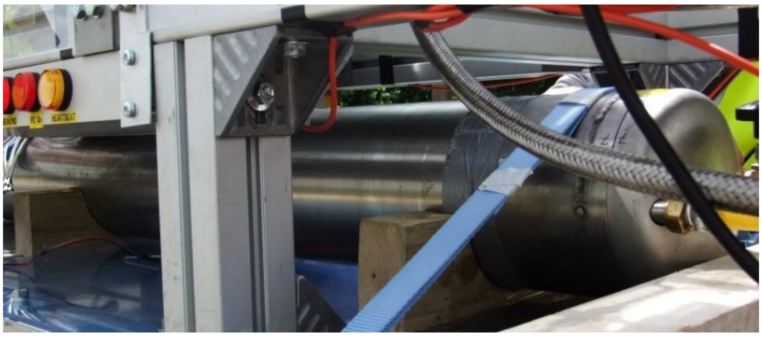


Figure 59: Metal-Hydride Hydrogen Storage Tank (Author’s Collection, 2012)

The utilised metal-hydride tank was developed at EMPA Laboratories in Zürich, Switzerland. The hydride powder is a Ti-V-Mn-Fe alloy, which is filled in horizontal stainless steel tubes. Seven tubes are part of one tank, and the tubes are surrounded by a water bath for temperature control, see Figure 60. The storage tank holds approximately 0.5 kg of hydrogen, operates at a pressure below 10 bar, and has a mass of approximately 50 kg. The tank has to be cooled for rapid filling and heated for quick release of hydrogen, but for the demonstration of the Hydrogen Pioneer ambient temperature was sufficient for the hydrogen flow rate required, and the tank was filled with water at ambient air temperature.

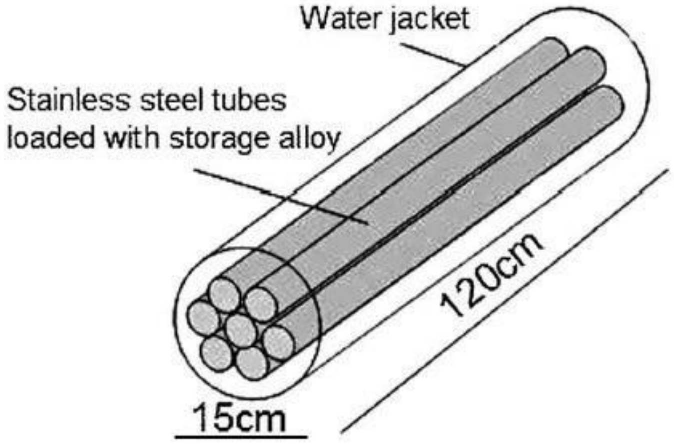


Figure 60: Metal-Hydride Hydrogen Storage Tank Illustration (Bevan, Züttel, Book, & Harris, 2011)

Compressed Gas Tank

The Hydrogen Pioneer was also demonstrated in September 2012 at a hydrogen event in Hannover, Germany. For this event, the more convenient option was to operate the locomotive with a compressed-hydrogen cylinder. The reasons were the difficulties of transporting the metal-hydride tank across borders, and compressed hydrogen could be delivered conveniently to the site in a standard cylinder. The gas supply panel was connected with the same hose as used for the metal-hydride tank; however, the connector had been changed from standard BS 341 No. 3 used in the UK to the standard fitting DIN 477 Nr. 1 used in Germany.

A standard compressed hydrogen cylinder was supplied by Linde AG to the demonstration site, and it had the following characteristics (Linde AG, 2008): the 200 bar steel cylinder held approximately 0.15 kg of hydrogen, had a mass of 20 kg, and the dimensions were 140 mm diameter and 975 mm length. Therefore, the dimensions were similar to the hydride tank and no modifications to the holder were necessary for installation in the locomotive. Figure 61 shows the compressed hydrogen tank mounted in the middle deck.

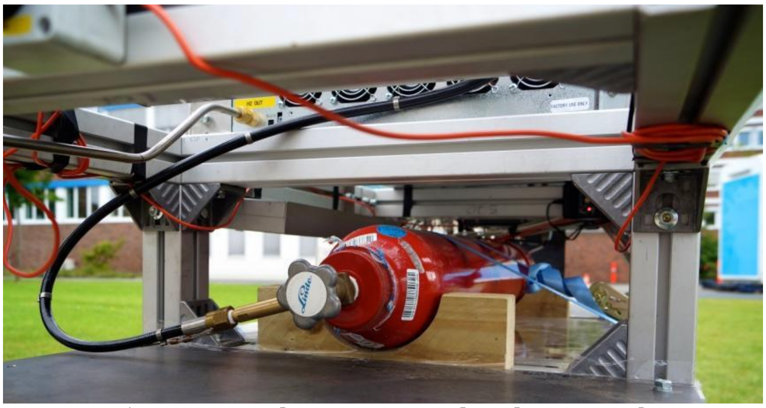


Figure 61: 200 bar Compressed Hydrogen Tank
Courtesy and Copyright Jon Tutcher, 2012

Pipe Work and Gas Supply Panel

The hydrogen tank was connected to the gas supply panel with a braided stainless steel hose. The gas supply panel has a high-pressure regulator, stainless steel piping, and a low-pressure regulator. The high-pressure regulator reduces the supply pressure from 200 bar to between 10 bar and 20 bar. The hydrogen flows then through stainless steel pipes to the low-pressure regulator. There, the pressure is further reduced to the supply pressure requirement of the power-plant of between 0.6 and 0.8 bar. After passing through the low-pressure regulator, the hydrogen moves through a pipe to the power-plant inlet. Figure 62 shows the hydrogen supply panel and pipe work.

Figure 62: Hydrogen Supply Panel, Pipe Work, and Rear of the Power-Plant
The right side of the panel is the high-pressure regulator, and the left side, the low-pressure regulator (Author's Collection, 2012)

Fuel Cell Power-Plant

The power-plant in the Hydrogen Pioneer is a 1.1 kW ReliOn E-1100™ Proton Exchange Membrane fuel cell system, which includes a DC converter for stable electricity output at 24 or 48 V; the 48 V being the same as the locomotives drive-train voltage. This fuel cell system is intended to be used for uninterruptable power supplies in the telecommunication industry. The power-plant was, therefore, not specifically designed for mobile applications, but commercially available, and chosen for this reason. The fuel cell system has a mass of 26.4 kg and comes in standard 4U dimensions, which allowed for trouble-free installation. Further, it includes various monitoring and control options that simplify the connection and communication with the locomotive's control system. The power-plant is designed to be maintenance-free and has an expected lifetime of several years. Figure 46 shows the power-plant mounted on the top deck of the locomotive.

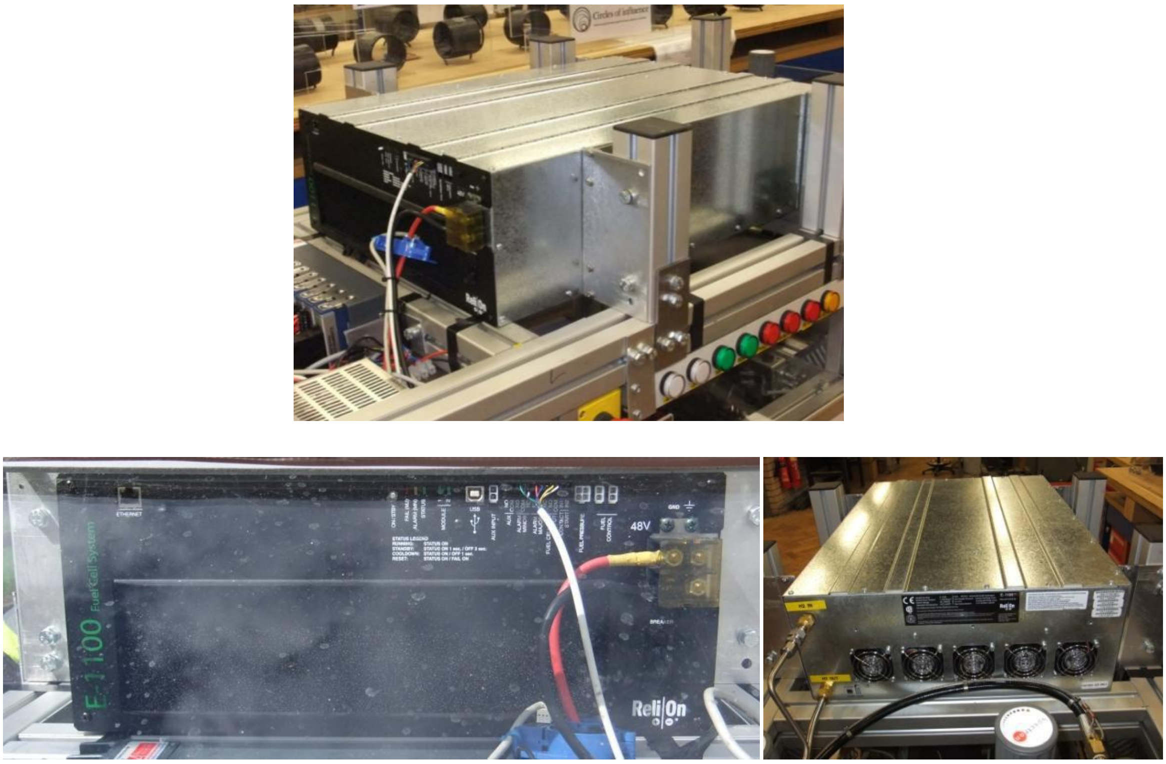


Figure 63: Fuel Cell Power-Plant
(Author's Collection, 2012)

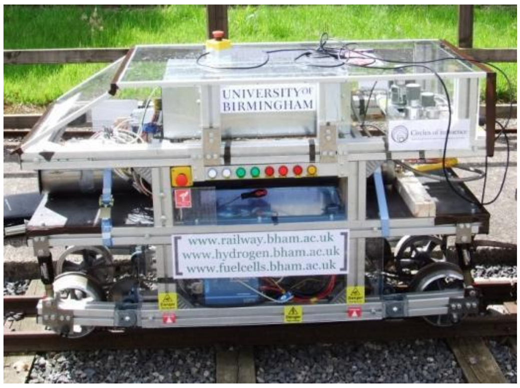
5.3 Performance of the Hydrogen Pioneer at the Railway Challenge

The Railway Challenge took place at the Stapleford Miniature railway on the weekend of June 30-July 1, 2012. Four teams took part in the challenge. All teams used a combustion engine as prime mover in their locomotive, except for Birmingham's team. The four contestant locomotives can be seen in Figure 64.

Interfleet Locomotive (Author, 2012)

Independent Team Locomotive (Author, 2012)

Manchester Metropolitan University Locomotive (Courtesy and Copyright Charles Watson, 2012)



University of Birmingham Locomotive Hydrogen Pioneer (Author, 2012)

Figure 64: Locomotives of all Four Teams that Participated in the Inaugural Railway Challenge

After unloading, the locomotive was ready for operation and no major modifications were necessary to change its status to the operational state. The Hydrogen Pioneer completed all three engineering challenges set by the IMechE and, therefore, the design was a success. The locomotive hauled one coach, seating the driver, scrutiniser, and brake man, see Figure 65, with a mass of approximately 400 kg for the majority of the weekend; this was the load anticipated in the design.

Figure 65: Hydrogen Pioneer Hauling one Coach With Three Persons (Author's Collection, 2012)

In an additional run the Hydrogen Pioneer was able to haul 4 000 kg, far beyond the designed traction load of 600 kg. The team members were particularly pleased with this achievement. Further, the locomotive operated quietly, as the only noise noticeable was from the power-plant and was due to the air fans.

The team was, in general, satisfied with the performance of the locomotive, particularly its traction capabilities. However, several improvement options were recognised and consequently implemented during the months after the Railway Challenge. The changes included: the use of bearings to attach the rigid driving axles to the frame, relocation of the mechanical brakes to be in-line and attached to the traction motors, improvements to the mechanical drive-train to minimise slippage of the chains, and improvements to the control software.

5.4 Summary

The University of Birmingham Railway Challenge team, of which the author was a member, designed and constructed a narrow gauge hydrogen-hybrid locomotive, called Hydrogen Pioneer – the first of its kind in the UK. The vehicle uses hydrogen gas as its primary fuel, a Proton Exchange Membrane fuel cell system as a power-plant, lead-acid batteries as electrical energy storage devices, and permanent-magnet traction motors. The choice of hydrogen as a fuel and the application of a fuel cell were inspired by the author's research, and he contributed in several ways to the design and demonstration of the Hydrogen Pioneer. The locomotive was conceived as a proof of concept prototype, motivated by the inaugural Railway Challenge of the IMechE, where it was first demonstrated.

The vehicle completed all three track-based competitions at the Railway Challenge day. Its performance compared to the competitors was similar and, therefore, the design of the locomotive was a success. Further, it was able to haul 4 000 kg, which is well beyond its designed hauling capabilities.

Since the Railway Challenge, the locomotive was exhibited at the 7th International Hydrail Conference, the Network Rail Innovation Day, and at the European Hydrogen Road Tour in Hannover. The Hydrogen Pioneer as a prototype locomotive generated world-wide interest in the possibility of hydrogen-powered railway traction vehicles and displayed the engineering capabilities available at the University of Birmingham. The expertise that the researchers gained in this field enables BCRRE to take a lead role in future designs of standard gauge hydrogen-powered locomotives and traction vehicles.

The development of this locomotive demonstrates that hydrogen can be applied to low-power railway traction requirements. The main components of the Hydrogen

Pioneer are scalable, so more powerful locomotives can be constructed using similar components, and the same concept drive-train can be used also. A chain-drive is, however, not recommended for higher-power standard gauge railway vehicles. The existing vehicle could, with minor modifications, especially to its appearance, be used in low-power applications, such as on industrial sites or on theme park rides.

The locomotive, being a hydrogen-hybrid, was utilised for additional tests to quantify the performance of the drive-train system. The method and results of these tests are presented in the next chapter.

6 PERFORMANCE EVALUATION OF THE HYDROGEN PIONEER

The hydrogen-hybrid locomotive Hydrogen Pioneer, which was designed and constructed at the University of Birmingham, as described in the previous chapter, was employed for an empirical evaluation of the performance of a hydrogen-powered railway traction vehicle. The evaluation consisted of several tests that can be grouped into two categories: (1) Run-Down Experiment, to determine the resistance to motion, and (2) Locomotive Operation Experiment, to establish the drive-train efficiency in operating conditions. The results of the Run-Down experiment were used as an input for the Locomotive Operation experiment.

First, the general data collection system is described, which was utilised fully or in part in the subsequent experiments. The more detailed method, results, and data analysis for each experiment are presented next. This is followed by a discussion about the vehicle performance. To finish the chapter a summary and implications of the evaluation for the subsequent research presented in this thesis are provided.

6.1 Data Collection System

The Hydrogen Pioneer has an on-board National Instruments Compact Rio real-time computer, as described in the previous chapter. This computer was used to collect the measured data, which was transferred to an off-board computer for processing and analysis. The data collection system was designed by Jonathan Tutcher, a member of the Railway Challenge Team as mentioned in the previous chapter, and installed by him with help from BCRRE laboratory technicians. The author was responsible for: research design, experiment organisation, determination of the necessary data that had to be collected, data processing, and data analysis and interpretation.

Data calibration was undertaken together with Peter Fisher, who is also a member of the Railway Challenge Team. The Hydrogen Pioneer's data acquisition system is able to measure and record the following:

- Hydrogen quantity into the fuel cell, measured through a hydrogen mass flow meter.
- Electrical current output of the fuel cell.
- Electrical voltage of each battery and current of all batteries. This data also shows the voltage and current across the electrical drive-train: the DC-BUS.
- Electrical current at the traction motor controller.
- Speed of the locomotive.
- Tractive effort at the draw-bar coupling, measured through a load-pin.

Depending on the experiment, all of the measurements were taken or a sub-set was collected, for example, inside the laboratory hydrogen flow was not measured as hydrogen is not permitted in the building. Further data that would have been useful to collect are: output voltage and current of the traction motor controller, current used by auxiliaries, and the torque of the traction motors. However, due to resource constraints this could not be implemented. In addition, a load for the locomotive such as carriages was not available, so all experiments were conducted with the locomotive only, resembling locomotive light running on the operational railway. Consequently, the force at the drawbar was not measured.

All the collected data had to be calibrated and processed before a data analysis was possible, two examples are: (1) The tachometer is mounted on the lay-shaft and, therefore, the gearing ratio and distance that the locomotive covers during one wheel revolution had to be taken into account to determine the speed. (2) The hydrogen flow meter output is a voltage; this voltage corresponds to a particular hydrogen flow rate. To determine the actual hydrogen quantity consumed at any point a conversion had to take place. Table 26 shows the conversion functions for all measurements to the desired units.

Table 26: Conversion Table for Data Collection

Component	**Unit of Measurement**	**Unit of Data Desired**	**Conversion Function**
Tachometer	tachometer count (number)	distance (m)	**Distance in metres per tachometer count s (m)** = tachometer count × distance travel per wheel revolution in metres × gearing ratio / tachometer counts per lay shaft revolution **s (m)** = tachometer count × 0.651 × (13/22) / 400
Batteries	tension (V)	tension (V)	The recorded voltage of each battery did not need any conversion
Batteries	tension (V)	current (A)	**Current (A)** = Voltage of data acquisition × 25
Power-Plant	tension (V)	current (A)	**Current (A)** = Voltage of data acquisition × 25
Traction Motor Controller	tension (V)	current (A)	**Current (A)** = Voltage of data acquisition × 12.5
Load-Pin	current (A)	load (lbf)	**Load (lbf)** = (current of data acquisition - 12) × 500
Hydrogen Flow Meter	tension (V)	volume (ln/min)	**normal litres per minute (ln/min)** = Voltage of data acquisition / k **ln/min** = (voltage of data acquisition – zero offset) / 0.25 *zero offset* = 0.060707973 (as measured)
Hydrogen Flow Meter	tension (V)	mass (g/min)	**grams per minute (g/min)** = Voltage of data acquisition / k **g/min** = (voltage of data acquisition – zero offset) / (5 / 1.8) *zero offset* = 0.060707973 (as measured)

The data collection and the subsequent processing, as described above and in Table 26, allowed data presentation in meaningful terms and is the style in which the data is presented in this chapter. In the next part the experiments and their results are discussed.

6.2 Run-Down Experiment

The resistance to motion for railway vehicles is often described through the Davis equation (W. J. Davis, 1926; Rochard & Schmid, 2000):

(7)

Where: Term A is independent of speed and mainly influenced by the mass of the vehicle, accounting for rolling resistance, track resistance, and friction in bearings. Term B increases proportionally with speed and accounts for flange friction, swaying and oscillation. Term C increases with the square of the speed and accounts for aerodynamic drag (W. J. Davis, 1926). Traditionally, the Davis parameters, A, B, and C, are determined through run-down tests of railway vehicles (Rochard & Schmid, 2000), which is the approach that was taken to determine the resistance to motion of the Hydrogen Pioneer. The Davis parameters do not include the resistance that results from the horizontal or vertical curvature of the track, and these have not been accounted for in this experiment.

6.2.1 Test Method

In this part the experiment set-up is described and thereafter the procedure discussed, before moving on to the results of the run-down tests.

Experiment Set-Up

The test track was installed in the BCRRE laboratory to conduct the run-down test. This allowed a straight, level alignment and an environment that is protected from external influences, such as high winds. The laboratory is spacious enough not to create higher air resistance, which would occur in small enclosed spaces, such as tunnels. Further, it was anticipated that the resistance resulting from aerodynamic drag would be negligible due to the low operating speed of the locomotive. Figure 66 shows the installed track for the run-down test in the BCRRE laboratory.

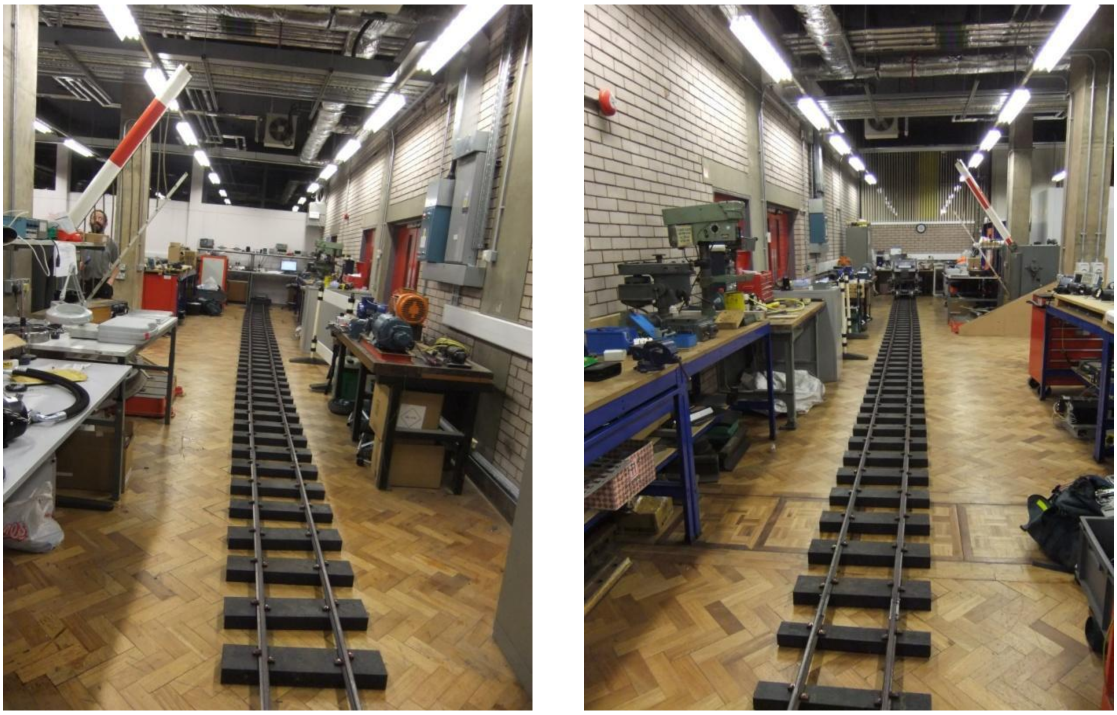


Figure 66: Installed Test Track in the BCRRE Laboratory to Conduct Run-Down Test (Author's Collection, 2013)

The distance that could be traversed along the track was 14 metres, which allowed tests within the normal operation speed of the locomotive.

The Hydrogen Pioneer is usually operated with an on-board hydrogen tank but, due to University safety regulations, it was not possible to have a hydrogen cylinder within the laboratory. For this reason, 16 kg were added to the locomotive to account for the missing tank, which is the same mass as the tank used for the other experiment discussed in this chapter. The installed weights can be seen in Figure 67.

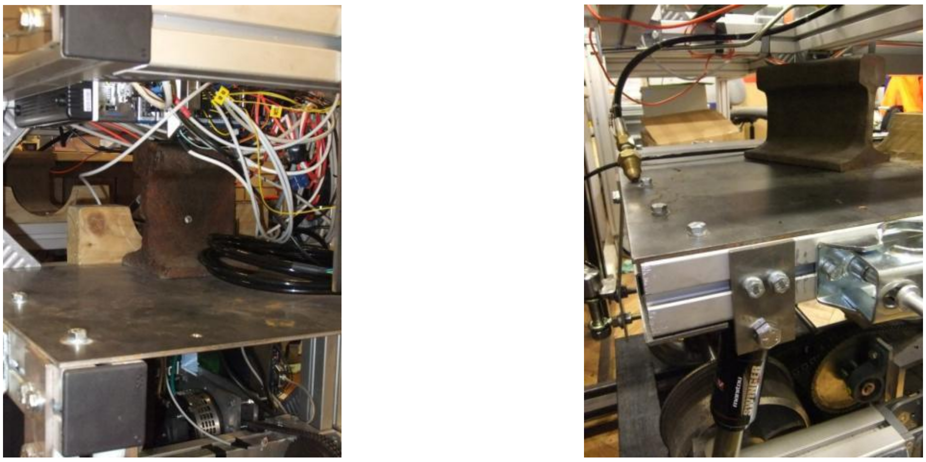


Figure 67: Additional Weights on the Locomotive to Account for the Mass of a Hydrogen Tank (Author’s Collection, 2013)

The traction motors were electrically isolated to ensure that regenerative braking was not employed, and the mechanical brakes were deactivated. Only the emergency brake was functional to allow for a quick stop if necessary.

Experiment Procedure

For the run-down test the locomotive was placed onto the test track, as shown in Figure 68, and the on-board data collection system was activated.

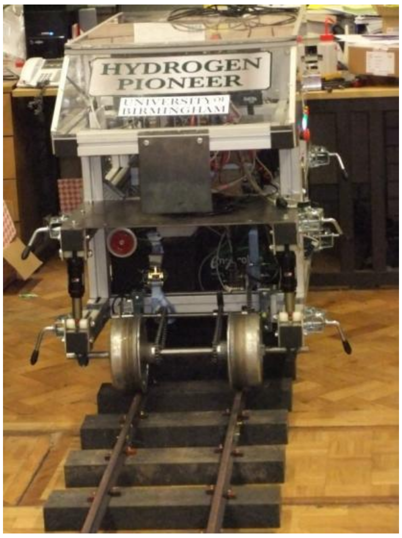


Figure 68: Hydrogen Pioneer Locomotive on the Test Track (Author’s Collection, 2013)

Next, the locomotive was accelerated through persons pushing the vehicle, who then released it at an observed target speed as seen on the tachometer display on the tablet computer. Thereafter, the locomotive coasted along the track to a standstill, without application of the brakes. Therefore, resistance to motion was the only force to overcome. After the test was completed, the collected data were transferred to an off-board computer to be processed and analysed.

Several tests with increasing release speeds were conducted to allow an estimation of the maximum safe target speed that would lead to the locomotive stopping before the end of the test track.

The most extensive data set to determine the Davis parameters is achieved at the highest release speed, because more data are collected and the resistance at lower speeds is naturally recorded during the slowing-down process of the vehicle. The highest speed that could be achieved safely was around 8 km/h, and the corresponding data set was used to determine the Davis parameters.

6.2.2 Run-Down Experiment Results

The collected data were tabulated and a function derived that fits the experimental data and conforms to the general Davis equation, as described earlier in the section. Modelling of the braking performance of the Hydrogen Pioneer was employed to establish its resistance to motion function. The measured data were transferred to a spreadsheet and the “solver” capability of Microsoft Excel employed to determine the equation with the lowest number of exponential terms that closely matched the measured values. The measured speed and the derived function are illustrated in Figure 69.

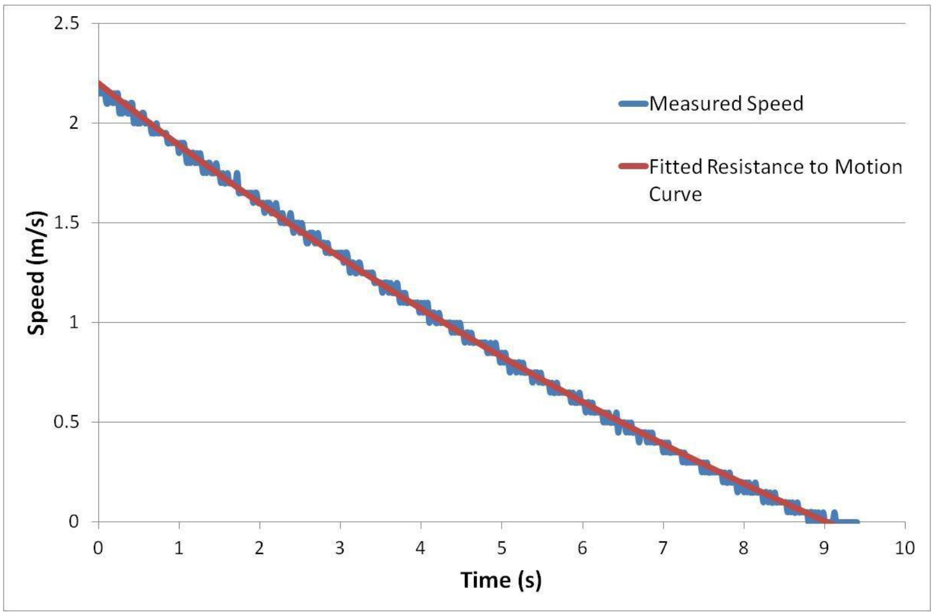


Figure 69: Measured Resistance to Motion and Derived Davis Equation Curve

From Figure 69 it can be seen that the calculated function provides a close match to measured deceleration. The function is as follows:

Where the Davis parameter A is 0.052 kN and B is 0.018 kN when rounded. (8)

Equation (8) above is the Davis equation for the Hydrogen Pioneer locomotive, without a trailing load. A coefficient C is not present, as was expected. Davis (1926) explains that an equation without an exponential term is to be anticipated for light vehicles that travel at low speeds and have a small cross section. The Hydrogen Pioneer conforms to these conditions.

The derived Davis equation allows computer modelling of the locomotive and, further, it is used in the analysis and interpretation of the data that was obtained through the other locomotive operation experiment.

6.3 Locomotive Operation Experiment

The purpose of the tests described in this section was to determine the vehicle efficiency, or tank-to-wheel efficiency, of the Hydrogen Pioneer locomotive. Tests that establish the vehicle efficiency of any hydrogen-powered railway vehicle have not been conducted before, to the author's knowledge. Therefore, the experiment and results are novel.

6.3.1 Test Method

In this part the experimental set-up is described and, thereafter, the procedure is discussed, before moving on to the results of the locomotive operation tests.

Experiment Set-Up

The tests were conducted outside; adjacent to the building that houses the BCRRE laboratory. The test track had a length of 30 metres, which was the maximum length available to the author, but only part of the track was used for the experiments to ensure safe stopping of the locomotive before the end of the line. The track only included straight alignment and a reasonably level right of way; however, a small gradient could not be avoided. It was assembled on gravel, similar to ballast, on a property that is currently used for car parking. The constructed test track is shown in Figure 70.

Figure 70: Test Track Alignment for Locomotive Operation Tests (Author's Collection, 2013)

The Hydrogen Pioneer was operated with hydrogen contained in a pressurised 200 bar standard gas cylinder, see Figure 71 depicting the red cylinder, which had a mass of 16 kg and was sourced from BOC. The cylinder is the UK equivalent to the tank used in Germany that is described in the previous chapter. All systems of the locomotive that were necessary to determine the vehicle efficiency were operational. The drawbar force was not measured because a trailing load was not available, so the tests are similar to locomotive light running on the operational railway.

Experiment Procedure

The locomotive was placed on the test track and operated in the forward and reverse directions. Figure 71 shows the locomotive on the test track prior to the start of the experiment.

Figure 71: Hydrogen Pioneer on Test Track Ready for Vehicle Efficiency Evaluation Tests (Author's Collection, 2013)

Tests at various selected maximum speeds of the locomotive were conducted to show the respective energy contribution of the power-plant and battery-pack. Attempts were made to find a speed at which the power-plant provides all the energy needed for vehicle movement while the battery-pack is not charged. The reason is that the primary drive-train is considered to be fuelled by hydrogen, and the results will allow comparison with other non-hybrid railway traction technologies. The speed was found to be between 6 km/h and 7 km/h and the results for both speeds are shown.

Further tests, at a much lower speed of 2 km/h, where the power-plant is charging the battery-pack as well as driving the vehicle, and much higher speed of 10 km/h, where the batteries provide additional energy to power the vehicle, were undertaken.

Each speed test consisted of five forward and five reverse movements, covering a distance in each move of between 20 and 25 metres, allowing for safe stopping of the locomotive at either end of the track. The vehicle accelerated as fast as possible to the selected maximum speed and, once the marker point for the experiment distance was reached, slowed as quickly as possible, utilising the regenerative service brake. Then, the run in the opposite direction started. The procedure continued until five laps were completed.

6.3.2 Locomotive Operation Experiment Results

The locomotive operation experiment results are presented and discussed in this section. First, processing that was undertaken for all tests is described, and thereafter the specific results for each test presented, starting with the lowest operating speed.

The presentation of the results for each test has the following sequence: (i) The distance graph of the duty cycle is shown, (ii) the speed graph is shown, (iii) the power graph is presented, and (iv) the energy account graph for the duty cycle is presented, followed by (v) an energy account for the whole duty cycle and during steady state operation. Thereafter, the (vi) total relative energy input and energy consumer shares are shown in a diagram. The section is completed with a discussion about the test results. A more general discussion covering all the tests is provided in a separate section after the 10 km/h test.

General Processing

The collected data were transferred to an off-board computer and converted to scientific units as described earlier in the chapter. However, further processing was needed for suitable data presentation, which is described here. All the results, data analysis, and data presentation conform to the law of conversion of energy, and the term *loss* is used in this context to refer to energy that could not be utilised for a useful purpose but led to non-recoverable heat generation. The lower heating value of hydrogen, at 120.21 MJ/kg, has been applied to all relevant calculations.

The electrical drive-train, or DC-BUS, can be fed either from the power-plant or the battery-pack or a combination of both. The power output of the DC-BUS is used to drive the traction motors, supply power to auxiliaries and, depending on the operating conditions, to charge the battery-pack.

The auxiliary power value was not measured but was determined through calculation: From the total DC-BUS input, the motor controller power and, depending on the operating condition, the power to charge the battery-pack is subtracted. The result is the power consumed by the auxiliaries and the losses in the DC-BUS, which are considered negligible due to the short cable length. Auxiliaries are all the components that are not directly necessary for the drive-train but are necessary for vehicle operation; they include: the Compact Rio control computer, the wireless router, the traction motor controller, all the measurement sensors, and the deactivation mechanism for the mechanical brakes.

In all graphs a battery-pack power contribution to the drive-train is indicated through positive values, and the charging of the battery-pack is indicated through negative values.

2 km/h Maximum Speed Test

In this test the target line-speed of the locomotive was 2 km/h (0.55 m/s), and each run was approximately 21 metres long, as shown in Figure 72. The target speed was maintained for the majority of the time, as illustrated in Figure 73. A slight variation in the actual speed can be observed between forward and reverse runs, indicating the gradient in the alignment, which resulted from the ground on which the track was assembled. The gradient does not have a large effect on the other results as the slightly higher energy consumption during the uphill run is balanced by the lower energy consumption during the downhill run.

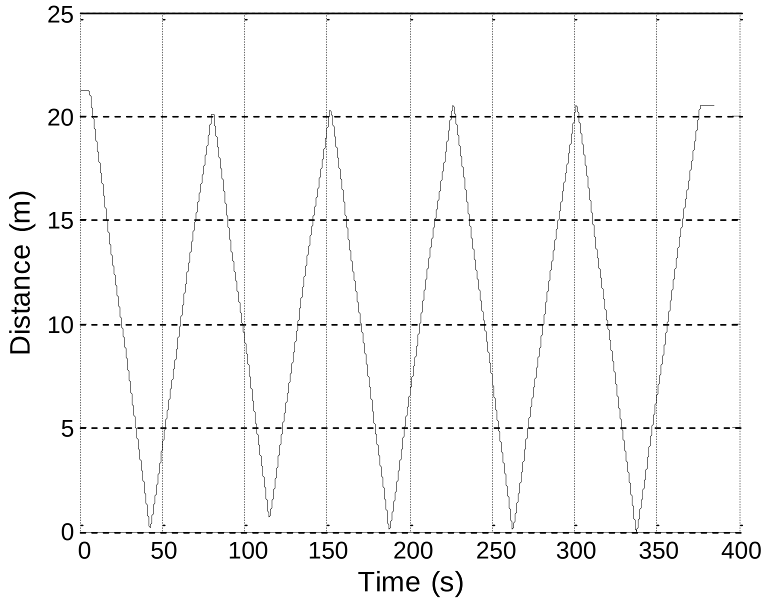


Figure 72: Distance Covered in the 2 km/h Runs

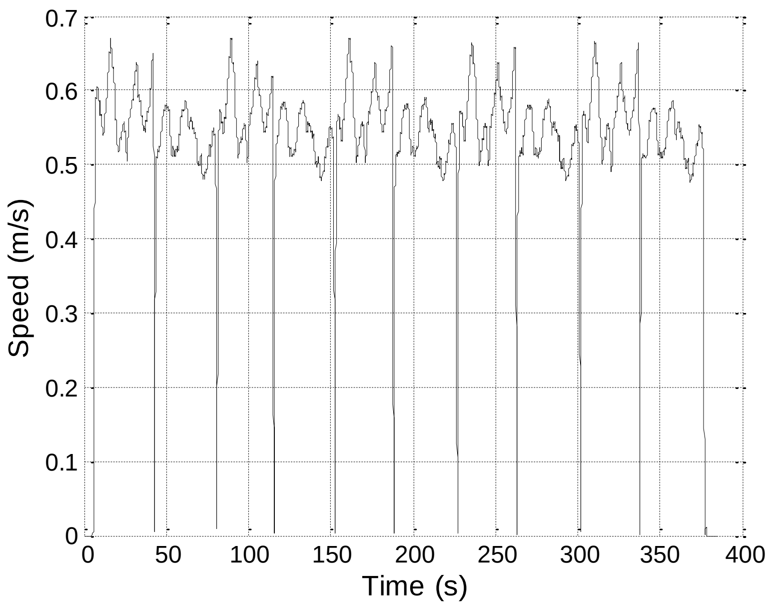
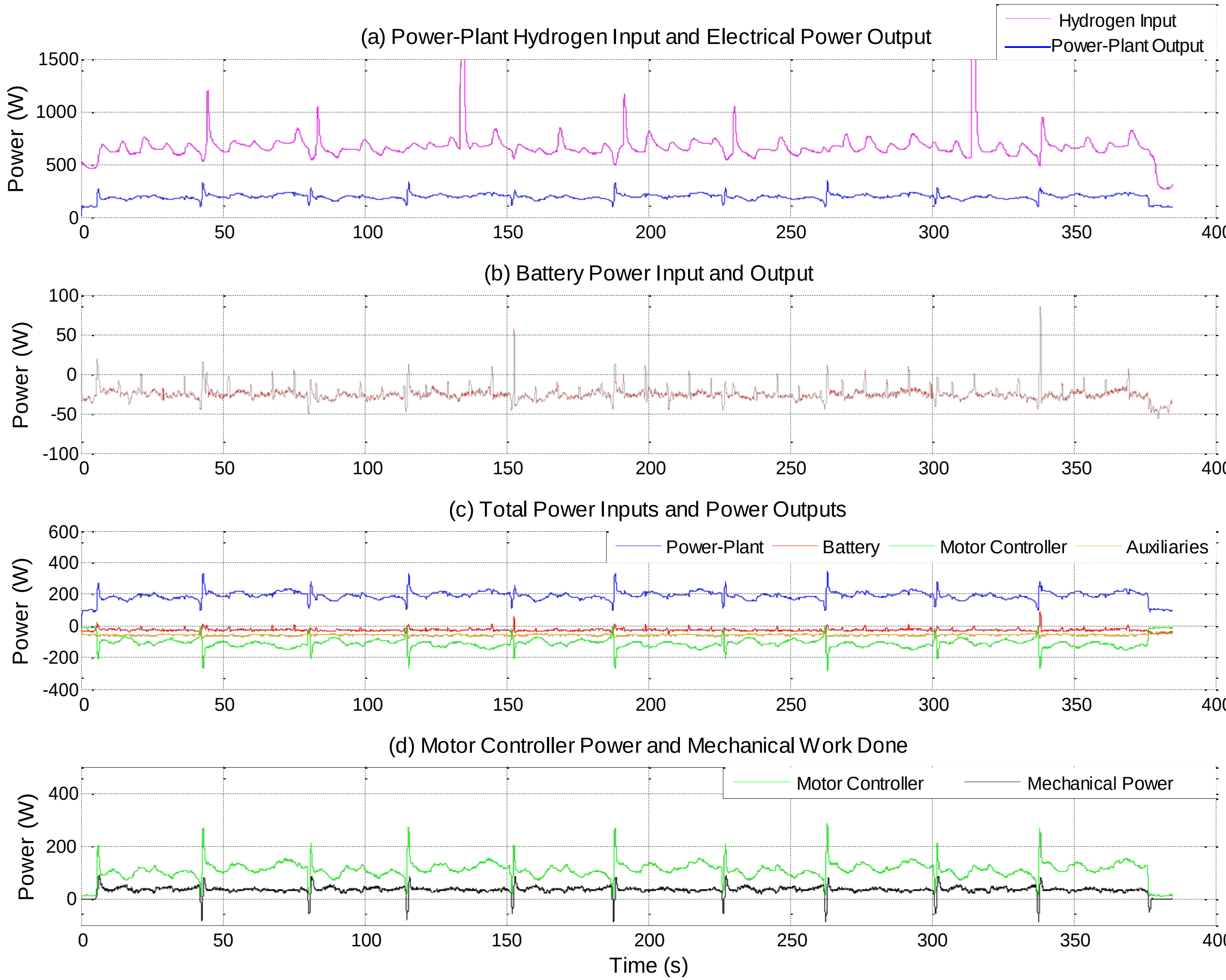


Figure 73: Actual Speed Graph of the 2 km/h Runs

The power that was necessary to complete the duty cycle is presented in Figure 74.


(a) Power-Plant Hydrogen Input and Electrical Power Output
Hydrogen Input
Power-Plant Output
Power (W)
(b) Battery Power Input and Output
Power (W)
(c) Total Power Inputs and Power Outputs
Power-Plant
Battery
Motor Controller
Auxiliaries
Power (W)
(d) Motor Controller Power and Mechanical Work Done
Motor Controller
Mechanical Power
Power (W)
Time (s)

Graph (a) in Figure 74 shows the hydrogen input into the power-plant and the corresponding electrical-power output of the plant. The peaks in the hydrogen-power are due to power-plant maintenance, where the fuel cells are purged with additional hydrogen to remove excess water in the power-plant. The hydrogen used for purging is not converted to power but ensures the reliable operation of the fuel cells.

Graph (b) shows the power contribution of the battery-pack, and it can be seen that the batteries are being charged for the majority of the duty cycle. Additionally, the battery-pack provides power in high power demand situations, such as during acceleration, which is illustrated by the positive peak values. Also, power recovered from regenerative braking is visible at the negative peak values.

Graph (c) shows the DC-BUS power inputs and outputs. The outputs are represented as negative values. The auxiliary power consumption remains relatively constant throughout the duty cycle, and the majority of the input-power is transferred to the traction motor controller and consequently to the traction motors.

Graph (d) shows the power-input to the traction motors and the power required to overcome the resistance to motion, based on the Davis equation determined earlier, combined with the power necessary or gained during acceleration of the vehicle, in other words its kinetic power.

The cumulative integration of the power of each main component over time, or in other words the cumulative energy distribution during the duty cycle, is visually presented in Figure 75. The *Hydrogen* designation in the graph's legend refers to hydrogen input into the power-plant. The depletion of hydrogen in the pressurised tank is not shown.

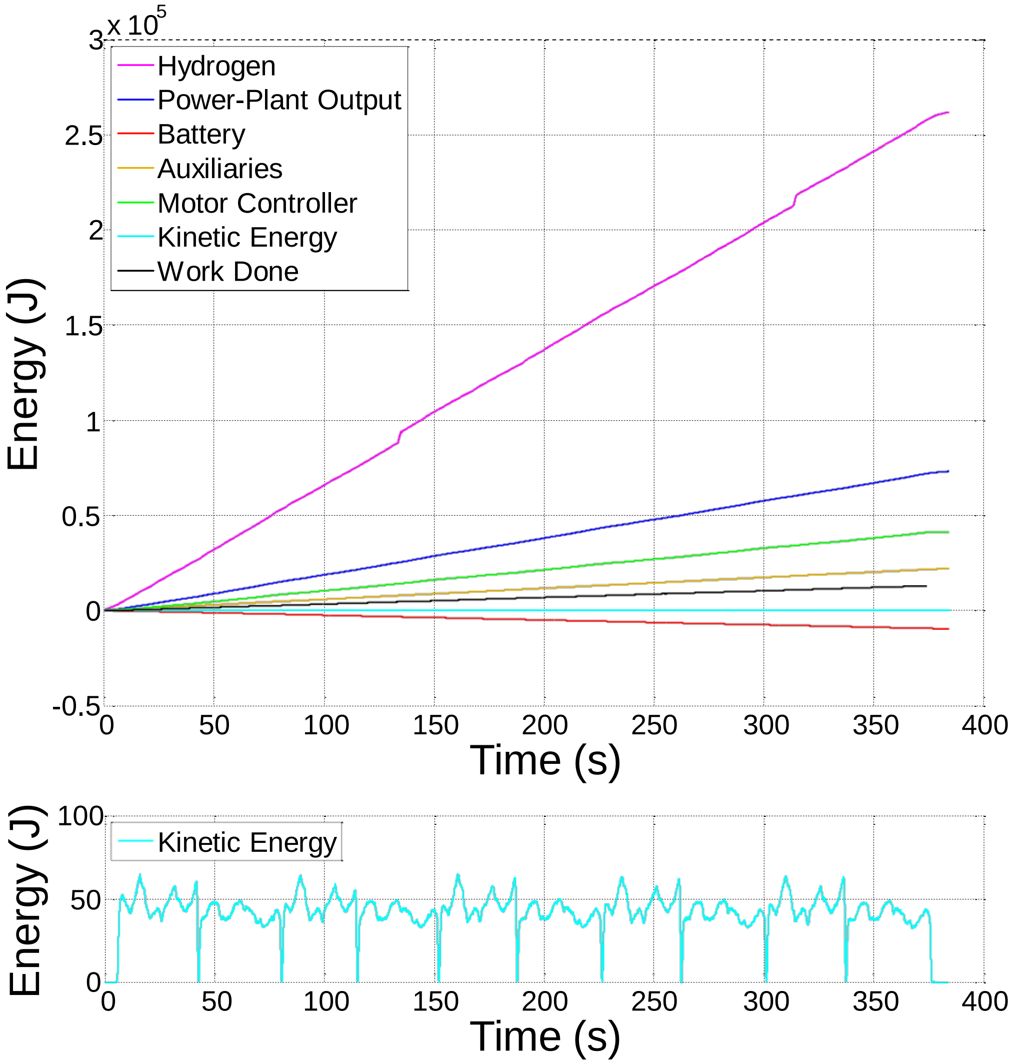


Figure 75: Duty Cycle Energy Graph for the 2 km/h Runs

In Figure 75 it can be seen that the overall energy consumption is rising with the time of operation, as can be expected. Further, it is shown that the battery-pack is overall increasing its charge and, therefore, the power-plant is providing the energy necessary to move the vehicle as well as charging the battery-pack. The kinetic energy has a value of zero at the beginning and at the end of the duty cycle when the vehicle is not moving, and is, due to the low operating speed, a straight line in top part of Figure 75 and the kinetic energy is shown in the bottom part of the figure in an expanded scale. The work done accounts for the energy that was required to overcome the resistance to motion during the duty cycle. The energy values at the end of the duty cycle as well as during steady state operation, being the energy required to maintain the vehicle speed after initial acceleration, are shown in Table 27. The account shows: in the first column, energy that is not used for the motion of the vehicle; in the second column, energy that is available for the motion of the vehicle, both columns designated in joules; in the third column, the drive-train component loss or energy available at the component in percentages; and in the fourth column, the cumulative tank-to-wheel efficiency chain in percentage. All the values presented in percentages have been rounded to the closest integer.

Table 27: Duty Cycle Energy Account for the 2 km/h Runs

DUTY CYCLE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Hydrogen		261696		100
Power-Plant	188630		72	
Electrical Energy Input		73066		28
Non Traction Consumption				
Battery-Pack Charge	9774		13	
Auxiliary and Electrical Drive-Train Losses	22008		30	
Total Non Traction Consumption	31782		43	
Traction Consumption				
Energy Available at Traction Motor Controller		41284	57	16
Traction Motors and Mechanical Drive-Train	28795		70	
Energy Consumed to Overcome Resistance to Motion		12489	30	5
Vehicle Efficiency				5

STEADY STATE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Primary Energy Input as Hydrogen		684		100
Power-Plant	481		70	
Electrical Energy Input		203		30
Non Traction Consumption				
Battery-Pack Charge	23		11	
Auxiliary and Electrical Drive-Train Losses	59		29	
Total Non Traction Consumption	82		40	
Traction Consumption				
Energy Available at Traction Motor Controller		121	60	18
Traction Motors and Mechanical Drive-Train	88		73	
Energy Consumed to Overcome Resistance to Motion		33	27	5
Vehicle Efficiency				5

From the energy accounts it can be seen that the overall efficiency is higher in the steady state compared to the duty cycle, which is expected, as the plant can operate in a continuous state rather than having to react to changes in energy demand. This is consistent with full scale experiments of electric traction vehicles (UIC, 2003). However, in our experiment the variation between the steady state and the duty cycle efficiency is low, which suggests a quick, reactive response to the change in demand. In Figure 76 the energy input share and the energy consumption distribution respective to the total energy input is presented.

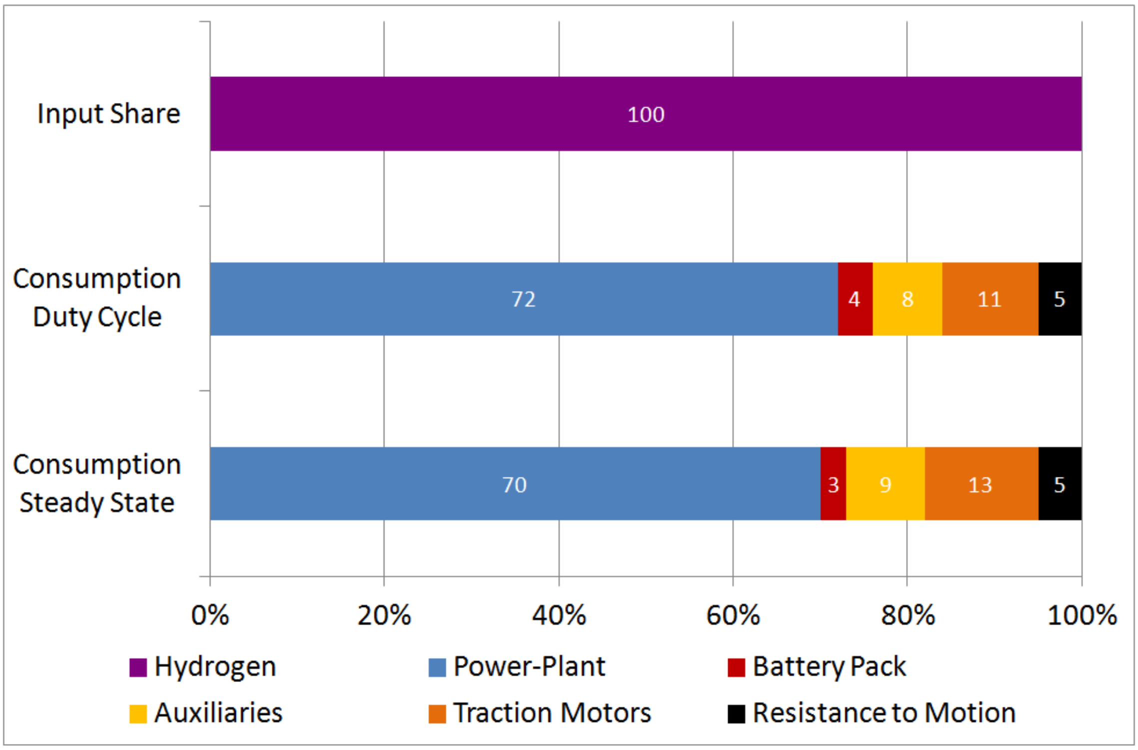


Figure 76: Energy Input Share and Tank-to-Wheel Losses of the 2 km/h Runs

From the energy accounts and Figure 76 it can be seen that the majority of the input energy is consumed in the power-plant, given its low efficiency. This is due to the relatively low power demand and, therefore, the operation of the plant in suboptimum conditions.

An additional large amount of energy is lost in the traction motors and mechanical drive train, with an efficiency of 30 % in the duty cycle and 27 % in the steady state. At such low speed the traction motors operate far from their maximum efficiency, similar to the power-plant. If the vehicle were designed to operate mainly at these speeds, then, a different gearing ratio as well as a less powerful power-plant would allow for more efficient operation of the entire system.

The battery-pack is being charged during the whole duty cycle as well as in the steady state but provides power when necessary, such as in the acceleration phase. Therefore, it is demonstrated that the hybrid concept of the vehicle is operating as designed, with the battery-pack providing the peak power.

Auxiliaries account for less than 10 % of the total energy used. However, some of the auxiliary components have comparatively constant absolute power consumption, increasing the relative consumption in low power electrical drive-train cases, such as in this test.

The overall vehicle efficiency is low at 5 %, which indicates that the locomotive is not meant to operate at such slow speeds for extended periods of time, which is consistent with the original design objective. The duty cycle and steady state vehicle efficiency are very similar and, when rounded, the same.

The results of the other three tests follow the same presentation style as this test and, hence, the detailed description of the graphs and accounts has been omitted in the next sections. A general discussion about all tests follows the 10 km/h results. The power-plant and vehicle efficiencies of all tests are presented in Figure 92, which allows a summarised overview of the vehicle's performance.

6 km/h Maximum Speed Test

In this test the target line-speed of the locomotive was 6 km/h (1.67 m/s), and each run was approximately 25 metres long, as shown in Figure 77. The target speed was maintained for the majority of the time, as illustrated in Figure 78.

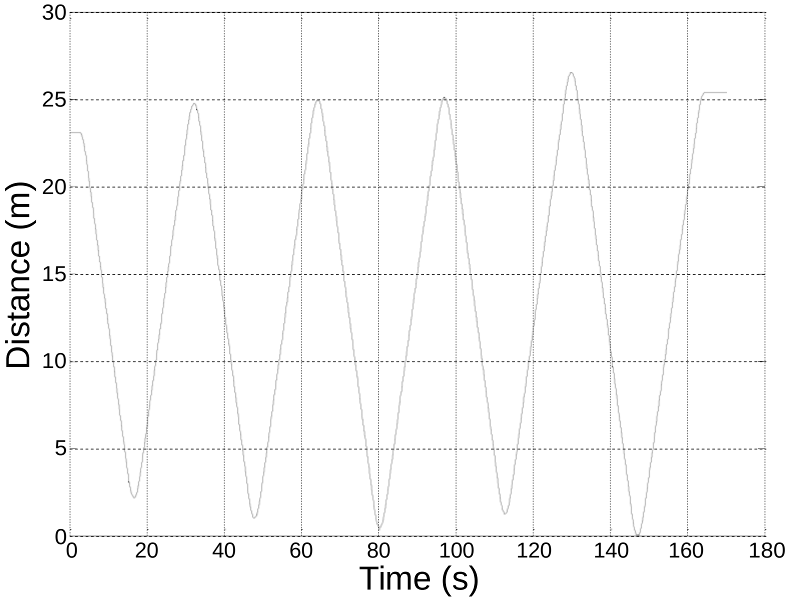


Figure 77: Distance Covered in the 6 km/h Runs

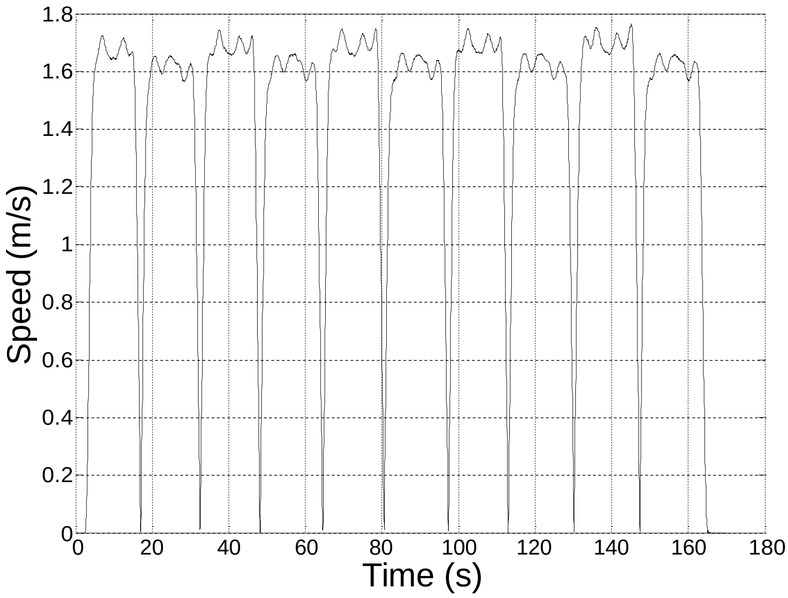
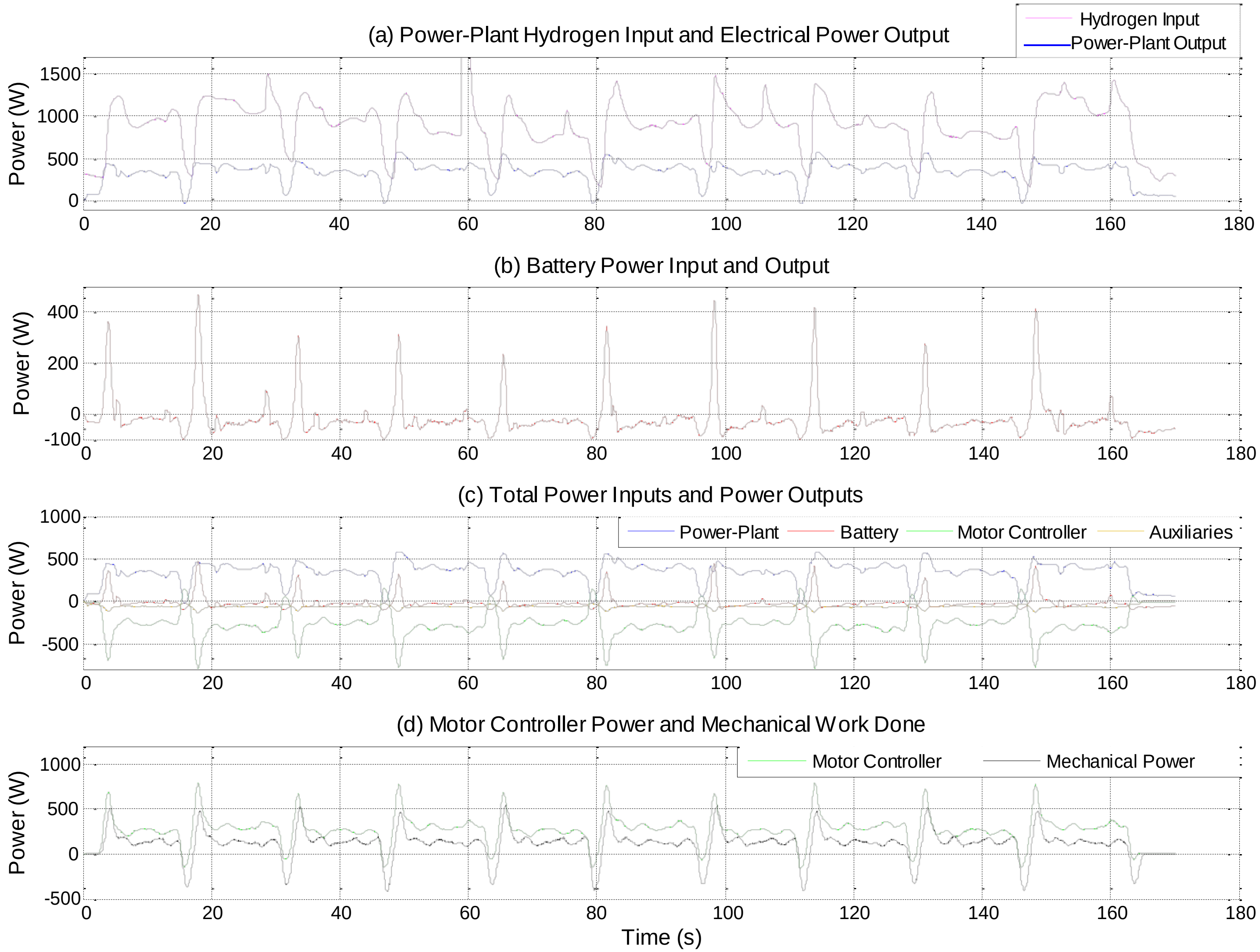


Figure 78: Actual Speed in the 6 km/h Runs

The power that was necessary to complete this duty cycle is presented in Figure 79.


(a) Power-Plant Hydrogen Input and Electrical Power Output
Hydrogen Input
Power-Plant Output
Power (W)
(b) Battery Power Input and Output
Power (W)
(c) Total Power Inputs and Power Outputs
Power-Plant
Battery
Motor Controller
Auxiliaries
Power (W)
(d) Motor Controller Power and Mechanical Work Done
Motor Controller
Mechanical Power
Power (W)
Time (s)

The cumulative energy distribution during the duty cycle is visually presented in Figure 80.

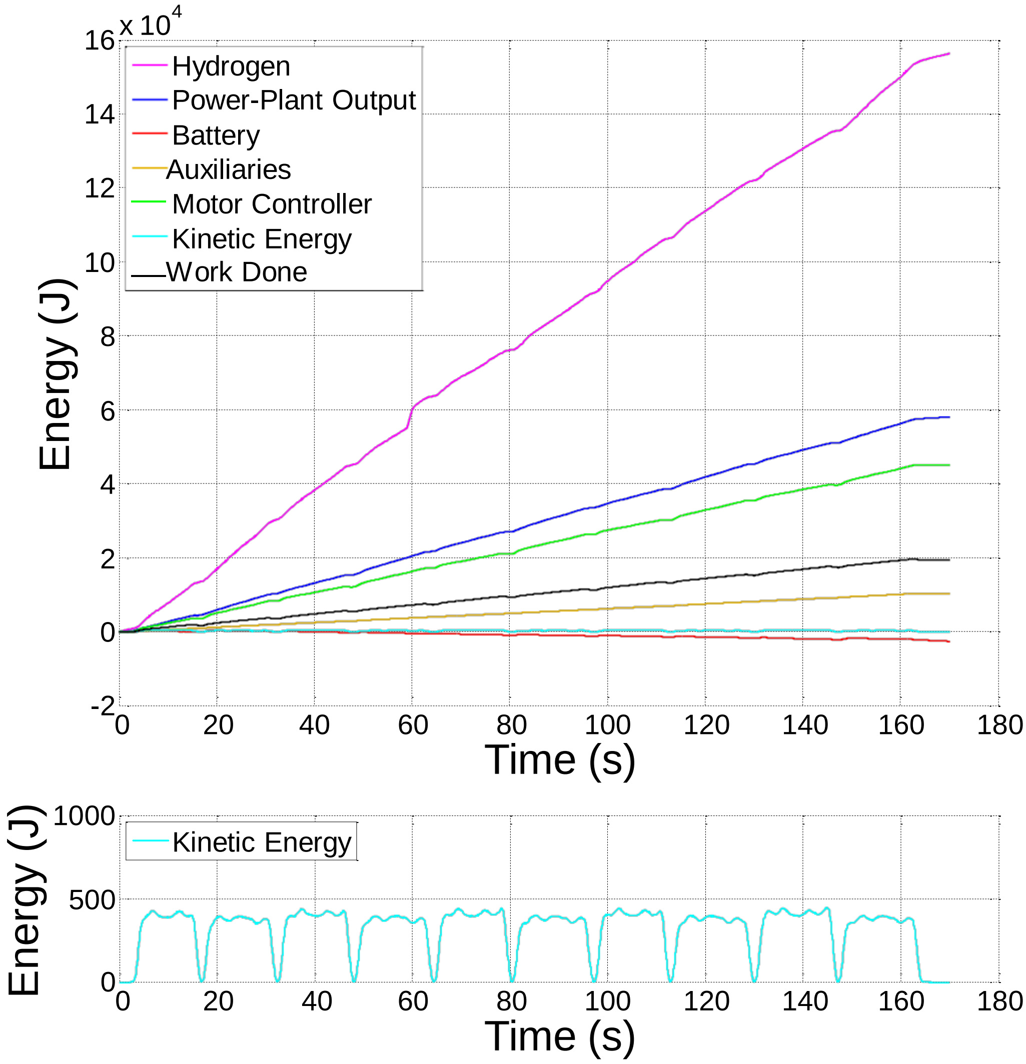


Figure 80: Duty Cycle Energy Graph for the 6 km/h Runs

The energy values at the end of the duty cycle as well as during steady state operation, being the energy required to maintain the vehicle speed after initial acceleration, are shown in Table 28.

Table 28: Duty Cycle Energy Account for the 6 km/h Runs

DUTY CYCLE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Hydrogen		156290		100
Power-Plant	98247		63	
Electrical Energy Input		58043	37	37
Non Traction Consumption				
Battery-Pack Charge	2541		4	
Auxiliary and Electrical Drive-Train Losses	10398		18	
Total Non Traction Consumption	12939		22	
Traction Consumption				
Energy Available at Traction Motor Controller		45104	78	29
Traction Motors and Mechanical Drive-Train	25690		57	
Energy Consumed to Overcome Resistance to Motion		19414	43	12
Vehicle Efficiency				12

STEADY STATE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Primary Energy Input as Hydrogen		914		100
Power-Plant	525		57	
Electrical Energy Input		389	43	43
Non Traction Consumption				
Battery-Pack Charge	26		7	
Auxiliary and Electrical Drive-Train Losses	62		16	
Total Non Traction Consumption	88		23	
Traction Consumption				
Energy Available at Traction Motor Controller		301	77	33
Traction Motors and Mechanical Drive-Train	172		57	
Energy Consumed to Overcome Resistance to Motion		129	43	14
Vehicle Efficiency				14

In Figure 81 the energy input share and the energy consumption distribution respective to the total energy input is presented.

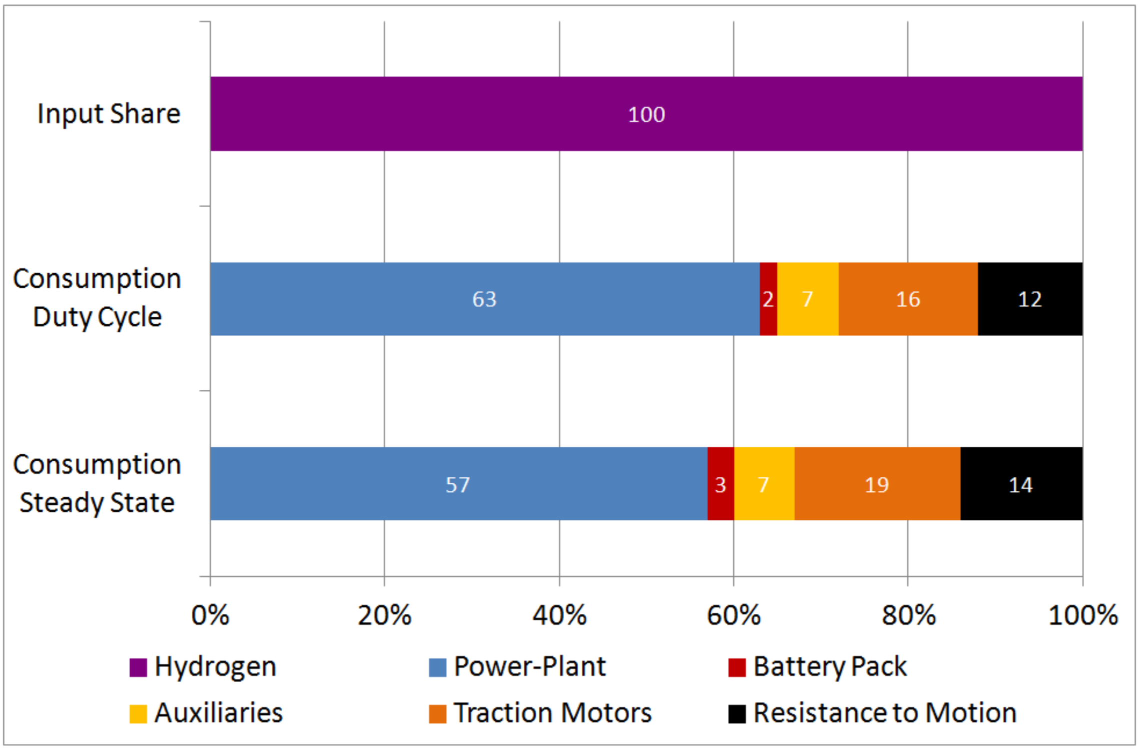


Figure 81: Energy Input Share and Tank-to-Wheel Losses for the 6 km/h Runs

From the energy accounts and Figure 81 it can be seen that the majority of the input energy is consumed in the power-plant, where the chemical to electrical energy conversion occurs. The power-plant efficiency of around 40 % was expected and matches the specifications provided by the manufacturer.

Auxiliaries account for around 7 % of the total energy; a smaller value than for the lower operating speed, as expected. This is due to the constant power consumption of some of the auxiliary components as already indicated in the lower operating speed test above.

The overall vehicle efficiency is 12 % during the duty cycle and 14 % in the steady state. The efficiency is lower than anticipated and mainly due to the relatively low efficiency of the traction motors; the power-plant performs as expected. The performance suggests that traction motor changes, or modifications to the mechanical drive-train may be necessary to increase the vehicle efficiency.

7 km/h Maximum Speed Test

In this test the target line-speed of the locomotive was 7 km/h (1.94 m/s), and each run was approximately 25 metres long, as shown in Figure 82. The target speed was maintained for the majority of the time, as illustrated in Figure 83.

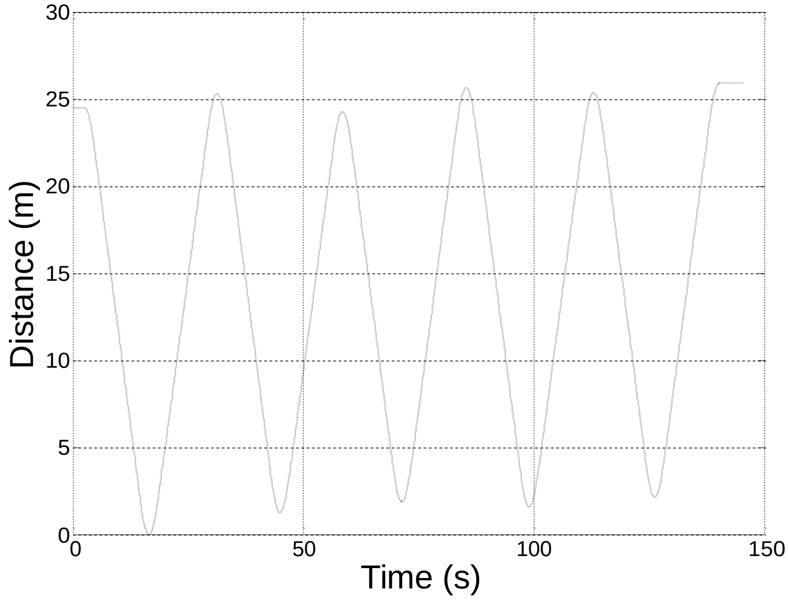


Figure 82: Distance Covered in the 7 km/h Runs

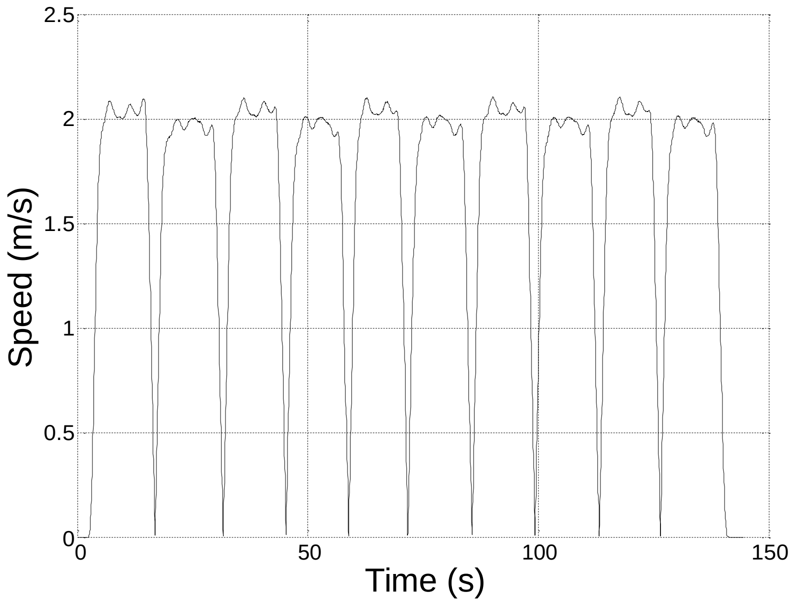
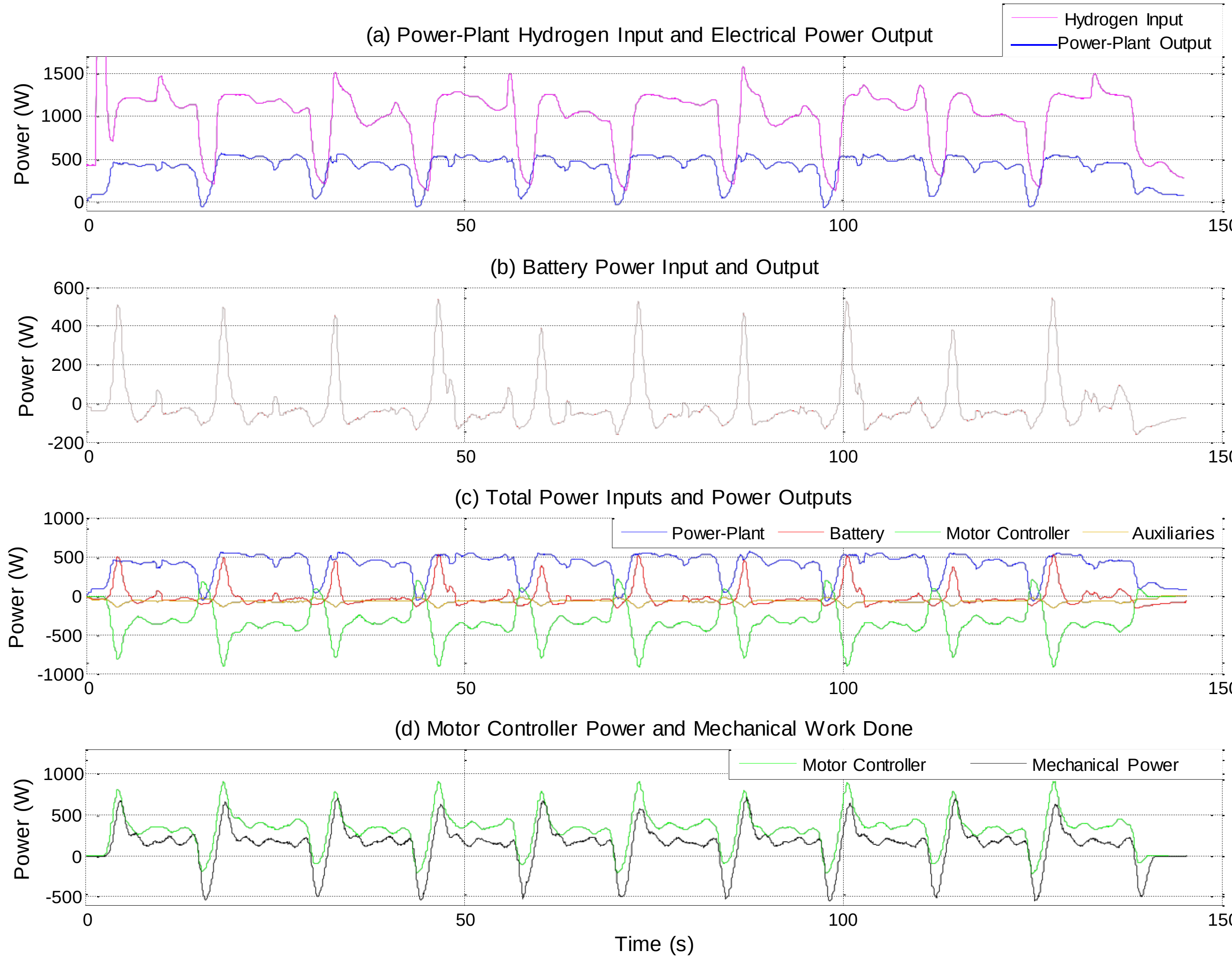


Figure 83: Actual Speed in the 7 km/h Runs

The power that was necessary to complete the duty cycle is presented in Figure 84.



(a) Power-Plant Hydrogen Input and Electrical Power Output
Hydrogen Input
Power-Plant Output
Power (W)
1500
1000
500
0
0
50
100
150
(b) Battery Power Input and Output
Power (W)
600
400
200
0
-200
0
50
100
150
(c) Total Power Inputs and Power Outputs
Power-Plant
Battery
Motor Controller
Auxiliaries
Power (W)
1000
500
0
-500
-1000
0
50
100
150
(d) Motor Controller Power and Mechanical Work Done
Motor Controller
Mechanical Power
Power (W)
1000
500
0
-500
0
50
100
150
Time (s)

The cumulative energy distribution during the duty cycle is visually presented in Figure 85.

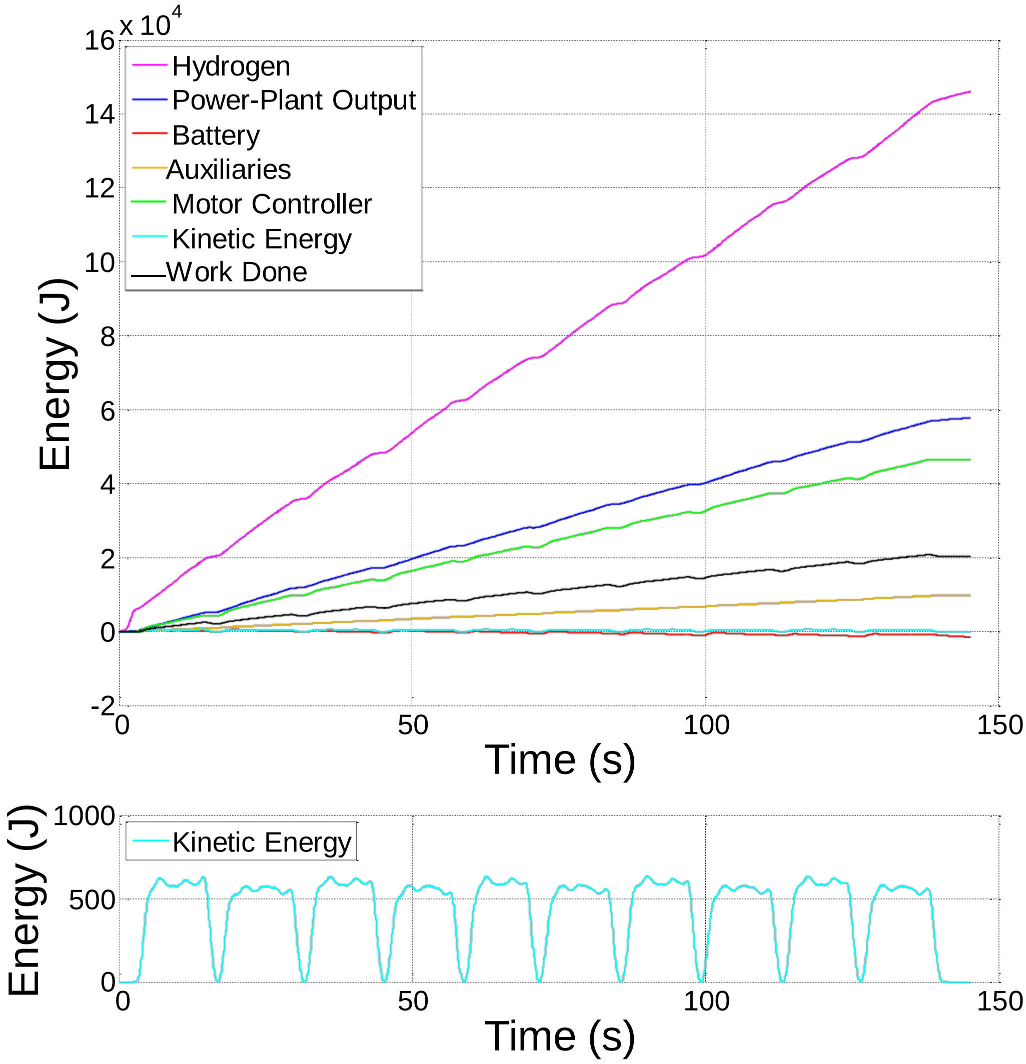


Figure 85: Duty Cycle Energy Graph for the 7 km/h Runs

The energy values at the end of the duty cycle as well as during steady state operation are presented in Table 29.

Table 29: Duty Cycle Energy Account for the 7 km/h Runs

DUTY CYCLE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Hydrogen		145867		100
Power-Plant	88101		60	
Electrical Energy Input		57766	40	40
Non Traction Consumption				
Battery-Pack Charge	1390		2	
Auxiliary and Electrical Drive-Train Losses	9813		17	
Total Non Traction Consumption	11203		19	
Traction Consumption				
Energy Available at Traction Motor Controller		46563	81	32
Traction Motors and Mechanical Drive-Train	26129		56	
Energy Consumed to Overcome Resistance to Motion		20434	44	14
Vehicle Efficiency				14

STEADY STATE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Primary Energy Input as Hydrogen		1189		100
Power-Plant	680		57	
Electrical Energy Input		509	43	43
Non Traction Consumption				
Battery-Pack Charge	52		10	
Auxiliary and Electrical Drive-Train Losses	70		14	
Total Non Traction Consumption	122		40	
Traction Consumption				
Energy Available at Traction Motor Controller		387	76	33
Traction Motors and Mechanical Drive-Train	214		55	
Energy Consumed to Overcome Resistance to Motion		173	45	15
Vehicle Efficiency				15

In Figure 86 the energy input share and the energy consumption distribution respective to the total energy input is presented.

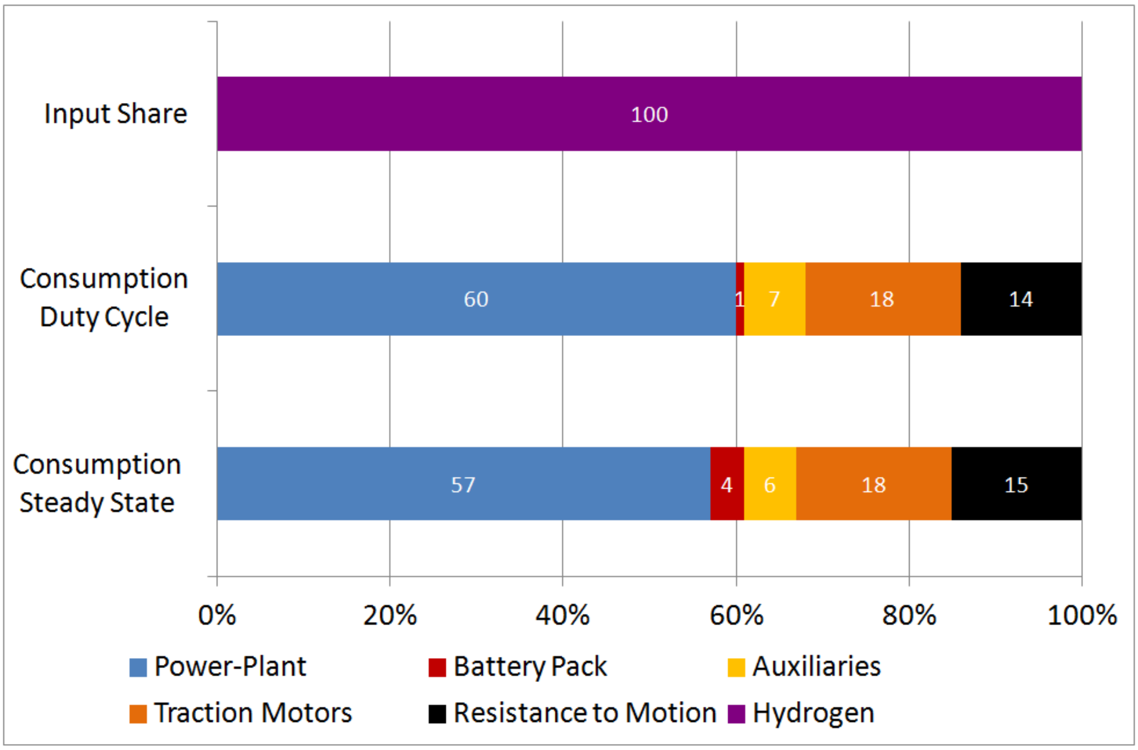


Figure 86: Energy Input Share and Tank-to-Wheel Losses for the 7 km/h Runs

The overall vehicle efficiency is 14 % during the duty cycle and 15 % in the steady state. The efficiency is lower than anticipated, mainly due to the relatively low efficiency of the traction motors; the power-plant performs as expected. This suggests that traction motor changes or modifications to the mechanical drive-train may be necessary to increase the vehicle efficiency.

10 km/h Maximum Speed Test

In this test the target line-speed of the locomotive was 10 km/h (2.7 m/s), and each run was approximately 22 metres long, as shown in Figure 87. The target speed was maintained for the majority of the time, as illustrated in Figure 88.

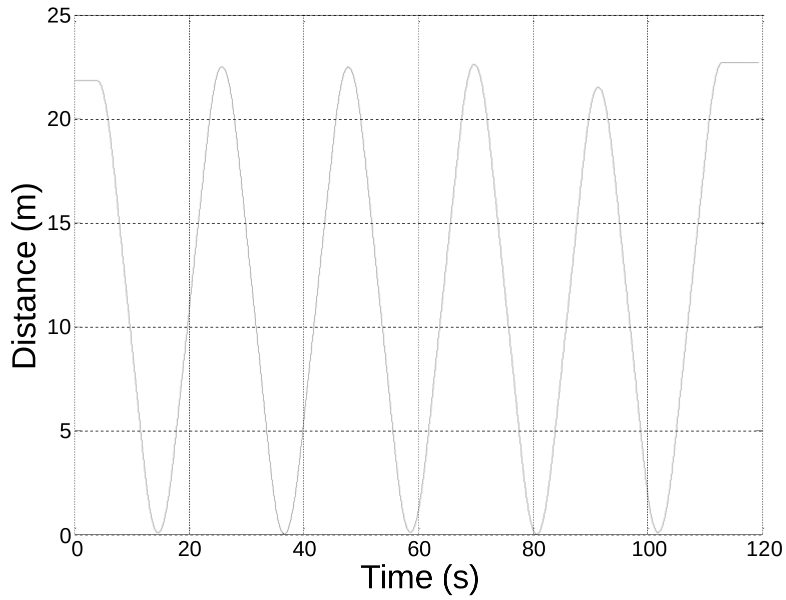


Figure 87: Distance Covered in the 10 km/h Runs

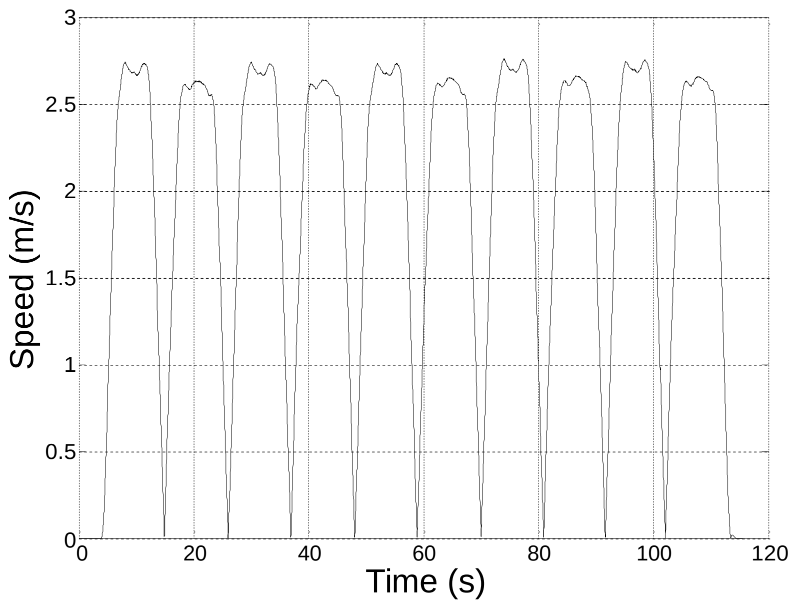
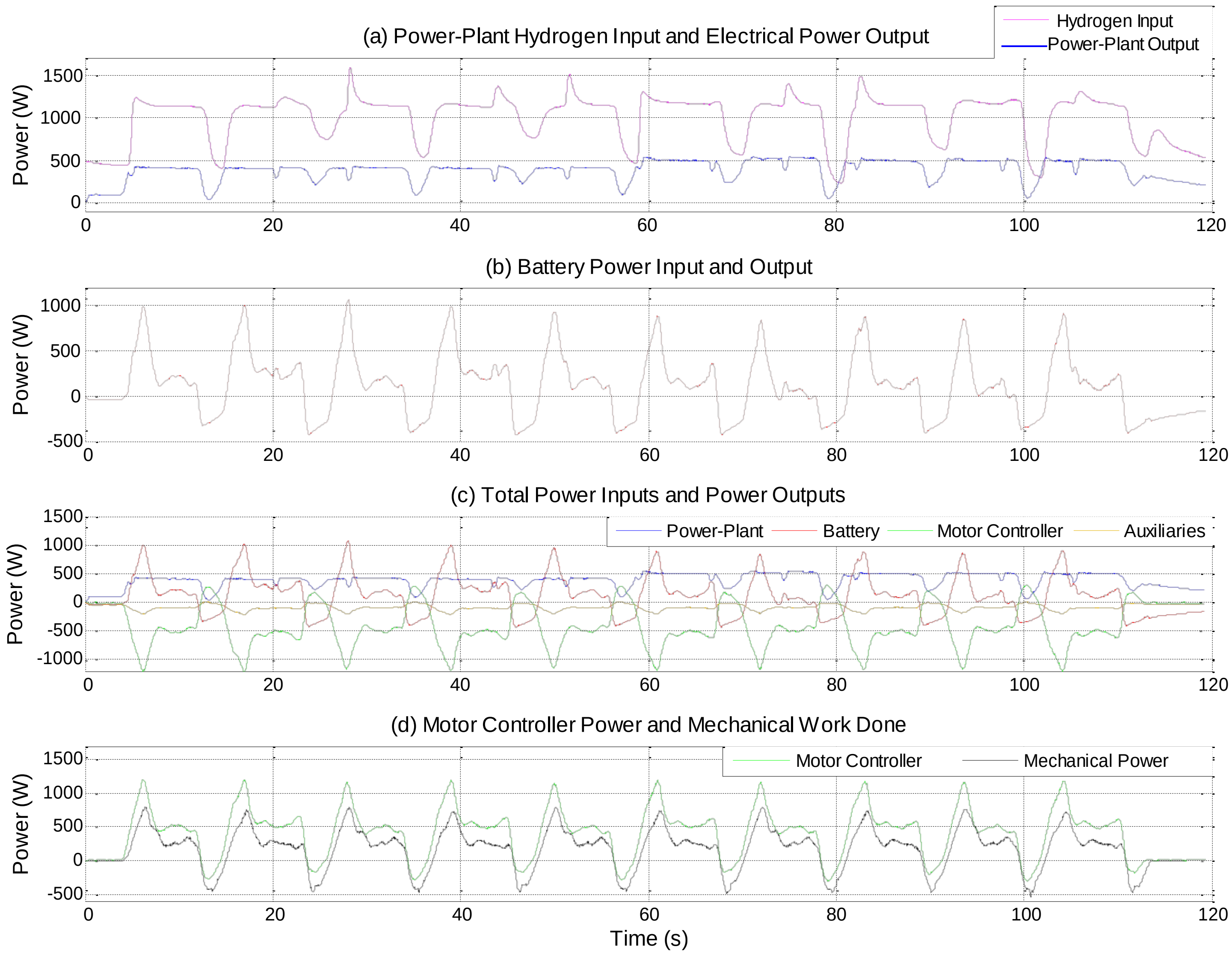


Figure 88: Actual Speed in the 10 km/h Runs

The power that was necessary to complete this duty cycle is presented in Figure 89.


(a) Power-Plant Hydrogen Input and Electrical Power Output
Hydrogen Input
Power-Plant Output
Power (W)
(b) Battery Power Input and Output
Power (W)
(c) Total Power Inputs and Power Outputs
Power-Plant
Battery
Motor Controller
Auxiliaries
Power (W)
(d) Motor Controller Power and Mechanical Work Done
Motor Controller
Mechanical Power
Power (W)
Time (s)

The cumulative energy distribution during the duty cycle is visually presented in Figure 90

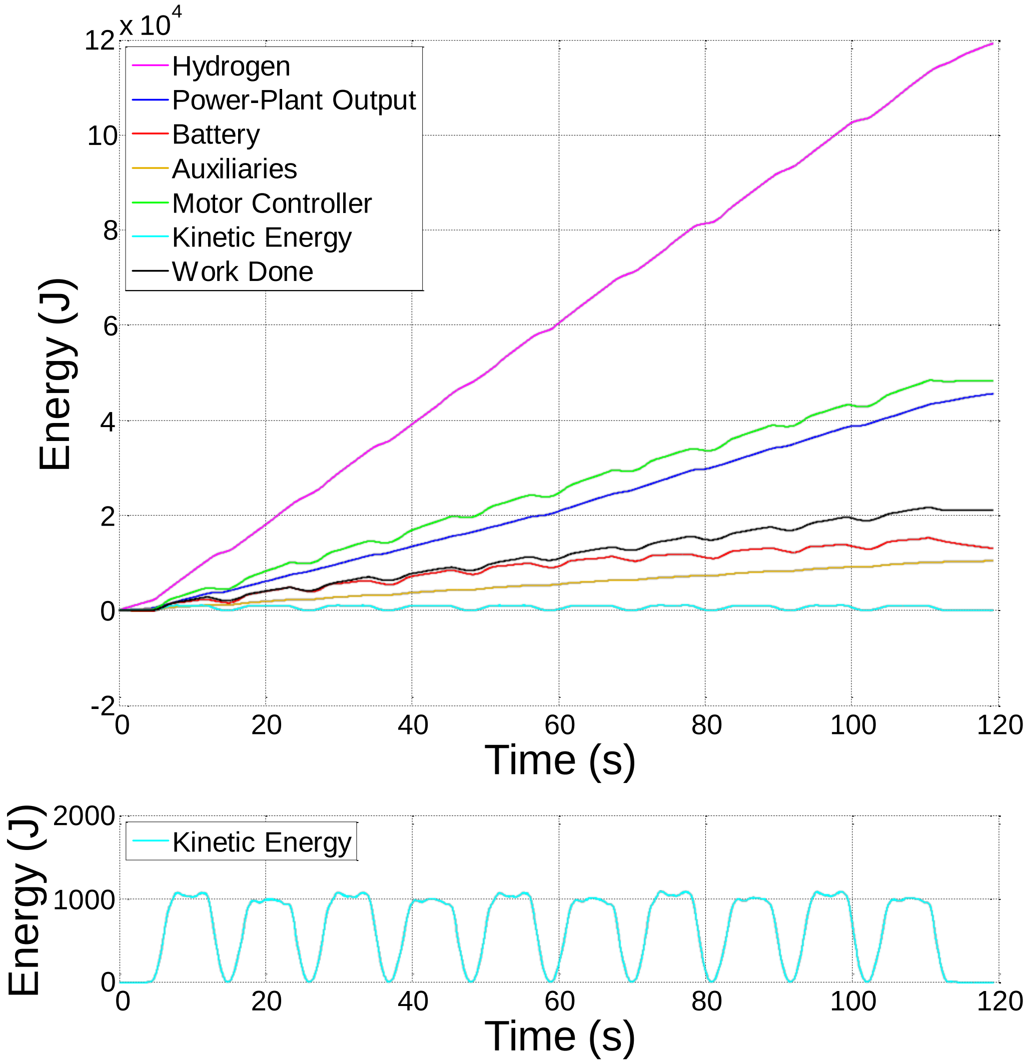


Figure 90: Duty Cycle Energy Graph for the 10 km/h Runs

The energy values at the end of the duty cycle as well as during steady state operation are shown in Table 30.

Table 30: Duty Cycle Energy Account for the 10 km/h Runs

DUTY CYCLE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Hydrogen		119336		100
Power-Plant	73702		62	
Power-Plant Electrical Contribution		45634	38	38
Battery-Pack Discharge		13084	100	
Electrical Energy Input		58718		
Non Traction Consumption				
Auxiliary and Electrical Drive-Train Losses	10436		18	
Total Non-Traction Consumption	10436		18	
Traction Consumption				
Energy Available at Traction Motor Controller		48282	82	31
Traction Motors and Mechanical Drive-Train	27260		56	
Energy Consumed to Overcome Resistance to Motion		21022	44	14
Drive-Train Efficiency			36	
Vehicle Efficiency				14

STEADY STATE ENERGY ACCOUNT

Energy Source or Consumer	J	J	%	%
Energy Source				
Hydrogen		1182		100
Power-Plant	695		59	
Power-Plant Electrical Contribution		487	41	41
Battery-Pack Discharge		165	100	
Electrical Energy Input		652		
Non-Traction Consumption				
Auxiliary and Electrical Drive-Train Losses	101		15	
Total Non-Traction Consumption	101		15	
Traction Consumption				
Energy Available at Traction Motor Controller		551	85	35
Traction Motors and Mechanical Drive-Train	284		52	
Energy Consumed to Overcome Resistance to Motion		267	48	17
Drive-Train Efficiency			41	
Vehicle Efficiency				17

In Figure 91 the energy input share and the energy consumption distribution respective to the total energy input is presented.

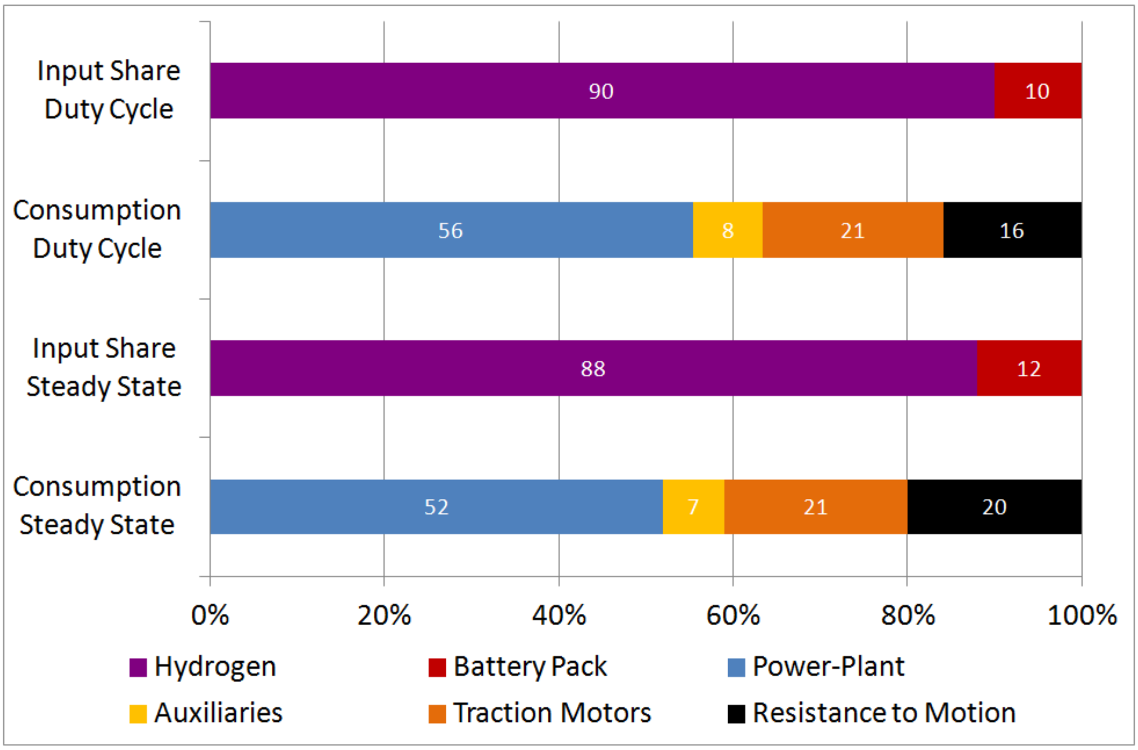


Figure 91: Energy Input Share and Tank-to-Wheel Losses for the 10 km/h Runs

From the energy accounts and Figure 91 it can be seen that the power-plant together with the battery-pack provide the energy to move the vehicle. The majority of the input energy is still contributed from hydrogen, and consequently the largest loss occurs in the power-plant, as in the other tests. The power-plant efficiency performs at an efficiency of 38 % in the duty cycle and 41 % in the steady state, which is expected, and matches the specifications provided by the supplier.

The overall vehicle efficiency is 14 % during the duty cycle and 17 % in the steady state. To compute this number the drive-train efficiency starting with the DC-BUS Input has been calculated, and the result was multiplied by the power-plant efficiency. The energy storage efficiency of the battery-pack was not determined, as the state-of-charge of the batteries was not monitored. For this reason, the battery-pack power contribution was assumed to be 100 %. The vehicle efficiency is lower than anticipated, which is mainly due to the relatively low efficiency of the traction motors; the power-plant performs as expected. This suggests that traction motor changes, or modifications to the mechanical drive-train may be necessary to increase the vehicle efficiency.

6.4 Discussion

The Hydrogen Pioneer completed all the tests without difficulty, proving that a hydrogen-hybrid locomotive can perform various duty cycles. The development of the locomotive was, therefore, a success and demonstrated the proof-of-concept of such a vehicle.

The resource limitations, leading to a short straight test track and not allowing a load at the drawbar, had an effect on all the tests. This is primarily shown in short steady state operation and in the relatively low vehicle efficiencies, as no useful work, such as moving passengers or goods, was undertaken. In actual railway operations a traction vehicle would perform useful work for the majority of the time and only occasionally operate in light running. Nevertheless, the tests provide some insight into the performance of a hydrogen-hybrid railway traction vehicle and derive efficiencies in general

6.4.1 Power-Plant

The power-plant performed as expected and provided an efficient prime-mover in all cases but the lowest speed test. A hydrogen-to-electrical power conversion efficiency of around 40 % was achieved, with a peak efficiency of 43 % in the 7 km/h run. The efficiency is expected to rise slightly, compared to the test results, to a level observed at the peak efficiency and higher, when electrical power output of 1 000 W is demanded (ReliOn, 2011).

The lowest efficiency was recorded at the 2 km/h test when only a fraction of the maximum power output was needed. This is expected, as with any chemical to other energy form conversion device, for example combustion engines, low efficiencies are common at partial loading.

All the tests indicate a quick response of the power-plant to changes in power requirements, which is necessary for vehicle operation and, particularly, when a hybrid drive-train is not present. Further, little difference between the duty cycle and steady state performance is observed. This is in contrast to many combustion engine-operated railway vehicles where the peak efficiency is often considerably different from the duty cycle efficiency (Lu, Hillmansen, & Roberts, 2011). An improved power management of the hybrid drive-train could lead to cases where the power-plant is operating close to its maximum efficiency for the majority of the time.

The performance of the power-plant, established by the tests, suggests that a hydrogen fuel cell based prime-mover is suitable for railway applications; the small scale of the Hydrogen Pioneer having little effect on the functionality of the power-plant. Further, a more powerful fuel cell system that is suitable for standard gauge railway vehicles will have a higher efficiency, as full-scale tests have demonstrated (Miller, et al., 2011; Yamamoto, et al., 2010). For these reasons, the author sees no technical barrier to the implementation of fuel cells as power-plants in railway vehicles.

6.4.2 Hybrid Drive-Train

In all tests the hybrid function of the locomotive was apparent: During high power demands, in the test cases during acceleration, the battery-pack contributed a significant part of the power. During the regenerative service brake application the batteries were recharged, recovering some of the braking energy. In steady state operation the power-plant was charging the battery-pack, in all but the highest speed test, as per locomotive design. The power-plant provided, in the three lower-speed cases, all the energy required during the duty cycle, and the average electrical power output was around 500 W for all but the 10 km/h test case. If the lower speed cases were the standard operating conditions, then the power-plant could be down-sized to an output of slightly more than the average power requirement, approximately 600 W. This would not affect the performance of the locomotive but conserve energy. A more sophisticated control system combined with a battery-pack controller would allow higher operating speeds with the current component sizing. The reason is that the peak power consumption, during the highest speed test, is around 1 000 W, which the power-plant could fully provide. If the 1 000 W were to be taken as the average power requirement and the peak power were met by the batteries, then, a highly efficient locomotive running at relatively high speed is created. However, in the present situation the battery-pack starts to provide power for steady state running at 10 km/h, limiting the power-plant output to 500 W.

The hybrid arrangement can be applied to full scale vehicles allowing autonomous railway vehicles to utilise regenerative braking, and it offers the potential to down-size the prime-mover, both modifications lowering overall primary energy consumption. The tests have demonstrated that this is a feasible option without compromising on performance. Autonomous hybrid railway vehicles have already been introduced on some railway services (Cousineau, 2006; Shiraki, Satou, & Arai, 2010), albeit not hydrogen-powered. The author believes, based on the test results and implementation of hybrid drive systems, that hydrogen-hybrid traction systems can be successfully implemented in full-scale railway traction vehicles,

6.4.3 Auxiliaries

The auxiliary load is fairly constant in all tests with a small difference between the duty cycle and steady state operation. Energy consumption of auxiliaries, in relative terms compared to the total consumption, changes little between the tests. A variable nature of the consumption is indicated during acceleration, when a high power demand is present, as the auxiliary load increases respectively; this can be seen in all the power graphs (c) except for the 2 km/h test. The largest energy consumers are the control computer and the wireless router, which both have a relatively stable power requirements. Therefore, components that may be responsible for the variable nature are the measurement sensors. However, their power consumptions should not vary drastically with the current being measured. The sensor supplier specifies an accuracy within a margin of 2 %, which might be the reason for the variability. The overall auxiliary power share is not excessive and the total consumption is reasonable for the locomotive operation.

A lower share of auxiliaries can be expected for larger vehicles, because some components used in the Hydrogen Pioneer could be used for those, such as the control computer. In addition, the literature suggests lower values as already presented in the well-to-wheel chapter.

6.4.4 Traction Motors and Mechanical Drive-Train

The traction motors and the mechanical drive-train perform poorly in all experiments in energy consumption terms, with a peak efficiency of 43 % in the 10 km/h test. The majority of the energy usage is most likely due to suboptimum operation of the traction motors, as the losses in the mechanical drive train are likely to stay practically constant independent of speed. The motors will operate in their optimum region at a large number of revolutions per minute, which would lead to high speeds of the locomotive given the present gearing ratio. However, higher speed tests were not possible due to the limitations of the test track.

The normal operating speed of the locomotive is within the range of speeds represented by the tests and, therefore, a change of gearing ratio is recommended to increase the motor revolutions and subsequently its efficiency, while maintaining the normal operating speed range of the Hydrogen Pioneer.

In full-scale railway traction vehicles a chain-drive would most likely not be implemented but rather, for example, a quill drive or cardan shaft arrangement employed. Further, there is a general move towards AC motors in the industry (Lustig, 2010c), and although a DC system is possible, a three-phase system is more likely. Larger scale motors will additionally boost efficiency, and losses in full- scale vehicles that can be attributed to the traction motors and mechanical drive-train are in the region of 10 % -15 %, as shown in the Well-to-Wheel Analysis chapter. The efficiency achieved by the traction motors in the Hydrogen Pioneer is, therefore, not transferable to full-scale vehicles.

6.4.5 General Performance

In general, the Hydrogen Pioneer performed better in the steady state than in the overall duty cycle, as illustrated in Figure 92, which is usual for any type of railway vehicle (UIC, 2003), but the difference in performance is small.

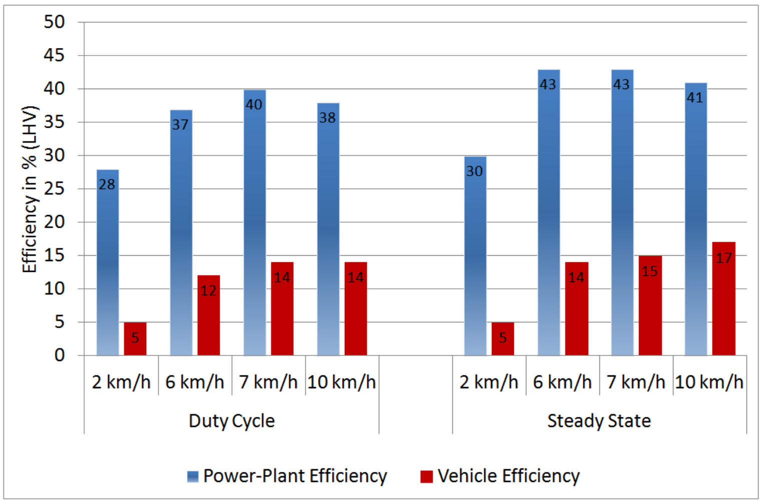


Figure 92: Power-Plant and Vehicle Efficiency of the Hydrogen Pioneer for all Test Speeds

In the steady state, components such as the power-plant, battery-pack, and traction motors do not have to react to changes, which positively affect their efficiency. A longer operation in the steady state would result in a decreased difference compared to the duty cycle. Given the short test track, longer operation in the steady state would be the norm.

At low speeds, the vehicle's performance was low, which is due to the partial loading of all components and could have been expected as it was not designed to operate at such speeds for extended periods of time. Once the normal operating speed is reached, between 5 km/h and 10 km/h, the efficiency of the power-plant and the vehicle stabilise at around 40 % and 15 %, respectively. A higher vehicle efficiency in the operating speed range is desirable, which can be achieved through a change in the gearing ratio of the mechanical drive-train and the author recommends that change. When evaluating the performance of the locomotive, the original design objective has to be considered: The demonstration of the proof-of-concept of a hydrogen-powered railway traction vehicle; which is established with the tests. Also, the original design effort was less focused on optimal efficiency, but rather on novel fuel and power-plant integration. Also, in general, small scale systems always have a lower efficiency than larger systems, which is apparent from the research presented in the concept design chapter as well as the well-to-wheel chapter.

The performance of the vehicle is expected to improve with load as the work done would increase, whereas the energy consumption would increase to a smaller extent. Under loaded operation, where the locomotive would be pulling carriages, is a more realistic scenario, although light running is common in locomotive operation, for example, when moving from the depot. The tests are, therefore, not unrealistic but merely represent a specific type of railway operation.. The tests establish that a hydrogen-hybrid locomotive can perform a duty cycle in an effective and efficient manner, and consequently prove that such a system is a suitable solution for railway traction vehicles.

6.5 Summary

The Hydrogen Pioneer locomotive was utilised to conduct tests that allow the performance evaluation of hydrogen-powered railway traction vehicles. The locomotive was operated without a load, which is an unusual situation for a railway traction vehicle, but takes place during light running, and on straight alignment for the whole evaluation.

First, the resistance to motion of the locomotive was established through run-down tests and a corresponding Davis equation was determined, which was used as an input for the operation experiment.

Second, an operation experiment consisting of four different tests at the target operating speeds of 2 km/h, 6 km/h, 7 km/h, and 10 km/h was conducted, wherein the locomotive operated with a 200 bar hydrogen cylinder. Collected data included: hydrogen flow, power-plant output, battery-pack power contribution, input power to the traction motors at the motor controller, and speed of the vehicle. The gathered data enabled the comparison of the vehicle performance among the different target speeds as well as between the duty cycle and steady state operation. The power-plant achieved a maximum efficiency of 43 % in the steady state and efficiencies in the high 30s in the duty cycle. In the 7 km/h test the power-plant achieved its maximum recorded efficiency and provided all the energy necessary for the duty cycle, plus a small amount of 1 % power to charge the batteries; a situation that is close to the operation of a non-hybrid vehicle. Therefore, a power-plant comparison to the vehicles discussed in the well-to-wheel chapter is possible. The peak power during acceleration was met by the battery-pack, and regenerative braking was employed. In the three lower speed tests the battery-pack was charged over the period of the duty cycle. In the 10 km/h test the battery-pack provided power throughout the cycle except during braking. Therefore, the hybrid-system operated as designed, establishing the suitability for traction vehicles.

The traction motors and mechanical drive train have been found to perform at a lower than desirable level, with a peak efficiency of 43 % due to the low revolutions per minute of the traction motors and, therefore, changes to the gearing ratio are recommended to improve the efficiency.

Overall, the evaluation showed a strong performance of the power-plant and hybrid-system, and established the suitability of both for railway traction purposes. A gaseous hydrogen on-board power supply system with a fuel cell based power-plant is demonstrated to be suitable for railway traction vehicles.

The performance evaluation, and its results, is the first of its kind for a hydrogen-powered railway traction vehicle, as far as the author is aware. And the method, especially the result presentation and energy accounts, are suitable for future evaluations of vehicle performance and determination of tank-to-wheel efficiency for hydrogen-powered railway vehicles as well as traditionally-fuelled vehicles.

Benchmarking of an existing traditionally powered vehicle and computer modelling of its performance over a typical route creating a corresponding duty cycle, will allow the creation of a virtual hydrogen-powered vehicle. And the concept design of such a vehicle will allow the simulation of its performance over the same route, while exposing design challenges. Thereafter, a comparison can be drawn and the overall engineering-based suitability of a hydrogen-powered railway traction vehicle established. The Hydrogen Pioneer energy storage and drive-train design, supported by the strong performance of the power-plant, will provide a valuable contribution towards a full-scale concept design. In the next chapter the author conducts such benchmarking, concept design, virtual creation, and simulation analysis, which is informed by the results and the research that is already presented in this thesis.

7 CONCEPT DESIGN

The well-to-wheel chapter has shown that a hydrogen-powered railway vehicle can reduce emissions compared to diesel traction, and the empirical performance evaluation of the Hydrogen Pioneer demonstrates that gaseous hydrogen utilised in a fuel cell power-plant is a practical option to provide power for a narrow-gauge railway traction vehicle. The next step is the design and evaluation of a full-scale vehicle to establish the suitability of a hydrogen-powered drive-train for railway operations, which is conducted and presented in this chapter. The evaluation is undertaken through computer modelling and the study is, therefore, an approximation.

First, a diesel-electric railway vehicle was selected and employed to generate a computer model of a train; thereafter, the performance parameters and journey time over a representative route were determined, also with computer simulation. The vehicle characteristics and simulation results were used as a benchmark for the concept design of a hydrogen-powered equivalent. Then, the performance calculations and journey time over the same route were established. The benchmark diesel-electric as well as the hydrogen-powered vehicle demonstrated potential for hybridisation, and a hydrogen-hybrid version was developed and its performance simulated. A direct comparison between the traditional and the novel vehicles was then conducted. Finally, a chapter summary is provided.

During the research period the author conducted computer simulations of train performance on several occasions and several journal publications resulted from this work. Part of this chapter, especially the description of the simulation software, is similar to already published material (Hoffrichter, et al., 2013), and the relevant journal paper is attached in Appendix D.

7.1 Benchmark Simulation

The BCRRE's Single Train Simulator software was employed for the investigations presented in this thesis. The simulator has been used by the author for previous research (Hoffrichter, Silmon, et al., 2012; Hoffrichter, et al., 2013) that led to publications, both attached in the Appendix, and for a MSc dissertation project (Hoffrichter, 2012), and therefore, the following description is similar to the aforementioned work.

The Single Train Simulator solves the equations of motion of a railway vehicle, see below equations (9) to (13), through numeric integration (Hoffrichter, 2012; Hoffrichter, et al., 2013).

$$F = ma \tag{9}$$

$$F = m(1+\lambda)a \tag{10}$$

$$F = TE - [mg\sin(\alpha) + Cv^2 + Bv + A] \tag{11}$$

Overall:

$$m(1+\lambda)a = TE - [mg\sin(\alpha) + Cv^2 + Bv + A] \tag{12}$$

Or:

$$m(1+\lambda)\frac{d^2s}{dt^2} = TE - \left[mg\sin(\alpha) + \ C\left(\frac{ds}{dt}\right)^2 + B\left(\frac{ds}{dt}\right) + A\right] \tag{13}$$

where: a is acceleration (m/s^2); A, B, C are the constant terms of resistance in the Davis equation; d is delta, change of the following variable; F is Force (kN); g is the acceleration due to gravity (9.81 m/s^2); m is mass (kg); s is vehicle displacement (m); t is time (s); TE is tractive effort (kN); v is velocity (m/s); α is the angle of the gradient (degrees); and λ is rotational allowance.

The equations above fully describe the forces that occur due to railway vehicle's motion, except for the resistance encountered due to curving forces, which was neglected in the investigation. The calculations are performed in the distance domain so

that the simulation ends once the train has completed the journey. A more detailed description about the operation of the simulator can be found in a paper by Meegahawatte, et al. (2010).

Route information, vehicle data, and the driving style are required inputs for computer modelling. The driving style has been assumed to be as fast as possible, while the simulated vehicles and the railway route are described below. The simulator was used extensively by various scholars in the past (Hoffrichter, et al., 2013; Lu, et al., 2011; Meegahawatte, et al., 2010; Silmon & Hillmansen, 2010); and the major changes to the software required for this investigation were: the creation of new vehicles, modifications to account for the various drive-system efficiencies, calculations to determine battery-pack capacity, and additional graph generation. The benchmark simulation is followed by modelling of a hydrogen-powered vehicle and thereafter a hydrogen-hybrid train is simulated, all over the same route.

7.1.1 Benchmark Vehicle Selection

The share of electrified railway lines is about 53 % in the European Union and the majority of traffic is carried on those lines but, in other areas, such as North America, non-electrified lines are the norm (UIC & IEA, 2012). In Europe it is not economical to electrify a significant additional proportion of the network, including regional lines, and an alternative propulsion technology is required for future operations. The author, for this reason, selected a railway vehicle that is designed to provide primarily regional services, and because the vehicle is autonomous it may be deployed globally. The specific train choice was inspired by a presentation given by Herbert Wancura (2012): The Stadler Gelenktriebwagen 2/6 (GTW).

Rationale for GTW Choice

More than 500 GTWs, in various configurations, haven 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 (Stadler Rail AG, 2013b). The autonomous version of the GTW has a diesel-electric power-module between two coaches, see Figure 93 to Figure 96 for an illustration of the vehicle as operated in Texas.

Figure 93: Stadler GTW 2/6 for MetroRail in Texas (Greg3564, 2009)

Figure 94: Stadler GTW 2/6 in Texas (Phelan, 2008)

Figure 95: Two GTW 2/6 in Denton, Texas (Edgepedia, 2013)

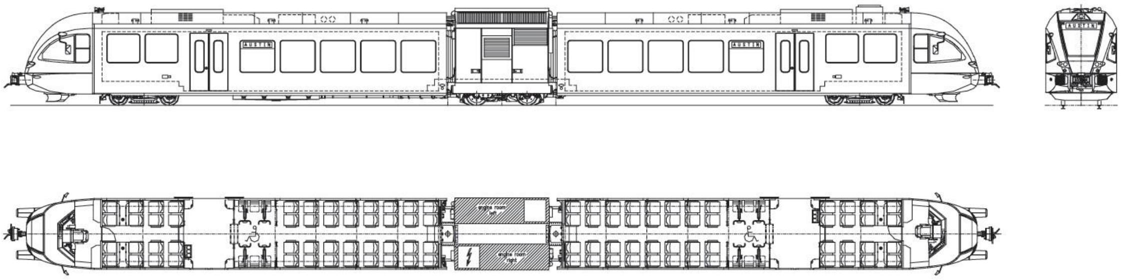


Figure 96: Illustration of the Diesel-Electric GTW 2/6 Employed in Texas (Stadler Rail AG, 2008)

The GTW was selected because it features a power-module, much like 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. Also, the power-module design of the GTW differs from traditional multiple units: the power-module houses the traction equipment rather than being distributed throughout the train, and the module is separated from the passenger carrying coaches. Therefore, the design enables the easy creation of longer formations, and GTWs with additional coaches or power-modules or both can be assembled, see Figure 97 (Stadler Rail AG, 2013b).

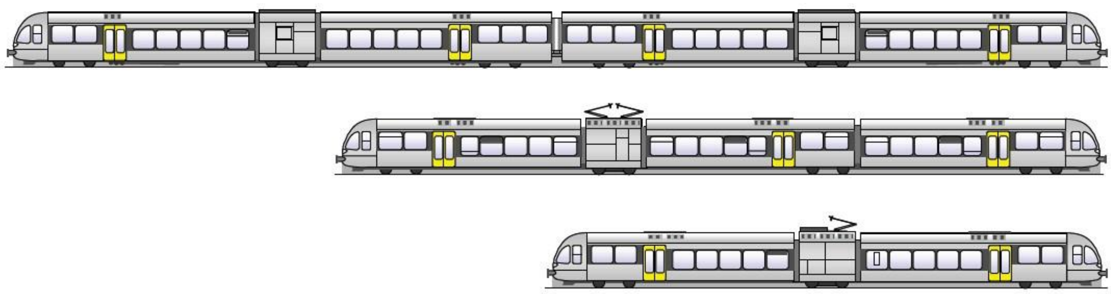


Figure 97: Modular Design of the GTW Electric and Diesel-Electric Power-Modules are Shown (König, 2007)

The combination of a multitude of power-modules leads to characteristics that are comparable to locomotives, for example: three power-modules are similar to a Class 43 High Speed Train locomotive and five power-modules are similar to a Class 66 Freight locomotive, in power, length and fuel tank sizes, and six power-modules are similar to a GE Evolution Series locomotive in power and length. Thus, an equivalent hydrogen based power-module could demonstrate the viability of several railway traction vehicles, which are suitable for a variety of services. The data for the British locomotives in the comparison were sourced from Marsden (2007), while the data for the American GE locomotive were obtained from Bachan (2007) and GE Transportation (2005).

Characteristics of the GTW

The characteristics of a diesel-electric GTW 2/6 are presented in Table 31. The data were sourced from literature with a focus on the Texas versions to provide consistency with the Figures above, and from personal communication with employees of Stadler during a visit to the factory in Bussnang, Switzerland.

Table 31: GTW 2/6 Vehicle Data
Parameters are Based on the Texas Versions (Stadler Rail AG, 2008, 2012a) unless otherwise indicated

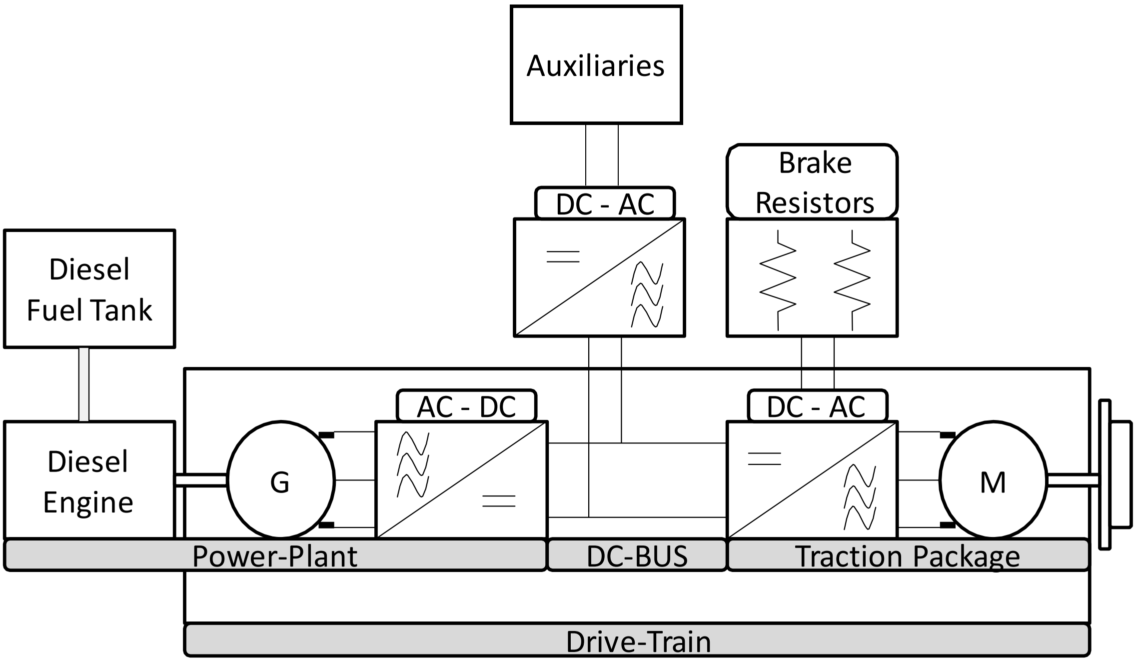
Train Characteristics	
Axle arrangement	2’Bo2’
Vehicle length	40 890 mm
Vehicle width	2 950 mm
Vehicle height[a, b]	4 035 mm
Tare mass	72 t
Coach mass[c]	20 t
Starting tractive effort	80 kN
Maximum acceleration	1 m/s^2
Maximum deceleration in the present evaluation[d]	1 m/s^2
Maximum speed	120 km/h
Davis equation[e]	$R=1.5+0.006v+0.0067v^2$
Power-module Characteristics	
Number of powered-axels	2
Floor height in the power-module	1 000 mm
Available height in the power-module	3 035 mm
Length of the power-module[b]	4 500 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]	1 500 l – 14 910 kWh[j]

[a]Based on the GTW delivered to Veolia Transport in the Netherlands (Stadler Rail AG, 2007)
[b]Personal communication from Stadler employees
[c]Calculated from data of the bogie manufacturer (LRS Engineering AG, 2008), GTWs for Veolia Transport in the Netherlands, (Stadler Rail AG, 2007) and GTW for Capital Metro, Texas (Stadler Rail AG, 2008)
[d]The maximum service braking rate for the Texas trains is 1.3 m/s^2 according to Stadler Rail AG (2012a)
[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 (LTK Engineering Services, 2009)
[g]Calculated from data provided by the U.S. Department of Transportation - Federal Transit Administration (2011), GTW for Capital Metro, Texas (Stadler Rail AG, 2008), and the drive-train efficiency
[h]Calculated from the power data and personal communication with Stadler employees
[i]Personal communication with Stadler employees, and GTW delivered to Veolia Transport in the Netherlands (CBRail S.a.r.l., 2007)
[j]Calculated from American data and based on the LHV of diesel at 9.94 kWh per litre (U.S. DOE, 2008a)

The focus in the evaluation is on the traction system, in the case of the GTW, on the power-module. More information on the power-module is presented in the next section.

GTW Power-Module Data

The GTW's power-module for Texas has two identical drive-systems, each consisting of a diesel engine, generator, power converters, and traction motor (Stadler Rail AG, 2008, 2012a), as illustrated in Figure 98.



Created from data of the Texas GTWs (Stadler Rail AG, 2008, 2012a) and data provided by the U.S. Department of Transportation - Federal Transit Administration (2011)

Figure 98: GTW Power-Module Drive-System Diagram

The efficiency of the GTW power-module was determined in the following way: a vehicle efficiency of 25 % has been assumed, based on data published by RSSB (2005); 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 32. The duty-cycle efficiency provided by the RSSB differs significantly from the maximum efficiency provided in the well-to-wheel chapter, and such a situation is not uncommon for combustion engines (Lu, et al., 2011). The evaluation considers a duty-cycle and, therefore, the lower vehicle efficiency provided by the RSSB has been employed in the analysis.

Table 32: Drive-Train Efficiency Calculations for GTW

Component	Cumulative Drive-Train Efficiency	Tank-to-Wheel Efficiency Chain
Diesel in Fuel Tank		100 %
Diesel Engine		29 %
Drive-Train		
Diesel Engine Mechanical Output	1	
Generator[1]	0.98	
AC-DC inverter[2]	0.975	
DC-AC converter[2]	0.975	
Traction Motors and Mechanical Drive[1]	0.95	
Drive-Train Efficiency		88 %
Vehicle Efficiency		25 %

[1]Assumed by the Author to give 88 % Drive-Train Efficiency as per personal communication with Stadler employees
[2]Based on Steimel (2006)

Resulting from the efficiencies presented in Table 32 is a traction-package efficiency of 92.6 %, and a diesel engine drive-shaft to DC-bus efficiency of 95.6 %. The data provided allow the simulation of the vehicle and an estimation of its fuel consumption, which will serve as the input for the hydrogen concept vehicle. Further, the efficiencies serve as input data for the hydrogen vehicle developments.

7.1.2 Route Selection

The route over which the train was simulated is from Birmingham Moor Street to Stratford-upon-Avon and return. It is a regional line with some commuter traffic, and the service offered is operated with vehicles that are similar in power and capacity to the GTW 2/6 (Marsden, 2007). There are 16 stops between the two terminals, and the line is 78.58 km long. The change in altitude and the gradient profile for the return journey is illustrated in Figure 99. The route data were pre-existing in the train simulator and sourced from Network Rail, as well as used in previous simulations (Meegahawatte, et al., 2010). It has been assumed that the alignment is straight throughout, as usual with Birmingham’s train simulator. In addition, horizontal curvature will have secondary effects on journey performance results and will not differ between the comparative vehicles under investigation.

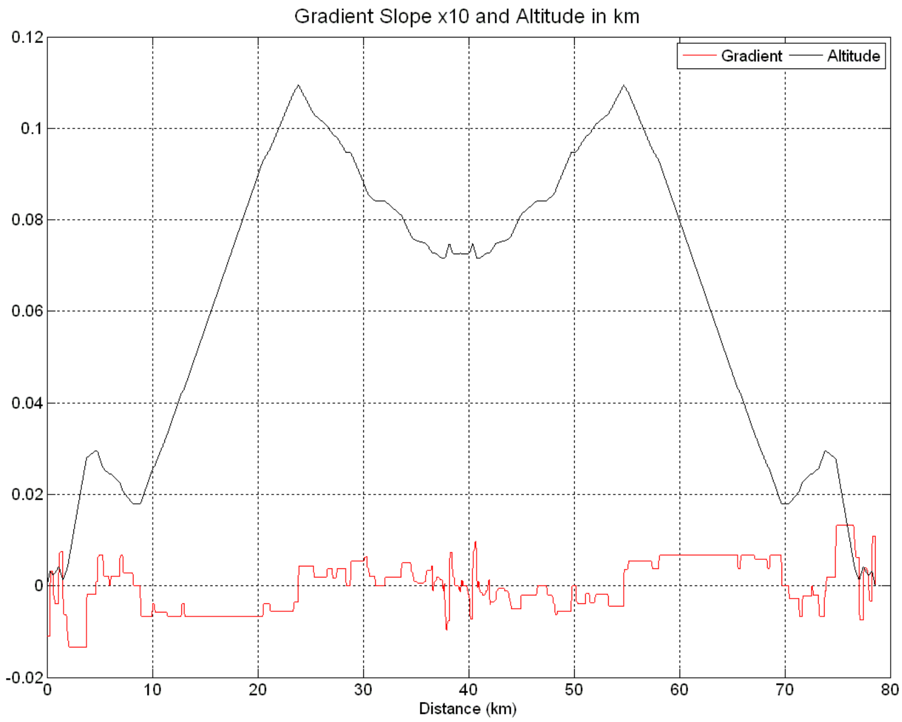


Figure 99: Gradient and Altitude of the Route From Birmingham Moor Street to Stratford-upon-Avon and Return

The route is in the UK, which has a more restrictive loading gauge than other European Countries or the USA. Therefore, the already existing standard-gauge GTWs could not operate over the route but would have to be reduced in size. However, as a general feasibility evaluation the smaller loading gauge and vehicle dimensions have been neglected; instead the dimensions of the Texas GTWs have been applied, which are suitable for continental and American operations. A UK-specific vehicle may be developed and sold in the future.

7.1.3 Simulation Results

The GTW 2/6 was run over the Birmingham Moor Street to Stratford-upon-Avon route and return. The dwell time at calling stations was 30 s and the stationary time at Stratford-upon-Avon five minutes. It was assumed that the restistance to motion based on the Davis equation stayed the same throughout the journey. The results for the diesel-electric train are presented in Table 33, and in Figure 100 to Figure 105. The figures begin with the journey's origin in Birmingham Moor Street and include a terminal time in Stratford-upon-Avon of five minutes before the return journey starts. A terminal time of six minutes in Birmingham Moor Street is added to the energy calculations, but not shown in the figures, as the starting location is reached by the train.

Table 33: 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[1]	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[2]	108 kWh
Power-Plant Output Energy	429 kWh
Diesel Engine Output Energy	449 kWh
Energy Contained in Diesel	1 548 kWh

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

Figure 100 shows the line speed and the speed that the train achieves while traversing the route.

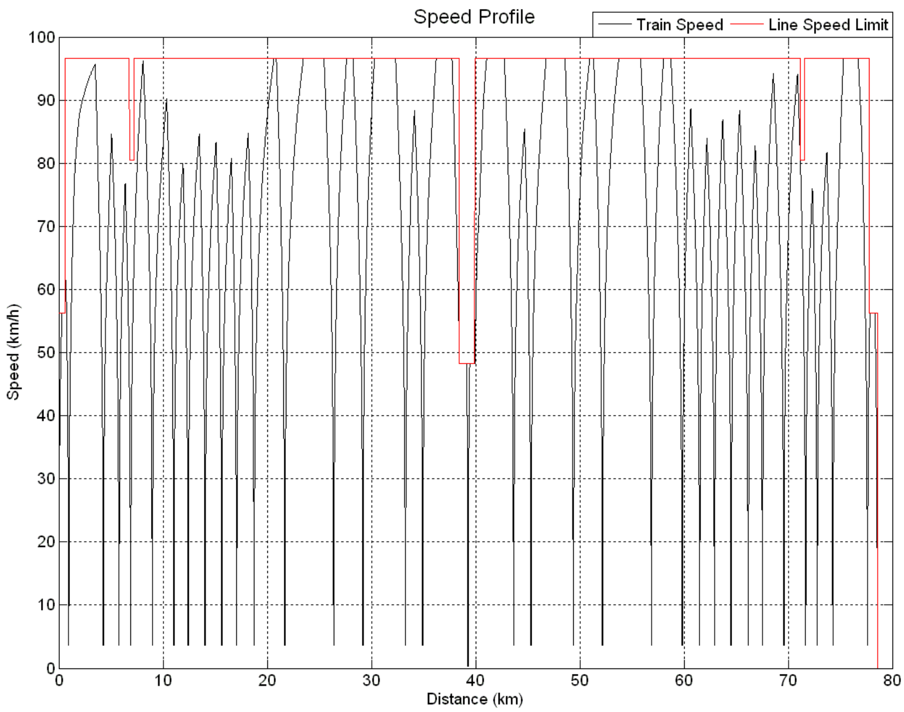


Figure 100: Speed Profile of the GTW From Birmingham Moor Street to Stratford-upon-Avon Compared to the Maximum Line Speed

Figure 101 illustrates the journey of the train along the line against time. The five minutes terminal time can be seen in level segments where time advances but the vehicle is stationary.

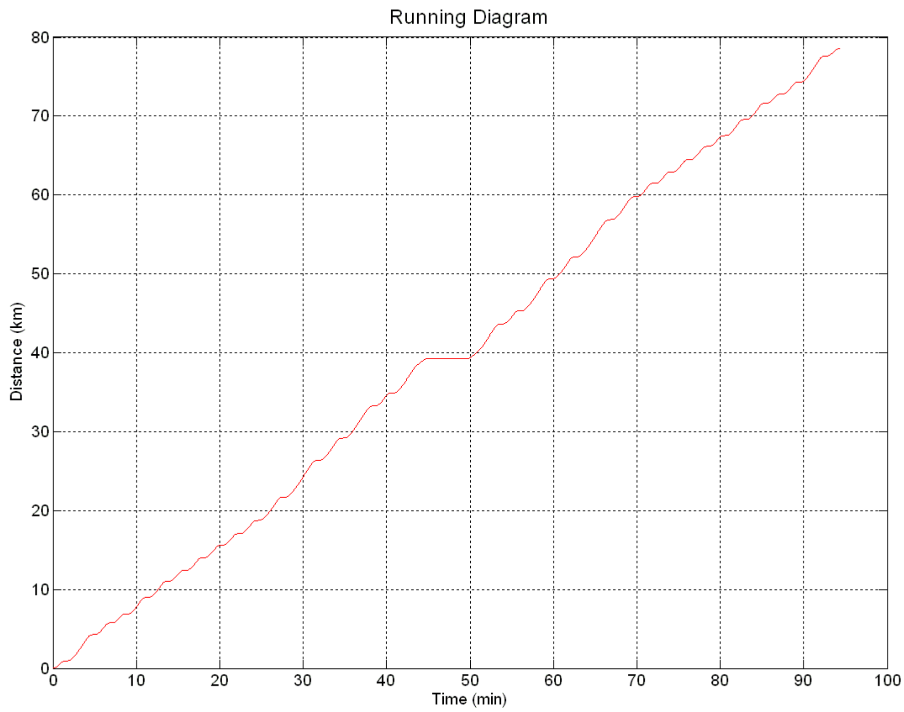


Figure 101: Running Diagram of the GTW

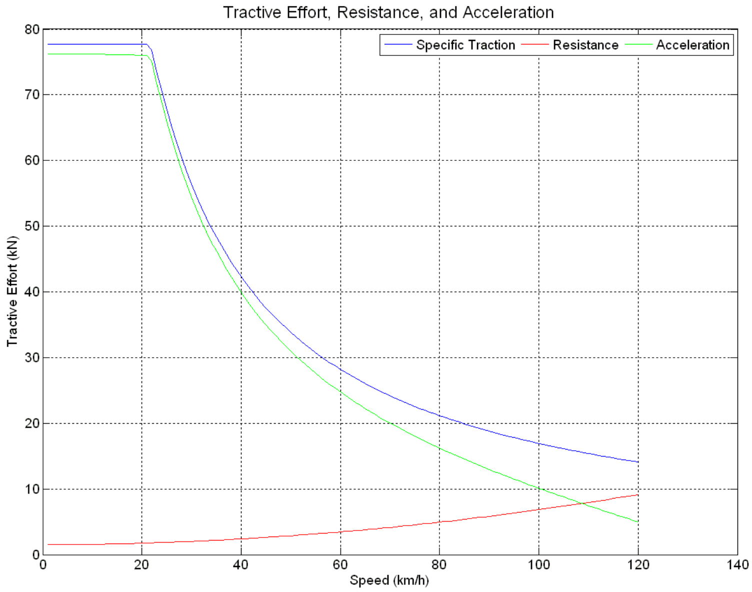


Figure 102: Tractive Effort, Resistance to Motion, and Acceleration of the GTW

Figure 102 shows the vehicle traction performance for various speeds as well as the associated resistance to motion at these speeds. In addition, the acceleration curve of the train is shown. A maximum acceleration of 1 m/s^2 has been applied in the simulation and the required tractive effort to achieve that acceleration is 78 kN, so the 80 kN stated earlier were not necessary. The traction power requirements during the journey and the average power at the wheels are illustrated in Figure 103.

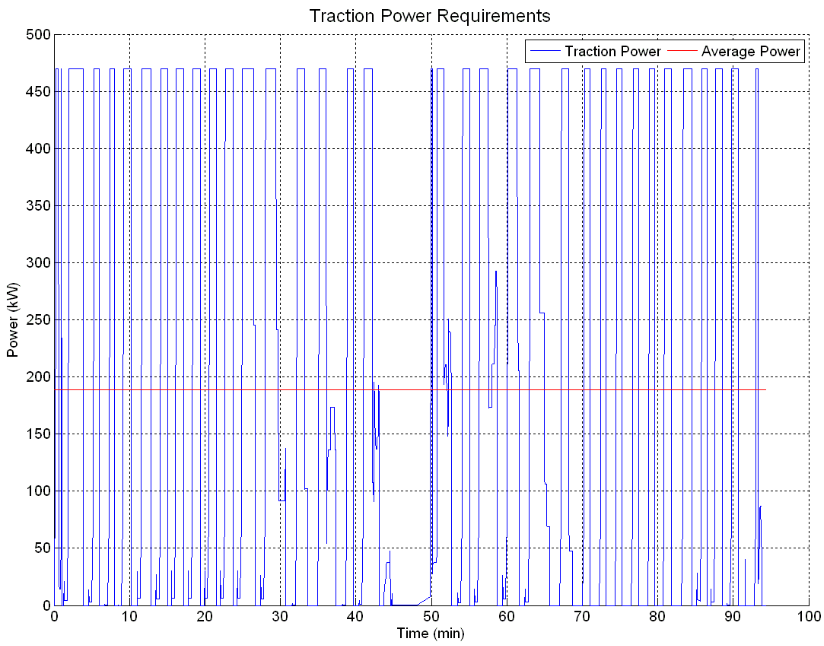


Figure 103: Traction Power and Traction Power Average at Wheels of the GTW

Figure 104 shows the traction power demand and the braking power that has to be dissipated, either in mechanical brakes or in dynamic brake resistors.

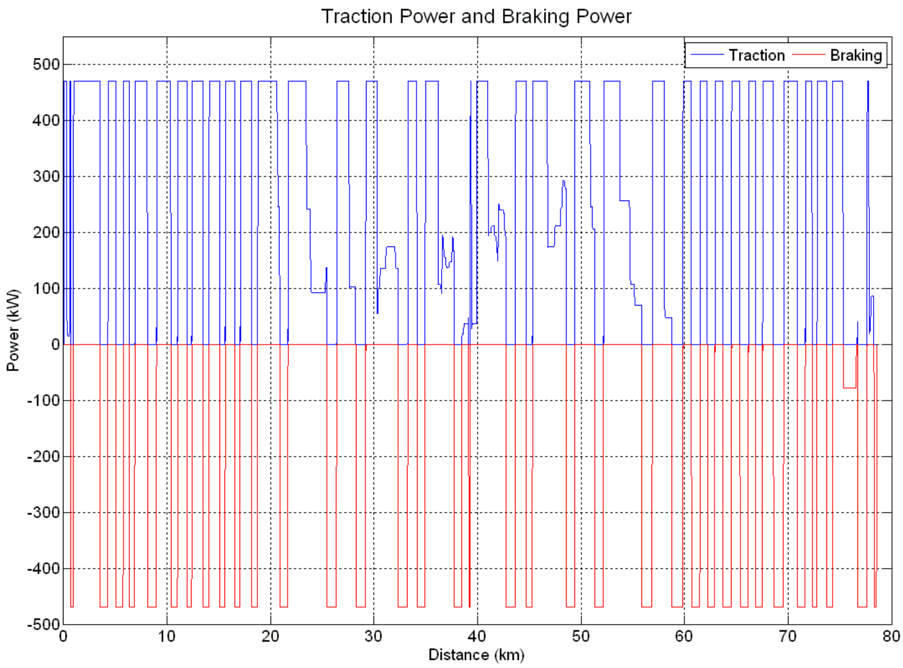


Figure 104: Traction Power and Braking Power of the GTW at Wheels

The power requirements of the GTW's drive-system, including the demand of diesel, are illustrated in Figure 105. 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. The representation in Figure 105 is similar to the previous chapter graphs, where: 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.

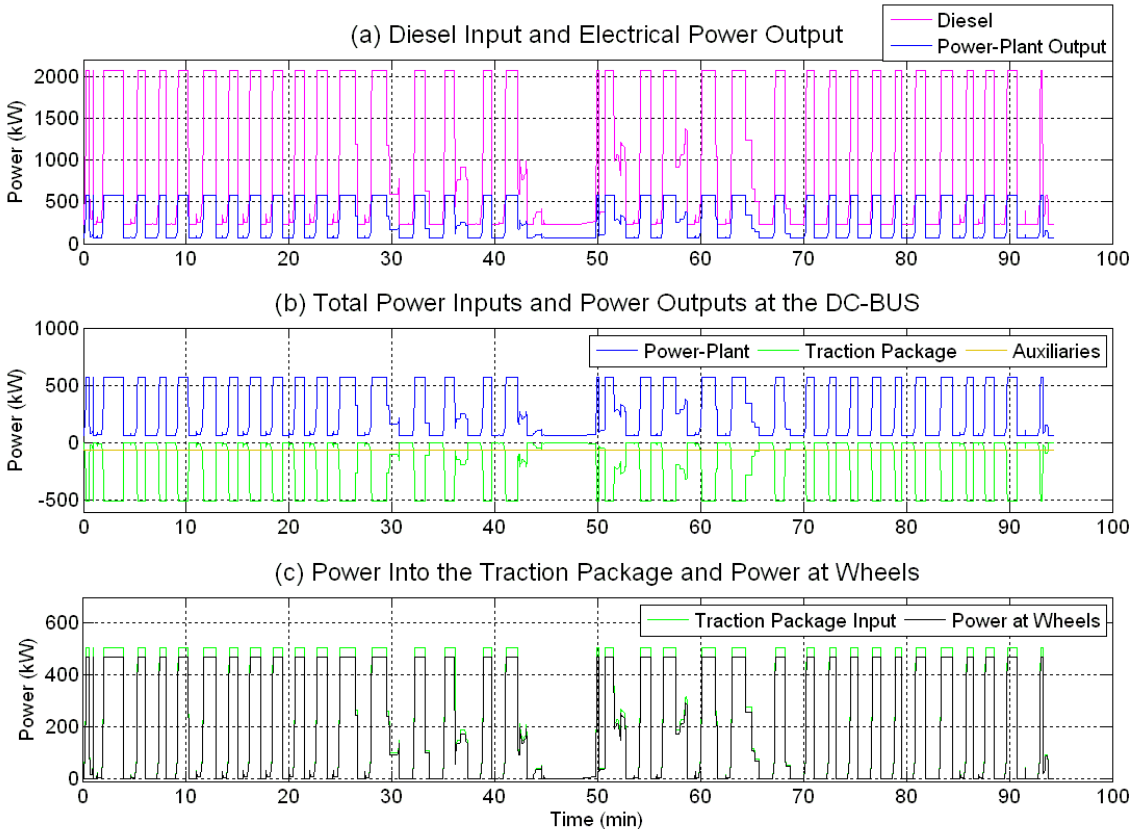


Figure 105: Power Across the GTW Drive-System

The data presented above provide the benchmarking case for the design of a hydrogen-powered vehicle. From the traction power graph, Figure 103, it is apparent that the average power is significantly lower than peak power. Further, the power due to braking, denoted in Figure 104, is considerable compared to the traction power. Both suggest that a hybrid design could lower the overall energy consumption, and a hydrogen-hybrid vehicle design is developed after the hydrogen-only design.

7.2 Hydrogen Simulation

In this section the author develops a hydrogen-powered vehicle based on the diesel-electric GTW's performance. Thereafter, a hydrogen-hybrid vehicle is created.

7.2.1 Hydrogen Vehicle Development

In this section the author develops a hydrogen-powered vehicle that has similar characteristics to the original diesel-electric version. First, the general drive-system alteration is presented, then the power and energy storage requirements are determined, which is followed by the volume and mass implications of the new system, to complete the vehicle concept design.

Hydrogen-Powered Drive-System

The existing GTWs employ an electric drive-train that is powered by a diesel-generator set, which is housed in a power-module, as described in the previous sections. A large part of the drive-system does not have to be altered in a conversion to hydrogen fuel 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 investigation presented. The hydrogen-powered drive-system is illustrated in Figure 106.

The hydrogen-powered drive-train efficiency calculation does not include an alternator, because the output of the fuel cell stack is already electricity, see Figure 106. A 90.3 % drive-train efficiency for the hydrogen power-module results when the relevant components of the diesel-electric GTW, see Table 32 and Figure 98, are used. Also, the energy storage system will be different from the original design: hydrogen instead of diesel.

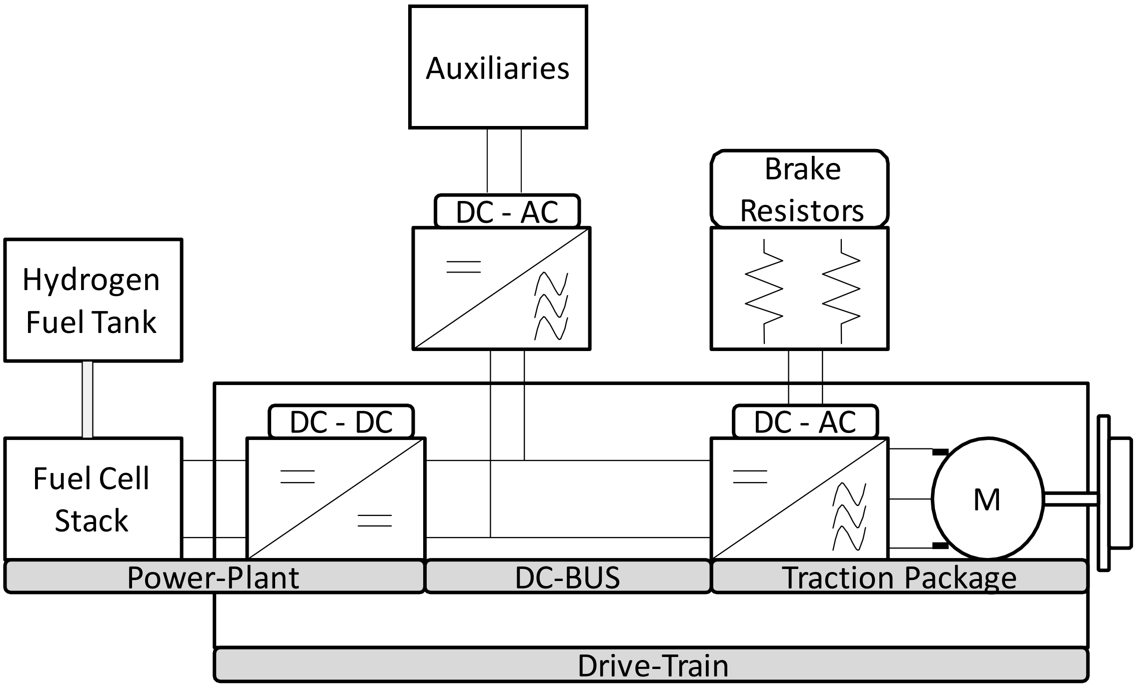


Figure 106: Hydrogen-Powered Power-Module Drive System Diagram

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.

The GTW requires 1 548 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 minute journey time, which includes terminal time at both end stations, the range of the vehicle is 960 minutes, or 16 hours, which represents a working day. Most diesel railway vehicles in the UK are refuelled on a daily basis (RSSB, 2005), including the vehicles currently operating on the example route (Personal communication with Rory Dickerson of Network Rail, 2013). The time required to refuel a diesel railway vehicle is in the range of 30 min to one hour, depending on the type of vehicle, fuelling station, and quantity of fuel that has to be added (McDonnell, 2012a; Personal communication with Rory Dickerson of Network Rail, 2013). This is comparable to the capability provided by existing hydrogen refuelling arrangements for road vehicles, see background chapter. Now, 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 34.

Table 34: Benchmark Criteria

Component	Parameter	Parameter
Power-Plant		
Maximum power-output		572 kW
Energy output		429 kWh
Vehicle range		
Operating time		960 min (16 hours)
Number of full return journeys		9
Mass		
Vehicle mass		72 t
Mass supported by power-module		40 t
Mass of diesel fuel (1 500 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, height 3.035 m)	29.36 m^3	
Power-module corridor[d] (length 4.5 m, width 0.8 m, 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, height 0.6 m)	8.28 m^3	
Volume available for power-plant and hydrogen		37.64 m^3

[a]Mass of one litre diesel is 0.837 t, based on American data (U.S. DOE, 2008a)
[b]Based on the two QSM11 Cummins Diesel-Generator set installed in the Capital Metro GTW (Cummins Power Generation Inc., 2013; Vantuono, 2007)
[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

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 Figure 107. Further, Figure 108 shows the vacant space on top of a Stadler FLIRT coach, which is similar to the GTW.

Figure 107: Austin Capital Metro GTW Depicting Available Space on the Roof (City of Austin, 2013)

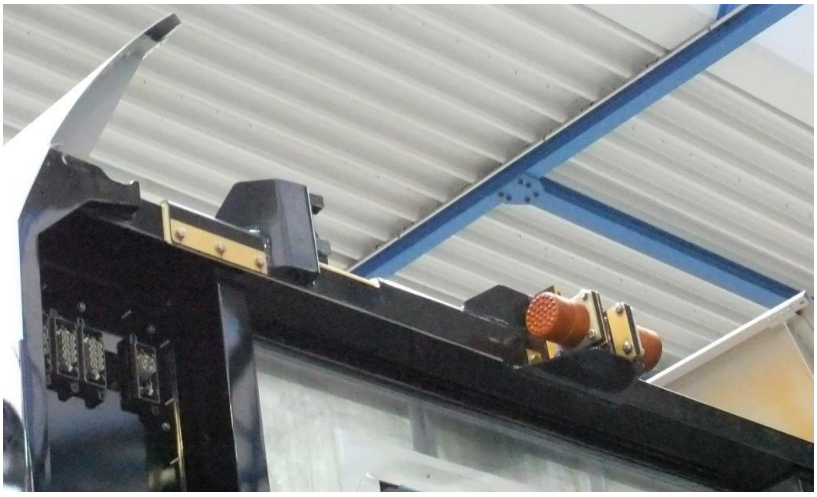


Figure 108: The Available Height on a Coach Roof of a FLIRT Vehicle (Author's Collection, 2013)

The diesel engine alternator set occupies the majority of the volume in the power-module, as illustrated in Figure 109 for a FLIRT.

Figure 109: Diesel-Generator Set in a FLIRT Power-Module (Author's Collection, 2013)

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 the study. The reasons are: practical in-service demonstration, most powerful fuel cell system integrated into a railway vehicle for traction, and the author's personal experience of the locomotive and plant in operation. The system provides 250 kW of electricity output utilising two Ballard fuel cell stacks (Miller, Hess, Barnes, et al., 2007), 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). A diagram of the system is shown in Figure 110. The fuel cell system, including heat radiators and other ancillaries, under test operation in Denver is illustrated in Figure 111, and the system installed in the switcher locomotive is illustrated in Figure 112.

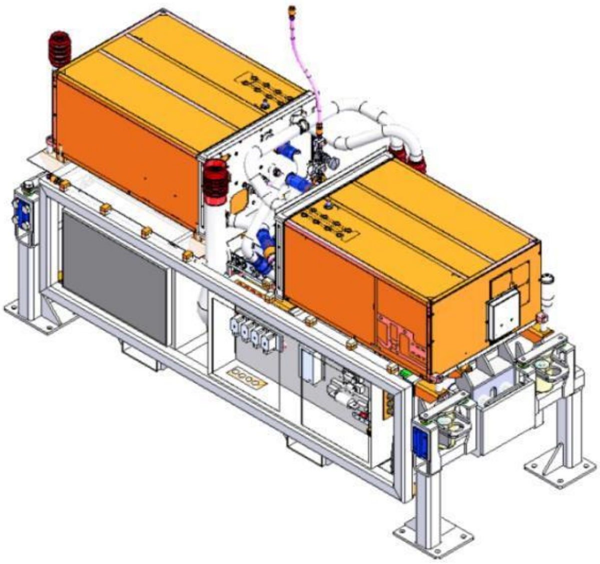


Figure 110: Fuel Cell System Utilised in the Vehicle Projects Switcher Locomotive Courtesy and Copyright Vehicle Projects Inc

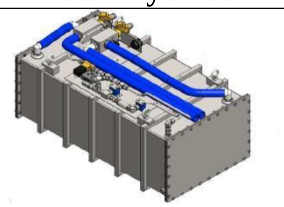
Figure 111: Vehicle Projects' Fuel Cell System Including Ancillaries Under Test in Denver (Miller, et al., 2009)

Figure 112: Illustration of a Fuel Cell Stack in Vehicle Projects' Hydrogen-Hybrid Switcher (Author's Collection, 2009)

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 35.

Table 35: Characteristics of Considered Hydrogen Storage Systems for Vehicle Design

	350 bar	**700 bar**	**Metal-Hydride**
Illustration			
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	0.260 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 (2012)	Personal Communication with Vehicle Projects (2013)

[a]Tank system employed in the hydrogen-hybrid switcher (Miller, et al., 2011)
[b]Demonstrated in automobile applications (Hansen, et al., 2010)
[c]Implemented in mining locomotives (Miller, et al., 2012)

The heaviest tank system is metal-hydride based and the system with the lowest volume requirements for hydrogen storage is 700 bar compressed gas. The number of required tanks is calculated in the next section.

Train Design

The power-plant has to provide 572 kW as determined earlier, see Table 34; 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. Therefore, the modules will deliver 25 kW more power than the original diesel engines that drive the alternators. Four 125 kW units and a less powerful Ballard fuel cell module providing gross 75 kW (Ballard Power Systems Inc., 2011) would not be enough to meet the power-plant requirement. The fuel cell system would have a volume of 11.78 m^3 and a mass of 5.5 t. Also, the power at wheels rises to 504 kW due to the increase of power.

One return journey requires 429 kWh output of the power plant, as calculated previously, see Table 34. Thus, the fuel cell system has to provide 440 kWh electrical-output taking into account the DC to DC converter. A fuel cell system efficiency of 45 % has been exercised, which is established in the following way: A 50 %, LHV, fuel cell efficiency (Miller, et al., 2011; Yamamoto, et al., 2010) 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 Hydrogen Pioneer in the previous chapter in the 6 km/h and 7 km/h tests. For a return journey the resulting hydrogen demand is 978 kWh. Sixteen hours operation time, allowing nine return journeys, requires 9 389 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. Table 36 shows the hydrogen vehicle possibilities with the three storage options.

Table 36: Hydrogen Vehicle Parameters with Various Storage Options

Storage System	**350 bar**	**700 bar**	**Metal-Hydride**
Number of tanks	57	47	81
Energy stored	9 516 kWh	9 416 kWh	9 466 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*

None of the vehicle options meet the mass target: the compressed gas options result in a vehicle mass of approximately 77 t, and the metal-hydride option in approximately 107 t. The first two are close to the benchmark and are similar to the mass of current regional trains (Marsden, 2007), 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, plus leaving additional free space. 350 bar tanks need a volume that is approximately 1.27 m^3 more than available. However, the dimensions are approximations and there might be more space free on the roof of the coaches, or the space on the power-module roof may be available, to accommodate the small additional volume. Also, the removal of three tanks would lead to a benchmark achievement, and the slightly shorter range might be acceptable. A further option would be to increase the length of the power-module, which is straightforwardly possible up to about six metres length (Personal communication with Stadler Employees).

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. 350 bar storage falls just outside the volume available but there might be more space on the roof to accommodate the tanks. Only 700 bar fulfils all the benchmark criteria.

The high axle loads that are placed on the power-module wheels, due to the design of the train, can be reduced when an articulated concept is employed. The third generation of Stadler FLIRT vehicles allows autonomous traction utilising a power-module like that of the GTW (Stadler Rail AG, 2013a). An articulated design was chosen to support the power-module as can be seen in Figure 113.

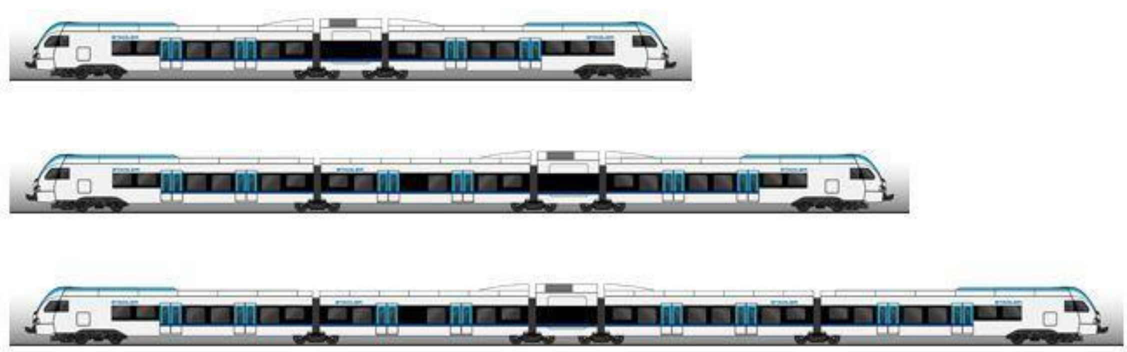


Figure 113: Third Generation of FLIRT Trains Allowing a Diesel-Electric Power-Module Diagram (Stadler Rail AG, 2013a)

The FLIRT vehicles are more traditional multiple unit designs and the traction packages are installed in the end coaches, while the prime movers are positioned in the power-module (Stadler Rail AG, 2012b). In addition to reducing the axle load, more space in the power-module is available thanks to having trailing bogies rather than a traction bogie, as illustrated in Figure 114. Usually, that volume is occupied by the diesel tank (Personal communication with Stadler employees).

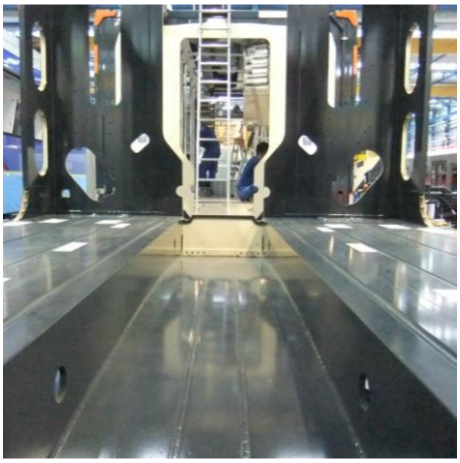


Figure 114: Available Sub Floor-Level Volume in a FLIRT Power-Module (Author, 2013)

A FLIRT type design would enable the use of 350 bar storage, while lowering the maximum axle load. However, these vehicles are still under construction and the only contract to date was for a broad gauge railway in Estonia, with deliveries expected to start in 2013 (Stadler Rail AG, 2012b). For those reasons the FLIRT train has not been chosen as a benchmark vehicle, although the author recognises the advantages of such a design. A future hydrogen-powered regional train may employ articulation, and the simulation results would not be affected dramatically by this design change.

The 700 bar option was modelled, because it meets all the benchmarking criteria based on 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, thanks to the 625 kW power-output of the fuel cell stack instead of 600 kW of the diesel engine. 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 the thesis scope. The simulation results of the hydrogen-powered train are presented in the next section.

7.2.2 Simulation Results

The Hydrogen GTW was run over the Birmingham Moor Street to Stratford-upon-Avon route and return, were the dwell time at calling stations was 30 s and the stationary time at Stratford-upon-Avon five minutes. 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 37, and in Figure 115 to Figure 120. The figures begin with the journey’s origin in Birmingham Moor Street and include a terminal time in Stratford-upon-Avon of five minutes before the return journey starts. A terminal time of six minutes in Birmingham Moor Street is added to the energy calculations, but not shown in the figures, as the starting location is reached by the train at that time and the simulation finishes.

Table 37: Hydrogen-Powered Train, 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	504 kW
Average Traction Power at Wheels[1]	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[2]	108 kWh
Power-Plant Output Energy	446 kWh
Fuel Cell Stack Output Energy	457 kWh
Energy Contained in Hydrogen	1 017 kWh

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

From Table 37 it can be seen that the energy at wheels requirement has been increased by 16 kWh compared to 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 1 017 kWh for the journey compared to the 978 kWh initial estimation, which was based on a mass of 72 t. Given the 9 416 kWh stored in the hydrogen tanks 9.25 journeys would be possible and the nine benchmarked journeys are achieved, whereas the 960 minutes operating time is not achieved, instead 925 minutes are reached. However, one 700 bar tank stores 200 kWh, so the addition of two tanks would raise the energy stored to 9 816 kWh allowing 9.65 journeys or 965 minutes operation 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. The remaining performance results are presented in the figures below. Figure 115 shows the speed of the train and the maximum allowable line speed. The performance is similar to that of the original diesel-electric vehicle.

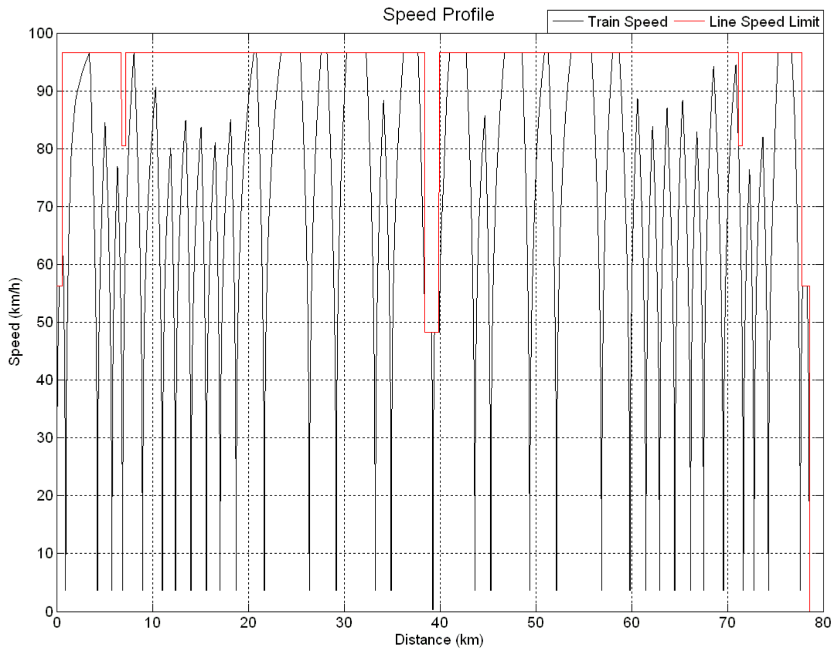


Figure 115: Speed Profile of the Hydrogen GTW Compared to the Maximum Line Speed

In Figure 116 the running diagram of the hydrogen-powered train is shown. The five minutes terminal time in Stratford-upon-Avon are indicated by the plateau half way through the journey.

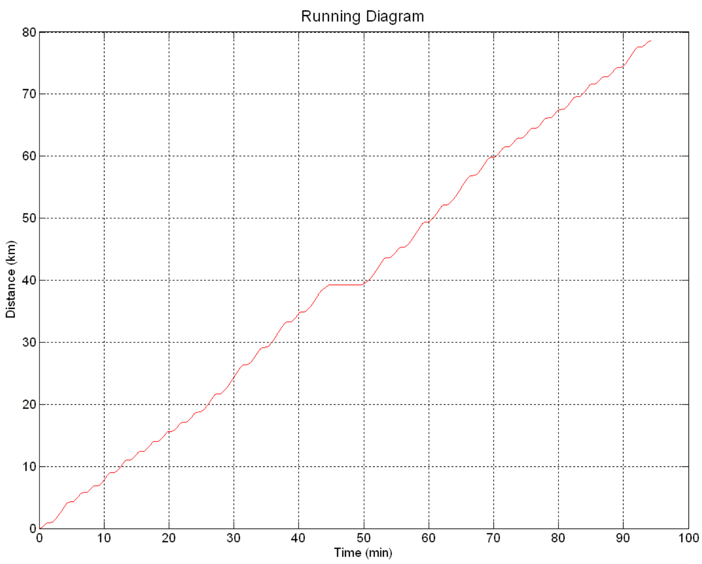


Figure 116: Running Diagram of the Hydrogen GTW

The tractive effort, resistance to motion, and acceleration curves are presented in Figure 117. The power at wheels increased by approximately 30 kW so the graphs are similar to those of the diesel-electric version, see Figure 102, but the tractive effort to achieve the 1 m/s^2 must be increased to 83 kN.

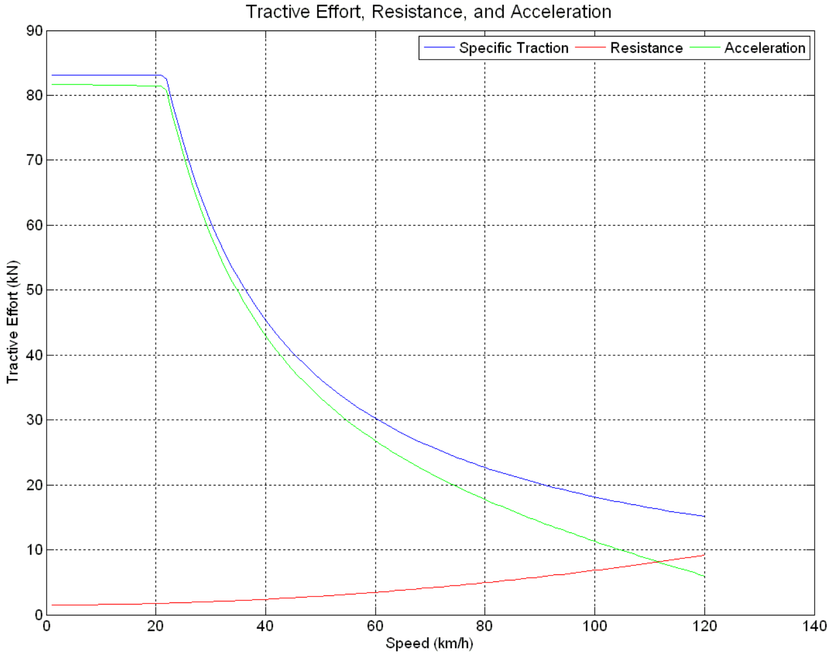


Figure 117: Tractive Effort, Acceleration, and Resistance to Motion of the Hydrogen GTW

Figure 118 shows the traction power during the duty-cycle and the average traction power, both at the wheels.

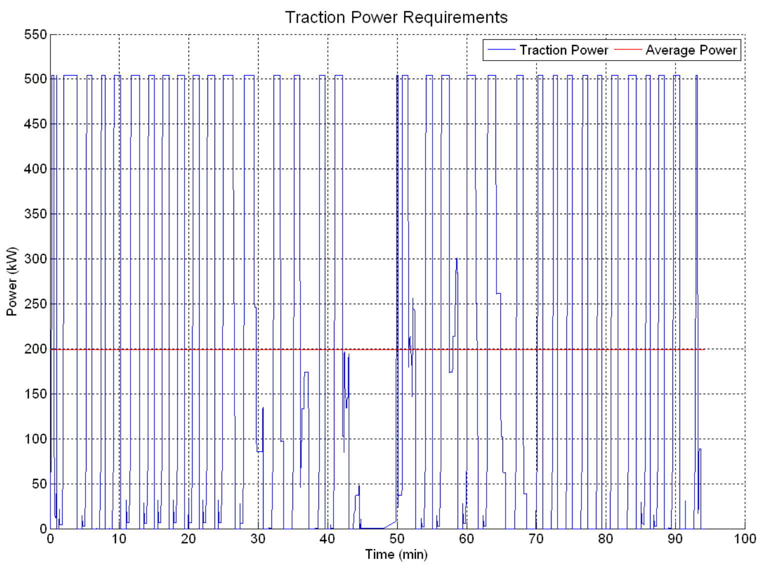


Figure 118: Traction Power and Average Traction Power at the Wheels of the Hydrogen GTW

Braking and traction power at the wheels is shown in Figure 119.

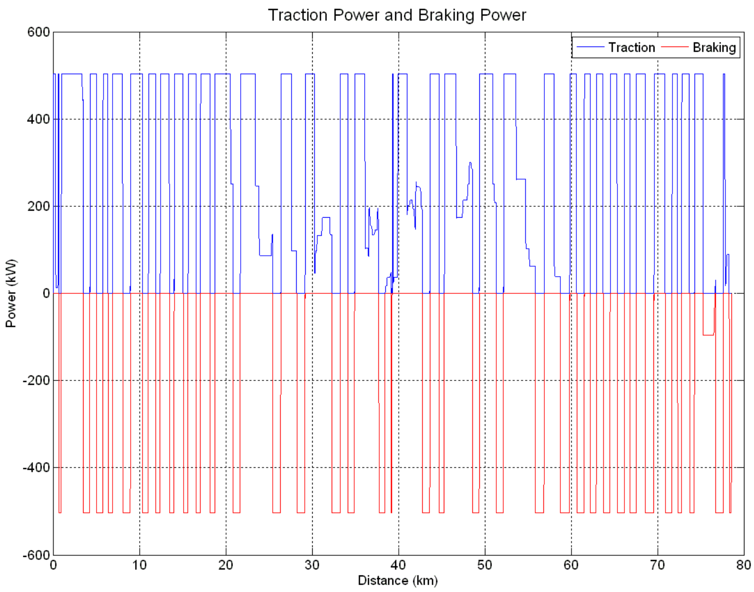


Figure 119: Traction and Braking Power at the Wheels of the Hydrogen GTW

Figure 120 presents the power across the drive-train and the fuel cell stack, in the same way as in the diesel-electric results.

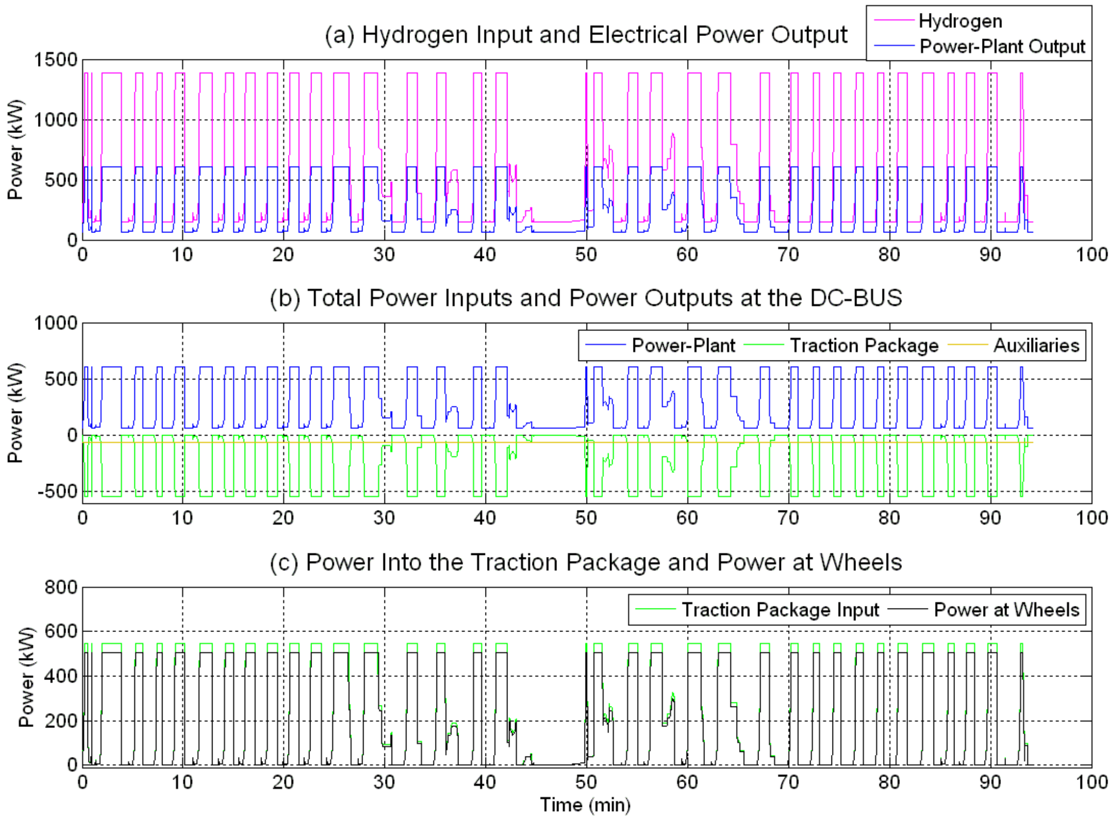


Figure 120: Power Across the Hydrogen GTW Drive-System

The 199 kW average traction power demand is approximately 2.5 times lower than the peak power demand at 504 kW, as shown in Figure 118, which indicates a high potential for hybridisation. In addition the braking power is significant, as illustrated in Figure 119, further strengthening the case for an on-board energy storage device. A hydrogen-hybrid train concept that is based on the hydrogen-powered train is developed in the next section. 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.

7.2.3 Hydrogen-Hybrid Vehicle Development

In this section the author develops a hydrogen-hybrid vehicle and the benchmark is the diesel-electric GTW. First, the general drive-system alteration is presented, then the power and energy storage requirements are determined, which is followed by the volume and mass implications of the new system to complete the vehicle concept design.

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 Figure 121.

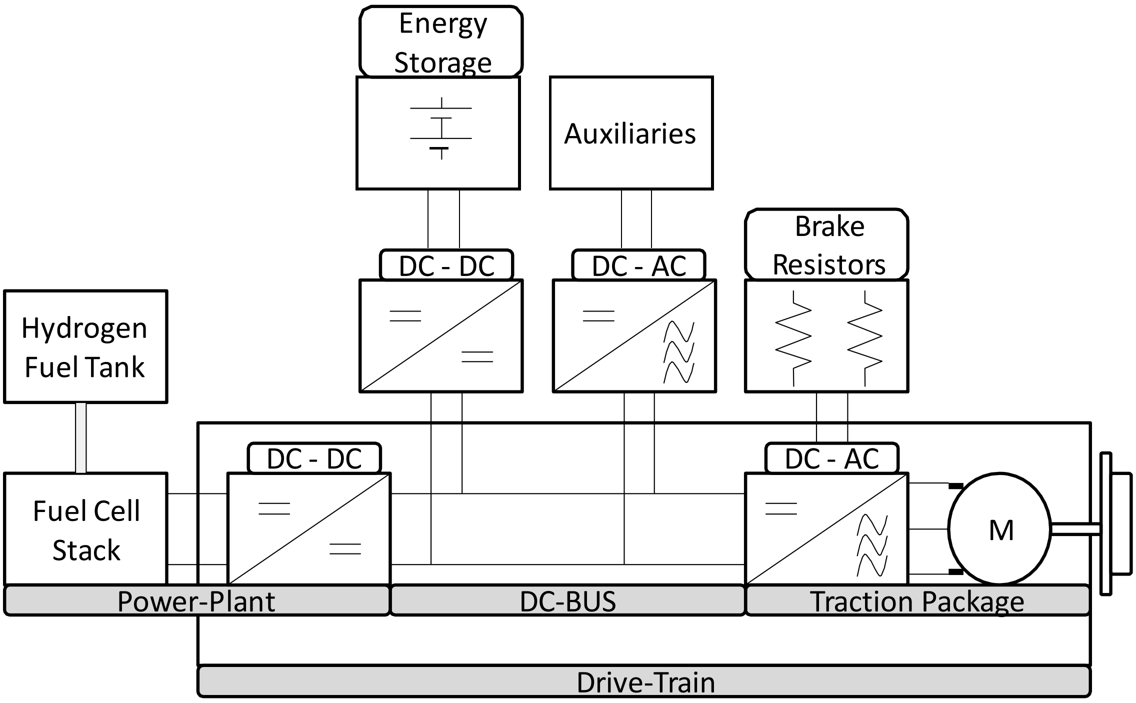


Figure 121: Hydrogen-Hybrid Drive-System

In the concept design presented here the energy storage device is based on a battery-pack system, as implemented in the Hydrogen Pioneer. Other storage technologies that could be employed are super capacitors or flywheels. The battery technology in the design is lithium-ion, due to the more favourable energy capacity parameters compared to competing batteries (Von Helmolt & Eberle, 2007). A drive-train efficiency of 90.3 % from the fuel cell stack to the wheels is assumed, which is the same as in the hydrogen-powered vehicle. The DC to 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 (U. Bossel, 2006), is assumed.

A 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 (Miller, et al., 2011; Yamamoto, et al., 2010). Therefore, the fuel cell stack efficiency has been increased to the aforementioned value, resulting in a power-plant efficiency of approximately 49 %. In Table 38 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, as described previously in the chapter, and information from the hydrogen-powered vehicle development.

Table 38: 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		6 624 kWh
Hydrogen Storage System Size		
Hydrogen energy required for all journeys	6 624kWh	
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

The power requirements of the power-plant and the battery-pack are determined in Table 39. Again, the data are based on the simulation of the diesel-electric GTW and the hydrogen-powered train.

Table 39: 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 hours (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

Markel and Simpson (2006) 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 the study. Together with the previously mentioned data, the determination of the battery-pack energy storage size is now possible. 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 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 Figure 122.

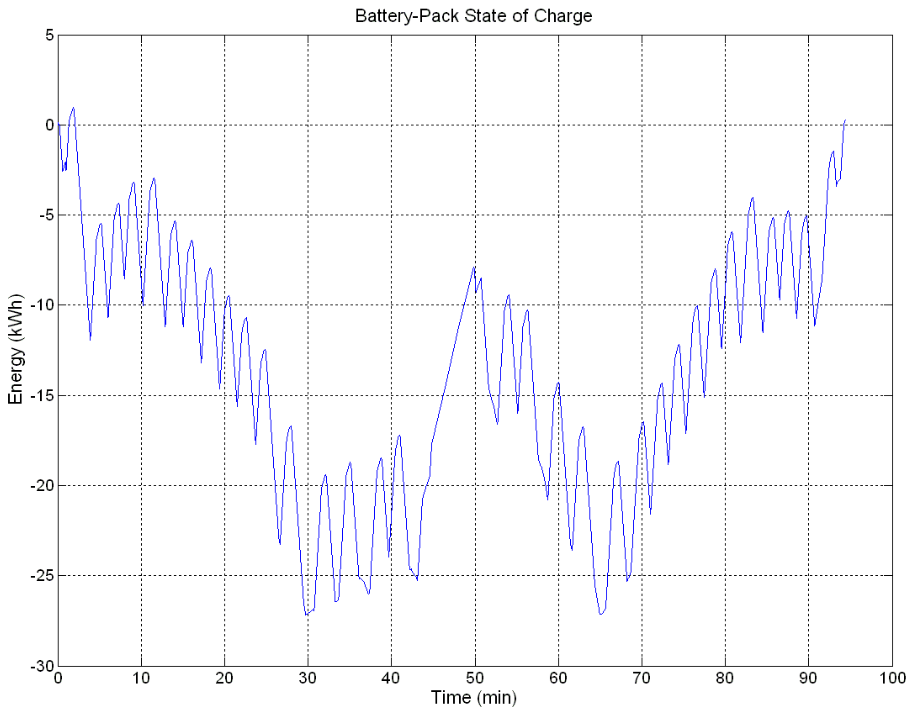


Figure 122: Battery-Pack State of Charge During the Duty-Cycle

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 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 (Brusa Elektronik AG, 2012). The train's battery-pack characteristics are calculated in Table 40, based on the data provided in this section.

Table 40: 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

A hydrogen-hybrid train with the characteristics presented in Table 41 could be developed. Most of the listed parameters changed in comparison to the diesel-electric benchmark version.

Table 41: Hydrogen-Hybrid Train Characteristics

Energy	
Energy stored in hydrogen	6 624 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]The author considers the 0.7 t additional mass as an acceptable increase compared to the benchmark.

The hydrogen-hybrid concept vehicle operation was modelled over the Birmingham Moor Street to Stratford-upon-Avon route and return, and the simulation results are presented in the next section.

7.2.4 Simulation Results

The Hydrogen-Hybrid GTW was run over the Birmingham Moor Street to Stratford-upon-Avon route and return, were the dwell time at calling stations was 30 s and the stationary time at Stratford-upon-Avon five minutes. It was assumed that the Davis parameters, based on the diesel-electric GTW, stayed the same throughout the journey. The results for the hydrogen-hybrid train are presented in Table 42, and in Figure 123 to Figure 128. The figures begin with the journey's starting point in Birmingham Moor Street and include a terminal time in Stratford-upon-Avon of five minutes before the return journey starts. A terminal time of six minutes in Birmingham Moor Street is added to the energy calculations, but not shown in the figures, as the starting location is reached by the train at that time and the simulation finishes.

Table 42: 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[1]	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[2]	108 kWh
Power-Plant Output Energy	336 kWh
Fuel Cell Stack Output Energy	345 kWh
Energy Contained in Hydrogen	690 kWh

[1]Calculated from the energy data: 298 kWh/1.58 h=189 kW
[2]Includes terminal time at Birmingham Moor Street on return of five-and-a-half minutes

The speed of the train compared to maximum allowable line speed is illustrated in Figure 123, and the running diagram is shown in Figure 124.

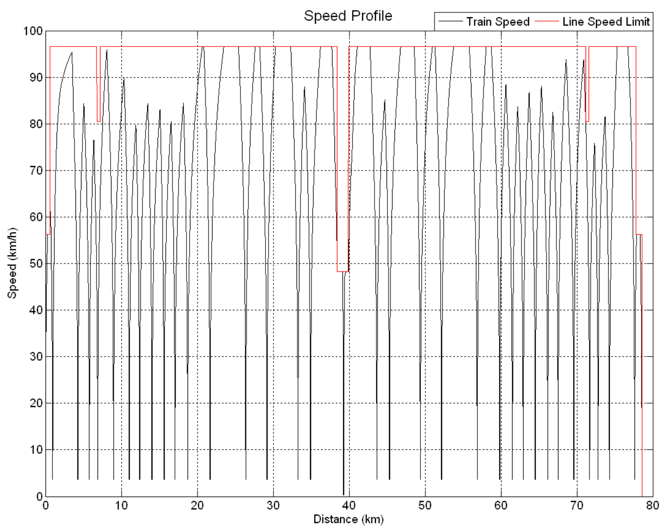


Figure 123: Speed Profile of the Hydrogen-Hybrid Train From Birmingham Moor Street to Stratford-upon-Avon and Return

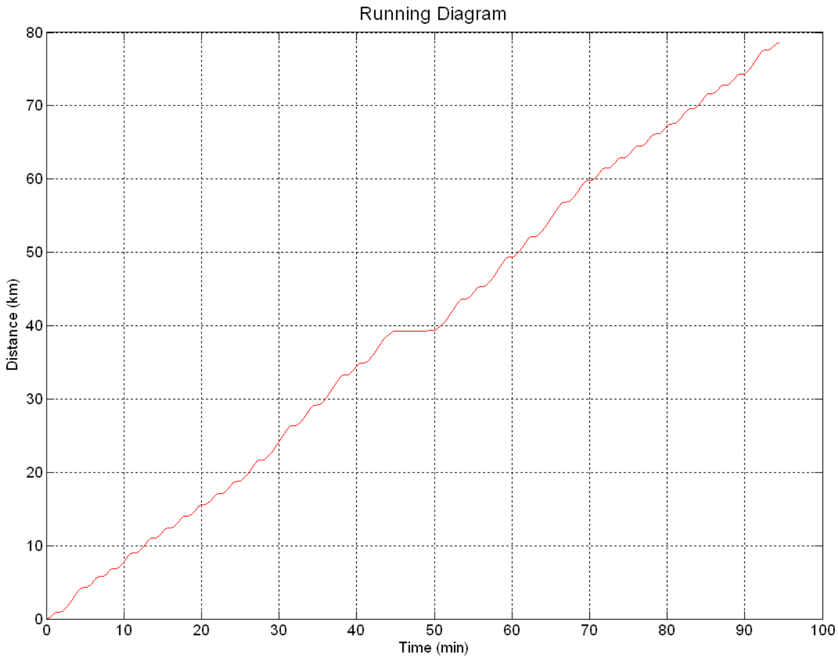


Figure 124: Running Diagram of the Hydrogen-Hybrid Train

The tractive effort, resistance to motion, and acceleration curves are presented in Figure 125. The curves are similar to the original vehicle, see Figure 102, as the power at the wheels is the same.

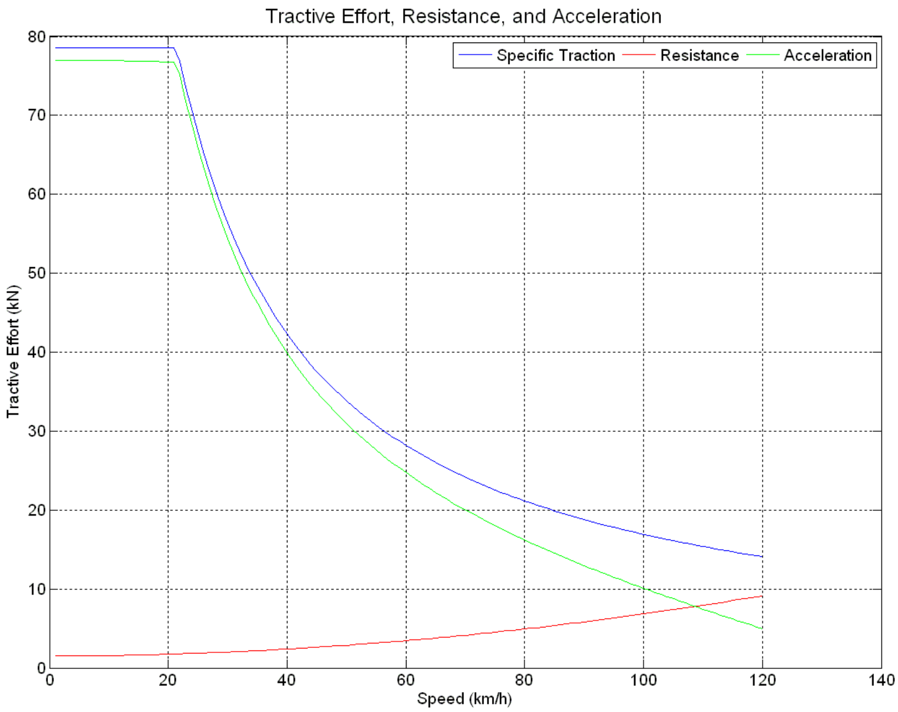


Figure 125: Tractive Effort, Acceleration, and Resistance to Motion of the Hydrogen-Hybrid Train

The traction power requirements and the average traction power at the wheels are illustrated in Figure 126. However, the average power provided by the power-plant is lower, as shown in Figure 128.

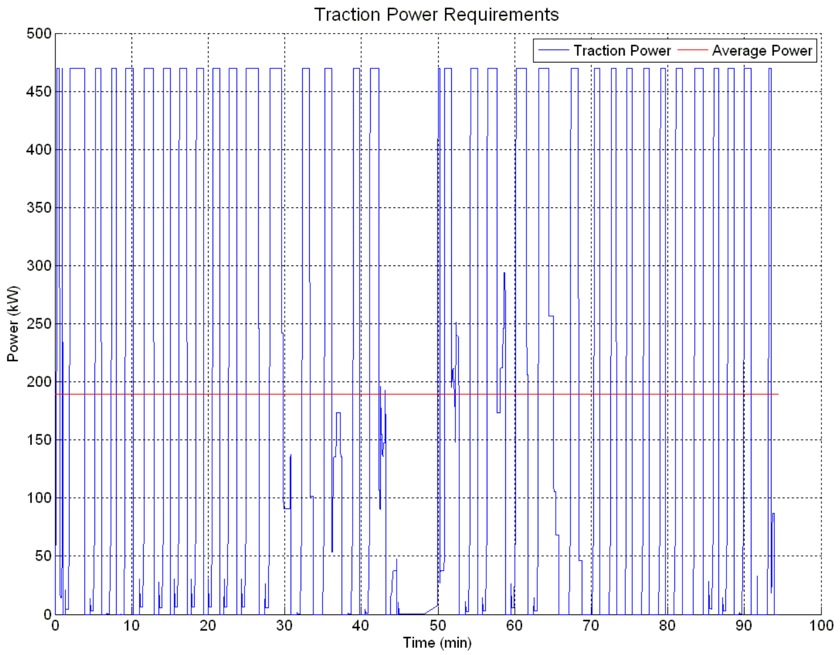


Figure 126: Traction Power and Average Traction Power at the Wheels of the Hydrogen-Hybrid Train

In Figure 127 the traction power and the power due to braking, both at the wheels, are presented.

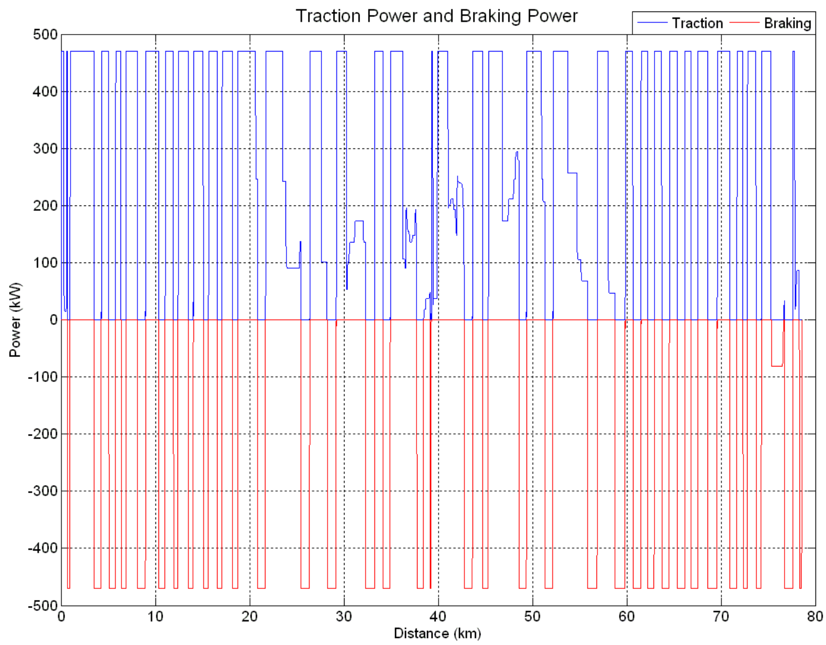


Figure 127: Traction and Braking Power at the Wheels of the Hydrogen-Hybrid Train

The power across the drive-system of the hydrogen-hybrid train is shown in Figure 128.

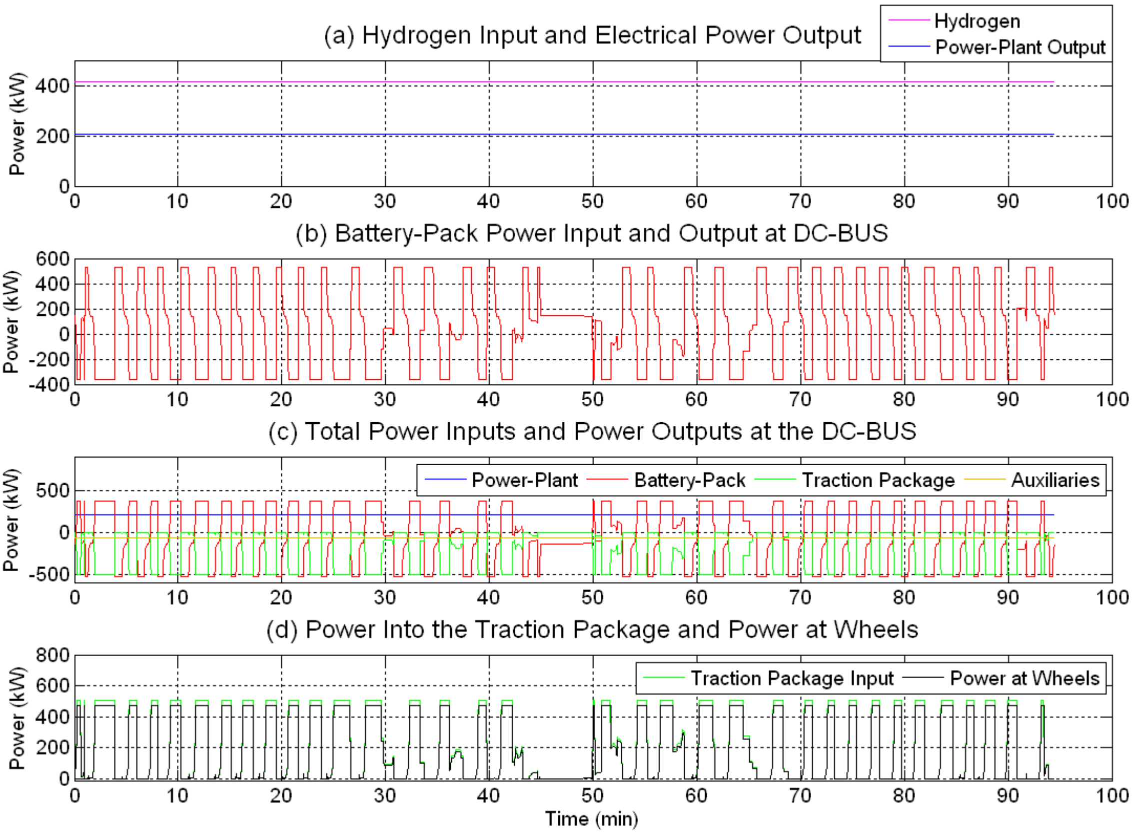


Figure 128: Power Across the Hydrogen-Hybrid Train Drive-System

Graph (a), in Figure 128, shows the hydrogen input and the power-plant output, and it is apparent that only the average power is supplied compared to hydrogen-only train, see Figure 120.

In graph (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. Further, the power contribution resulting from regenerative braking can be seen in the positive peak values.

Graph (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 (d).

In general, the modelled hydrogen-hybrid vehicle performed well, leading to a similar journey time and range compared to the other vehicles, while reducing primary energy consumption. A more detailed comparison and general discussion is provided in the next section.

7.3 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 43. Other data, such as the coach mass and the Davis equation are not shown in Table 43 because there was no change from the original.

Both hydrogen trains could meet all but the mass benchmark, with the hydrogen-only train being the heaviest at 77 t, while the hybrid version weighs 72.7 t compared to 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. Metal-hydride storage would lead to a vehicle mass of approximately 107 t and was, therefore, considered not feasible.

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 as employed by the Stadler FLIRT trains, can decrease the maximum axle load significantly, although the train mass increases. Therefore, the slightly higher mass of the two hydrogen trains is manageable.

Table 43: 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 hours)	965 min (16 hours)	960 min (16 hours)
Mass			
Train mass	72 t	77 t	72.7 t
Maximum axle load	20 t	22.5 t	20.4 T
Energy			
Primary Energy Consumption for the Journey	1 548 kWh	1 017 kWh (34 % less than diesel)	690 kWh (55 % less than diesel)
Energy from regenerative braking	-	-	138 kWh
Duty Cycle Vehicle Efficiency	25 %	41 %	45 %
Well-to-Wheel Efficiency[1]	21 %	24 %	26 %
Well-to-Wheel Carbon emissions[1]	1 895 kg	862 kg (55 % less than diesel)	533 kg (72 % less than diesel)
Primary Energy Source	Diesel	Hydrogen	Hydrogen
Primary Energy Storage Quantity (LHV)	14 918 kWh (1 500 l)	9 816 kWh (294 kg)	6 624 kWh (204 kg)
Power			
Maximum Power at Wheels	470 kW	504 kW	470 kW[2]
Power-Plant Power	572 kW	609 kW	207 kW[3]
Prime-Mover Power	600 kW	625 kW	250 kW
Maximum Battery-Pack Power	-	-	400 kW

[1]Calculated from the results presented in the well-to-wheel chapter, based on the LHV. Only natural gas SMR production of hydrogen was considered, no renewables contribution was added
[2]Limited to 470 kW to provide the same range and journey time as the diesel-electric GTW
[3]Fuel Cell Stack operating at 85 % of maximum capacity

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. The 350 bar cylinders require 1.27 m^3 more space than benchmarked, but further volume may be available on the roof in an improved, more detailed design. Alternatively, the range of the vehicle could be reduced. 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 hours, 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. Also, 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. 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. The hydrogen-hybrid version has been limited to 470 kW at the wheels in the evaluation, although the drive-system could provide more power, leading in turn to a higher energy consumption but shorter journey time.

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. The feasibility of hydrogen and fuel cells in railway vehicles, is therefore, proven. In a next step, the author recommends a more detailed design study and subsequent construction of a hydrogen-powered GTW, either with a hydrogen-only or a hydrogen-hybrid drive-system, the latter offering greater energy savings and, with the addition of more tanks in the available space, greater range.

7.4 Summary

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 350 bar storage option would require 1.27 m^3 more space than benchmarked. However, a more detailed study may reveal additional volume that could be utilised for energy storage, such as on the roof of the power-module.

The 72 t diesel-electric train achieved a journey time of 94 minutes, while consuming 1 548 kWh of energy, which leads to an operational range of 16 hours. The 77 t hydrogen-only train also achieved a journey time of 94 minutes, with an energy consumption of 1 017 kWh, resulting in an operational range of 16 hours. Results for the hydrogen-hybrid train are: 94.5 minutes journey time, 690 kWh hydrogen consumption with a vehicle mass of 72.7 t and an operational range of 16 hours. Both hydrogen-based trains reduce energy consumption compared to the diesel version: 34 % for the hydrogen-only and 55 % for the hydrogen-hybrid employing regenerative braking, savings that the author considers 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. Further, a reduction in carbon emissions compared to 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 SMR without a renewables contribution.

The evaluation demonstrates, on the basis of benchmarking, computer simulation, and associated results analysis, that hydrogen and fuel cells are feasible for train propulsion systems, which confirms the empirical results from the Hydrogen Pioneer. The energy savings and carbon reductions that are achieved while performing the same service, provide a strong case for more detailed design and construction of a demonstration train..Further, the author would expect similar results with full-scale trials as were estimated with computer modelling. Therefore, the author recommends the design and construction of a full-scale demonstrator train and believes that the diesel-electric GTW provides a suitable platform for development. This chapter, combined with the previous chapter, and supported by the other chapters, shows that hydrogen-powered railway vehicles are technically feasible, while reducing energy consumption and subsequently, GHG emissions. In other words: the research hypothesis is true.

8 CONCLUSION

The conclusion is divided into four sections. First, a summary of the research and the key findings are provided. Second, the author proposes further areas of research and makes recommendations about future developments of hydrogen-powered traction. Third, a brief review of the methodology employed is provided, followed by a critical discussion about hydrogen as a fuel, which includes barriers to implementation.

8.1 Summary and Findings

Transportation is a key element of civilisation and railways are an integral part of the system: on land, they provide the most efficient way of transporting large quantities of cargo and allow passengers to travel in substantial numbers. Propulsion for railways has developed from humans pushing wagons, to animals pulling carts, to mechanised alternatives, of which steam-power was the first. Towards the end of the 19th century electric traction became a viable alternative and was employed to solve specific problems, such as fuel supply uncertainty and disruption, as well as emissions that prevented operation in tunnels or to react to legislation governing exhaust gases.

However, the high initial cost inhibited the deployment of the technology, despite the superior traction characteristic compared to steam. In the 1930s diesel-electric vehicles combined the advantages of both, autonomous operation and favourable traction characteristics, while avoiding most of the drawbacks, such as high infrastructure cost and excessive amounts of exhaust emissions. Diesel and electricity have formed the major energy sources for railways, with diesel currently meeting about 70 % of the global demand. Today, conditions exist that are similar to those that led to railway traction changes in the past: concerns about emissions at the point-of-use and overall greenhouse gases, as well as uncertainty about diesel fuel supply. Exhaust gases of diesel trains are regulated in Europe and the USA to decrease emission of substances such as particulate matter and nitrogen oxides that cause cancer and smog, respectively. Alternative propulsion methods for autonomous traction are necessary, and these have to broaden the primary energy spectrum while being less polluting, as well as more efficient in operation. The energy carrier hydrogen has been identified by the automotive sector as the only long-term viable alternative to liquid petroleum-based fuels.

Hydrogen rarely occurs as an element on its own, but usually as part of another substance and, therefore, it has to be released from the compound through energy input. Thus, it is a secondary energy, like electricity, and can be produced from many sources, such as fossil fuels, for example, natural gas and coal, or through renewables, such as biomass, and water-splitting through water-electrolysis or thermo-chemical splitting, processes that can be powered by wind or solar energy.

Fuel cells, in which hydrogen and oxygen are combined to create electricity and heat while forming water, are an effective way of power generation, with reported efficiencies of up to 60 %. Alternatively, hydrogen can be burned in a combustion engine similar to gasoline.

An ambivalent property of hydrogen is its volumetric density and volatility which, on the negative side, requires advanced storage methods such as high compression of typically 350 bar to 700 bar, but on the positive side, ensures quick dissipation in case of leaks, improving safety. However, the storage volume requirements are counteracted by the higher efficiencies of fuel cells compared to combustion engines, which allows a similar range to current gasoline-powered vehicles.

Vehicles with hydrogen fuel cells are efficient and the only exhaust is pure water, which satisfies the requirement to reduce emissions at the point-of-use. However, the evaluation of overall greenhouse gas emissions has to be conducted on a well-to-wheel basis. For the secondary energies, electricity and hydrogen, the emissions depend directly on the production method and, in most cases, a mix of primary sources is employed for electricity generation.

The well-to-wheel analysis conducted for railway traction powered by diesel, electricity, or hydrogen in the areas of the UK, USA (on a national basis), and California (specifically) – chosen for its stringent emission standards and high renewable contribution to the electricity mix – has shown that diesel is the most polluting option. Electricity reduces emissions compared to diesel, and hydrogen fuel cell vehicles have a similar efficiency to electric trains at 25 %, while reducing emissions compared to diesel by 19 %, and by 3 % compared to electricity in the USA. Electric traction in California achieved the highest efficiency at 28 % and the lowest carbon emissions, highlighting the effect of a generation mix for secondary energies. Hydrogen combustion engines led to the lowest efficiencies and highest emissions compared to all other options. The reasons being the inherent energy conversion stages of the combustion engine drive-system: chemical energy, to thermal, to mechanical, and then to electrical energy, and the lower supply chain efficiency compared to diesel. In fuel cells there is only one conversion stage: chemical energy to electrical energy and, therefore, higher efficiencies are possible. If only renewable sources are used for energy production then hydrogen, as well as electricity, results in no carbon emissions. All mentioned efficiencies are based on the lower heating value of fuels, assume typical maximum vehicle efficiencies rather than duty-cycle parameters, and do not take embedded carbon into consideration. The requirement to reduce overall emissions can, therefore, be fulfilled with hydrogen fuel cell traction.

Several hydrogen-powered railway traction prototypes have been developed and demonstrated, including a mining locomotive, a switcher locomotive, streetcars, and multiple units. In addition, low volume (five) mining locomotives have been produced commercially, and these are in everyday operation. Also, the switcher locomotive has been tested in full service operation for about three months. Further, a hydrogen fuel cell locomotive, named Hydrogen Pioneer, has been developed, designed, and constructed at the University of Birmingham. The locomotive was successfully run on several occasions and pulled coaches with several persons on-board. No major problems due to the employment of hydrogen were encountered. Therefore, it has been demonstrated that a hydrogen fuel cell system can be utilised for railway traction. The scale and power-output of the Hydrogen Pioneer locomotive are not sufficient for full-scale vehicles, but the drive-system concept is suitable for larger vehicles, and has been employed in the design of the modelled hydrogen-hybrid train.

In an evaluation study the Hydrogen Pioneer was employed to determine the performance characteristics of hydrogen traction and, in particular, the duty-cycle efficiency. The results show that the fuel cell stack operates close to the manufacturer's maximum efficiency specification, at a measured high of 40 % during the duty-cycle and 43 % in steady-state operation. But, the overall vehicle efficiency was low, at a duty-cycle peak of 14 % and a steady-state peak of 17 %. However, the reasons could clearly be identified as drive-train related, particularly the traction motors. Also, the locomotive was developed as a proof-of-concept and high overall vehicle efficiency was not a goal at this stage. A change in gearing ratio to allow the motors to operate closer to the maximum efficiency would result in a higher vehicle efficiency. Hydrogen fuel cell systems have, therefore, been shown to enable high duty-cycle efficiencies.

A typical regional diesel-electric train, the Stadler produced GTW, was modelled to enable the creation of virtual hydrogen-powered vehicles that would allow comparisons between established vehicles and hydrogen traction. The simulated GTW was operated over the route from Birmingham Moor Street to Stratford-upon-Avon and return, and the achieved journey time as well as the available volume and mass limits of the train formed the benchmark for the hydrogen-powered trains. It could be shown that the hydrogen equipment can be accommodated in the available space and, although an increase in vehicle mass was inevitable, this was not prohibitive for operation, except if metal-hydride storage were to be employed. Two models of a hydrogen-powered train were developed: a hydrogen-only and a hydrogen-hybrid version. Both trains met the benchmark journey time and range of 16 hours, while reducing energy consumption for a return journey by 34 % and 55 % respectively. On a well-to-wheel basis, carbon emissions were reduced by 55 % in the hydrogen-only case and 72 % in the hydrogen-hybrid case, assuming that hydrogen is solely produced from natural gas. Therefore, it was established that hydrogen-powered trains can match the performance of diesel trains while reducing energy consumption and overall emissions, as well as avoiding emissions at the point-of-use. Further, the energy reductions suggest that operational cost-saving could be achieved if hydrogen were available at competitive prices, which is currently the case in some regions, for example, Los Angeles, CA.

Overall, the research hypothesis: “Hydrogen is a suitable energy carrier for autonomous railway traction”, which was split into five test statements, has been shown to be true, as the research evidence presented in the thesis clearly demonstrates.

8.2 Review

Various methods have been employed in the research and the work covers a wide range. Therefore, many parts could not be investigated in detail but the overall feasibility of hydrogen as an energy carrier for railway traction was determined. In particular, the well-to-wheel study could have included more primary energy sources and geographic areas, as well as further greenhouse gases rather than just carbon dioxide. Nevertheless, the analysis provides useful results and the approach is recommended for future comparisons of traction systems.

The Hydrogen Pioneer, as a prototype locomotive, was intended to demonstrate technology feasibility, which it did successfully, but changes to increase the vehicle efficiency are needed. Also, the performance evaluation could be improved: (1) through the operation on a longer railway that includes curves and (2) through the haulage of wagons or, ideally, through the combination of both. The locomotive is a narrow gauge vehicle operating on 10.25 inch gauge track and a more realistic evaluation would be possible with a full-scale locomotive. However, the tests provided useful data, especially about the response of the fuel cell stack to changing loads, and it was demonstrated that the hybrid-drive system worked effectively.

Computer modelling is always an approximation, and validation with physical tests is necessary to ensure accuracy. However, in general the performance results are similar for both methods and, therefore, the simulation offered a less risky and less costly alternative.

Overall the author considers that the methods employed in the research were suitable to test the hypothesis and he would employ a similar approach if another novel railway traction system needed evaluation.

8.3 Discussion and Alternative Scenarios

The application of hydrogen as a transportation fuel is primarily influenced by (1) the availability and cost of diesel, (2) emissions, at the point-of-use as well as overall, and, currently, (3) the cost of the hydrogen system compared to incumbent alternatives.

Liquid fuels, especially diesel, have a high volumetric and gravimetric energy density. Therefore, they are well suited to transport applications and the supporting infrastructure already exists. If diesel continues to be available at low prices or prices fall, for example, when demand subsides or new large petroleum resources are discovered, then the author expects that diesel will remain the preferred choice for railway traction and exhaust emissions will be reduced through combustion technology advances, employing after-treatments and filters. Unconventional petroleum resources, such as tar sands, have the potential to secure supply in the medium term, and although the cost of extraction is high and the efficiency low at present, the current fuel price seems sufficient for economical production.

Emissions at the point-of-use are already governed by regulations and the author expects that tighter regulations will be initiated, once the present stages have been fully implemented. However, advanced technologies and possible prime-mover changes, for example the use of more cleanly combusting heat engines such as turbines, may be able to satisfy future legislation and, therefore, the introduction of alternatives would be delayed.

Currently, it is suspected that greenhouse gas emissions due to human activity are the primary cause for the rise in global temperature. If the temperature should drop, despite continued combustion of fossil fuels or the climate change theory is invalidated, then it is unlikely that hydrogen fuel will be implemented. Other fossil fuels, such as natural gas, in particular shale gas, and coal have known reserves that are expected to last for several decades, or in the case of coal at least a century, probably longer. So, in case carbon release proves not damaging to the environment, continued combustion of fossil and synthetic fuels is likely. Also, bio-fuels in their second or third generation may offer a more economical alternative to hydrogen, especially if emissions are not important and conflict with food production can be avoided.

Batteries can offer similar benefits to hydrogen: avoiding emissions at the point-of-use, overall reduction of greenhouse gases, and enabling a variety of primary energy sources. Currently, the low energy densities and the long recharging times do not allow batteries to substitute for liquid or gaseous fuels. But technology advances may overcome these problems. If that is the case, then the direct use of electricity could be more effective and efficient, especially when electricity is the direct output of conversion devices, such as in wind turbines or hydro power stations. Other electrical energy storage devices, for example super capacitors, could equally overcome the aforementioned disadvantages. Both technologies would have to be produced at a much lower price than at present, similar to hydrogen system components.

A further problem with on-board electrical energy storage is the required infrastructure that has to be implemented to allow rapid charging. Currently, no electricity grid is able to allow quick recharging of a sizeable number of vehicles at the same time, and significant investments in infrastructure are required to overcome this problem. Often, it is considered more cost effective to build a hydrogen fuelling infrastructure rather than upgrading the electricity grid for rapid charging.

Railway electrification can be an alternative to autonomous operation of trains, and electric trains have preferable characteristics, such as additional space on-board the vehicle for passengers, and trains are often lighter than diesel equivalents. Currently, wide-spread electrification is delayed or not economical due to the high capital cost. If significant cost reductions can be achieved, then the use of electricity, supplied through wayside infrastructure, is likely to increase.

Fuel cells and hydrogen tanks are costly and sizeable reductions are needed for commercial viability. If these cannot be achieved, then implementation of hydrogen systems will be delayed or not executed at all. Also, a supporting refuelling infrastructure is necessary and, if fuel supply proves to be uneconomical, against the current trend, then hydrogen vehicles will not be sold in large numbers. Stack lifetime must be increased for most applications and a longer lifetime is essential for buses and railway vehicles. An alternative would be low cost fuel cell stacks, enabling the economical annual or bi-annual replacement of the stack. Currently, most materials used in fuel cells can be recycled, so waste is less of a concern.

At present, hydrogen is not classified as a greenhouse gas and scientific evidence suggests that the secondary contribution to the greenhouse effect is negligible, if present at all. Also, the quantity of water vapour emitted at the point-of-use is similar to the water exhaust that results from the combustion of petroleum products, therefore little or no change to the present situation is expected. However, future research might show that hydrogen does contribute to the greenhouse effect or another undesirable characteristic is discovered. In such a case the wide-spread adoption is unlikely.

Despite all the enumerated barriers, hydrogen is, currently, the only viable alternative to petroleum-based fuels. In addition, the author deems the discovery of large additional petroleum reserves as well as reduced concern about emissions and greenhouse gases unlikely. Therefore, the advantages of hydrogen prevail, including: non-toxicity; abundance; high energy density; neutral to Earth's climate; various production pathways; chemical energy carrier, allowing storage over long periods of time; water as the only combustion product when used in fuel cells; and competitive tank refuelling times.

Currently, economic considerations are the primary factor preventing adoption. However, mass production of equipment and ongoing efforts to reduce the cost of specific elements, such as fuel cells, will lead to lower prices, continuing the trend of the last decade.

For railways, much higher traction equipment capital expenditure and shorter power-plant lifetime could be offset through operational savings, in similar respect to diesel replacing steam: diesel-locomotives were two to three times more expensive than steam while having a shorter lifetime but reduced operational cost.

Hydrogen volumetric density is less of an issue for railways, as a tender could be added if needed, but the research as well as previous prototypes has demonstrated that regional and switching services can be provided without a tender. In addition, advances in storage technologies are likely to reduce the mass and volume of tanks.

In the author's opinion, the primary barrier, aside from economics, is the lack of in-service demonstration of the technology. Prototypes for all the major railway services, intercity, regional, commuter, and freight have to be built and their performance demonstrated. Railway undertakings are generally conservative, and exhibition of superiority is often initiated by a manufacturer or an outsider to the industry, which has been the case for all past traction changes: horse to steam, steam to electric, steam to diesel. A past example of a traction change initiator is General Motors; the determination to replace steam with diesel, through assumption of development risk and production of vehicles, as well as U.S.-wide demonstration of trains, was a major contributor to the success of diesel traction. In the author's opinion a similar approach is needed for the wide-spread adoption of hydrogen-power. The pioneer of hydrogen traction is likely to gain market dominance for a long period of time - in General Motors' case it was about 50 years.

8.4 Further Areas of Research and Recommendations

The research evidence suggests that hydrogen-powered railway traction is possible and can achieve energy reductions as well as decrease carbon emissions. Further, the simulation results indicate that the necessary hydrogen equipment can be installed in a typical regional train and that the performance of a diesel-electric vehicle can be matched.

The author suggests that a prototype train should be constructed to validate the computer simulation. A more detailed design must be developed before train construction, and several partners who are willing to fund and construct such a train have to be found. In addition, the suitability of the proposed test route must be assessed in more detail and train operators, infrastructure managers, as well as regulatory bodies must be involved. A hydrogen supplier that is willing to support the demonstration would have to be found, and refuelling arrangements made. The proposed project could take a similar shape to the hydrogen-bus trials, but most likely with fewer demonstration partners.

The risk of hydrogen as a railway traction fuel has to be investigated in more detail and, in particular, operation in tunnels and other enclosed spaces must be considered, as the gas cannot dissipate freely, should a leak occur. On-board high pressure tanks may pose an additional challenge for railway standards, but the regulations can probably be adapted, as these tanks are deemed safe in vehicles, such as cars, that are operated by the general public.

A detailed economic feasibility study for hydrogen-powered trains should be conducted. This should include the consideration of fuel savings, renewable hydrogen supply, cost of infrastructure, and vehicle cost and life expectancy, and should be conducted over the whole life-cycle of typical trains. A comparison to electrification of routes would be wise to include, especially if hydrogen-powered trains are to be produced with similar traction characteristics to electric traction. It may be possible that hydrogen trains could be more economical, even if a tender to accommodate the tanks were to be necessary, as wayside infrastructure fixed costs can be avoided. Such investigations should consider intercity services, commuter train services, regional operations, metro systems, and freight locomotives. Recommended geographic regions include areas where diesel traction dominates, as the highest environmental savings can be realised through a traction change, for example, in the USA, China, and Australia. Also, legislation could encourage traction change through mandating that no exhaust emissions are allowed from railway operation, as has happened in the past with prohibition of steam trains.

Also recommended is an empirical study, similar to the Hydrogen Pioneer evaluation, with two full-scale vehicles, a diesel-electric and a hydrogen-hybrid, pulling the same load over a set distance, which would provide valuable data and would most likely confirm the results of the Hydrogen Pioneer tests.

An early attractive market for hydrogen-powered railways is light rail networks, especially if they are to be newly constructed. The elimination of electrification infrastructure is a benefit and should result in significant capital cost reduction while similar service patterns could possibly operated with hydrogen traction. Islands, such as Aruba, where energy autonomy is especially desirable, and a carbon-free economy might be easier achieved than in large industrial nations, are particularly good candidates for hydrogen-powered systems.

Also, areas without domestic petroleum resources would particularly benefit from hydrogen-powered railways, in a similar way to countries that electrified in the past for coal shortage reasons. Finally, areas where electrification is unaffordable, such as the large freight networks in North America, are strong candidates for hydrogen-traction deployment in the medium to longer term.

The author believes that hydrogen-powered railway vehicles are likely to be introduced in the medium-term, if not before, which is supported by the research results as:

The research provides evidence that hydrogen-powered railway traction is technically feasible, reduces energy consumption, has as exhaust water, decreases overall greenhouse gas emissions, and is not dependent on petroleum

RAIL FREIGHT IN 2035 – TRACTION ENERGY ANALYSIS FOR HIGH PERFORMANCE FREIGHT TRAINS

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ABSTRACT

This paper provides a comparison of the energy consumption and carbon emissions of rail and road vehicles for two routes. The scenarios considered are a high running speed container train, in locomotive hauled and electrical multiple unit (EMU) configuration, and a converted passenger EMU for pallets, as well as the corresponding road heavy goods vehicles. The container route is over the UK's East Coast Main Line and the pallet route from the UK Midlands to the edge of the country. The "well-to-wheel" 2008 and projected 2035 energy figures and carbon emissions are determined. It is demonstrated that, despite higher running speeds, a modal shift to rail reduces carbon emissions. The higher speed results in more flexible paths allocation for freight trains, enabling more attractive and flexible offers to shippers, therefore encouraging modal shift. The paper also shows the particular advantage of rail in hauling large volumes of cargo, particularly if locomotives are used for traction.

KEYWORDS: high speed rail freight; freight rail traction energy; CO_2 emissions; road – rail comparison, freight electrical multiple unit

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1 INTRODUCTION

Most consumer and finished goods cargo is moved on the road in the UK [1]. High flexibility and low cost are reasons for this. Encouraging modal shift from road to rail will result in lower carbon emissions [2] and contribute to government commitments to lower CO_2 emissions. This paper compares the energy consumption and CO_2 emissions for rail and road transport for two scenarios: High Speed Container Train, and Pallet Network Trunk Routes.

2 METHODOLOGY

In order to facilitate easy comparison with contemporary freight services, the scenarios were based on load units in use around the UK. The units considered were:

- ISO Shipping containers between 12 190 mm (40') and 16 150 mm (53') in length,
- Pallets of the dimension 1 200 mm x 1 000 mm.

In each case, an outline train specification was developed that was capable of transporting freight with similar acceleration and speed characteristics to passenger trains. The novelty of the proposed train sets required simulations to obtain performance figures to allow a comparison with road transportation. All train consists shown in the paper assume similar improvements in design, e.g. tare weight reduction. A route was identified, which would serve an existing freight flow, and train sizes were specified with an assumption of multiple-unit operation and spreading of services throughout the day, rather than a single trainload to address the flow requirements of a whole day.

The following section describes the models used for calculating the energy use and the carbon emissions of road and rail vehicles.

2.1 Dynamic Train Simulator

Previous work on rail vehicle simulation has used numeric integration methods in the distance domain to estimate the dynamic performance of rail vehicles [3]. To undertake this study a new simulator was built to calculate train performance in the time-domain, using the differential equation solving capabilities of the Simulink modelling tool. Figure 1 shows a simplified block diagram of the simulator.

The train is modelled using a position control system, where the reference variable is set to the position of the stations served along the route. Feedback is used to provide an error signal, the distance left to travel. This is the inherent required speed of the train, which is then limited to the current target speed (determined from an analysis of speed limits, the top speed of the train and the distance to the next speed limit, which may require deceleration so that the train is at the right speed when it enters the restriction). Achieved speed forms a second feedback loop, providing an intrinsic acceleration error signal, which is again limited by the maximum acceleration and deceleration capabilities of the train. These are calculated from constants based on assumed coefficients of friction, the wheel configuration of the train and the vehicle masses. When moving, the maximum acceleration of the train is further qualified by the amount of power available. The jerk rate, i.e. rate of change of acceleration, is limited to 0.65 ms^{-3}.

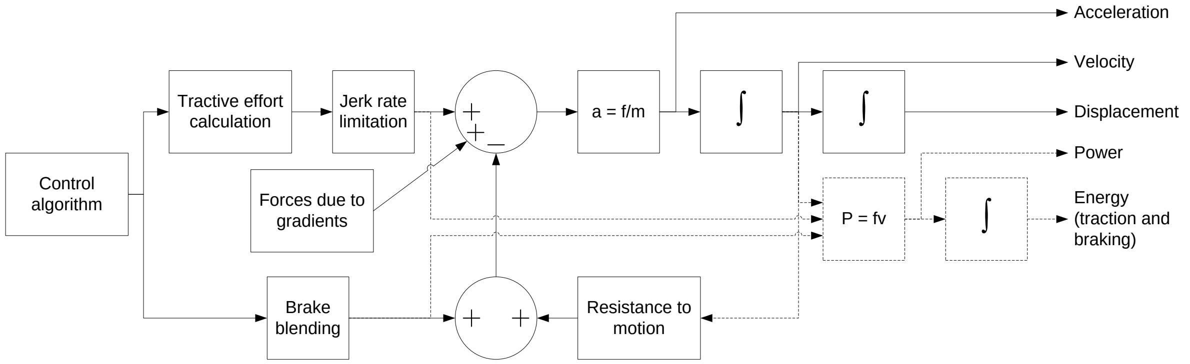


Figure 1: Simplified block diagram showing the structure of the Dynamic Train Simulator

Braking and resistance to motion, including rolling and air resistance, are added to the forces acting on the effective mass of the train in such a way as to always resist movement, by multiplying them by the negative of the sign of the current velocity. This prevents a high brake force from simulating the train being pushed backwards.

Gradients are simulated, adding the component of the weight of the train along a slope to the forces acting on the train.

The control algorithm is designed to control the position of the train with some error margins. It calculates the distance to the next speed limit or stopping point, and applies the brakes when this is less than the distance required to stop or slow the train from its current speed (which is calculated using a lower rate than the maximum deceleration, providing a safety margin). The brakes are released if the train slows too quickly, resulting in a chopping effect, which mimics the actions of a train driver when approaching a stopping point at slow speed. Because maximum brake applications are made, this algorithm does not provide the most energy-efficient braking strategy possible. This has been demonstrated on the UK's West Coast Main Line [4]; gentle and early braking enables more energy to be captured through regeneration than if the brakes are applied harshly. The simulator is capable of deriving energy from dynamic braking. This energy has been scaled by the vehicle efficiency and was then subtracted from the energy required for traction. The simulations take regenerative braking therefore into account, under the assumption that the catenary line is always receptive.

Future work on this model will focus on the modelling of the train driver as a controller, based on control and energy data measured on-board service trains, and will be aimed at replacing the basic control algorithm with a more sophisticated feedback controller using optimal control techniques to balance the conflicting needs of the timetable, speed limits and energy use.

Train resistance is modelled using the Davis equation, $F_r = A + Bv + Cv^2$, where F_r is the resistive force, v is the velocity of the train, and A, B and C are constants. The resistance coefficients have been calculated with an analytical tool based on the High Speed Train (HST).

The higher air resistance encountered in tunnels was ignored, since open track dominates all routes simulated. Resistance specifically resulting from curves along the routes has not been included, because additional resistance from curves having a radius larger than 1 000 m is negligible [5], and the routes used in the simulation do not have many curves where the radius is significantly shorter. In a more detailed future study resistance resulting from curves could be included.

The coefficient of friction between the wheel and rail was assumed to be 0.3 for the purposes of calculating maximum tractive effort; this figure is a reasonable median value according to studies on the wheel-rail interface [6]. Traction system machine limits were neglected; the tractive effort of the system was modelled with constant-torque and constant-power regions only. The output power and energy were scaled by the reciprocal of the efficiency of the traction system.

2.2 Lorry Energy Use

The energy use of road vehicles was modelled using efficiency statistics gathered in UK government-sponsored research [7]. Efficiency figures from this document were expressed in kilometres per litre of fuel. A direct conversion to CO_2 emissions was possible, using the conversion factors provided by the UK government in their CO_2 reporting guidelines [8].

Pallet lorries were assumed to be double-deck, with a capacity of 38 pallets. The average efficiency of a 44-tonne (maximum gross mass) lorry is, in these simulations, 2.89 km/l [7].

Container lorries, which are in operation today, do not perform as well as a smooth-sided trailers, because the corrugation of the container walls induces more turbulence; however, the conservative assumption in this study takes into account the possibility of aerodynamic improvements to containers over the next 25 years, as road haulage firms invest in fuel-saving measures.

The distance for each journey was simply divided by the fuel efficiency figure to arrive at a total number of litres consumed. This was then converted to energy by multiplying the volumetric energy content of diesel fuel at 35.6 MJ/l [7].

In 2035 it may be possible to have lorries powered through an electric drive train. This is unlikely, at the current state, to be realised with batteries as the energy density of batteries is low compared to diesel. Batteries would require too much volume, would be too heavy, and the recharging time is too long for practical operation over the routes with the assumed payload that are simulated. For these reasons lorries powered by electricity have not been considered in this paper.

2.3 Calculation of CO_2 Emissions

A well-to-wheel analysis [9] was used to convert energy use by the vehicles from the rail and road models to energy requirements at the source. CO_2 emissions, taking into account the efficiencies of electricity generation, resource extraction, refining and transport, are also included.

The well-to-wheel analysis accounted for vehicle efficiency; since both vehicle models already account for vehicle efficiency, the emissions and energy factors were adjusted to give an effective “well-to-tank” or “well-to-line” figure.

The results of this analysis are that 2008 UK generated electricity, see Figure 2, emits 0.618 kg CO_2 per kWh at the well when drawn from the line, and that the energy demanded from the line has to be multiplied by a factor of 2.901 to obtain well figures. This takes into account losses in both, the National Grid, and the railway transmission and distribution network. The 2008 electricity mix has been applied to the expected trains in 2035 to show the energy consumption and emission if the mix would not change, i.e. comprised of a higher share of less carbon intensive sources.

Each kWh of energy contained in the diesel fuel tank emits 0.306 kg CO_2, including well-to-tank emissions, and the energy at the tank has to be multiplied by a factor of 1.164 to obtain the figure at the well. Comparing this figure with the CO_2 emissions result for electricity suggests that diesel vehicles are likely to have lower emissions than electric vehicles. However, the advantage of electric traction is the higher vehicle efficiency compared to diesel traction. Modern electric railway traction systems are as much as 85 % efficient [10], compared to 30 % for diesel traction [9].

Another advantage of electric traction, which may be increasingly signification in the future, is that emissions are dependent on the electricity mix, which can be varied, whereas road vehicles are more or less confined to the use of diesel for long journeys. A projected 2035 electricity mix was created, see Figure 2, conservatively reducing the share of fossil fuels and increasing the contribution of renewables and nuclear power. This mix has been proposed by the authors because it is not possible to directly forecast the electricity mix in 2035. The government has however ambitious carbon reduction targets [11] and with this in mind the fossil fuel contribution has been reduced. The resulting factors of this electricity mix to obtain well figures are 0.393 for CO_2 emissions and 3.075 for the energy from the line; this assumes no improvements in efficiencies at any stage in the supply chain. Figure 2 shows pie charts comparing the two electricity mixes.

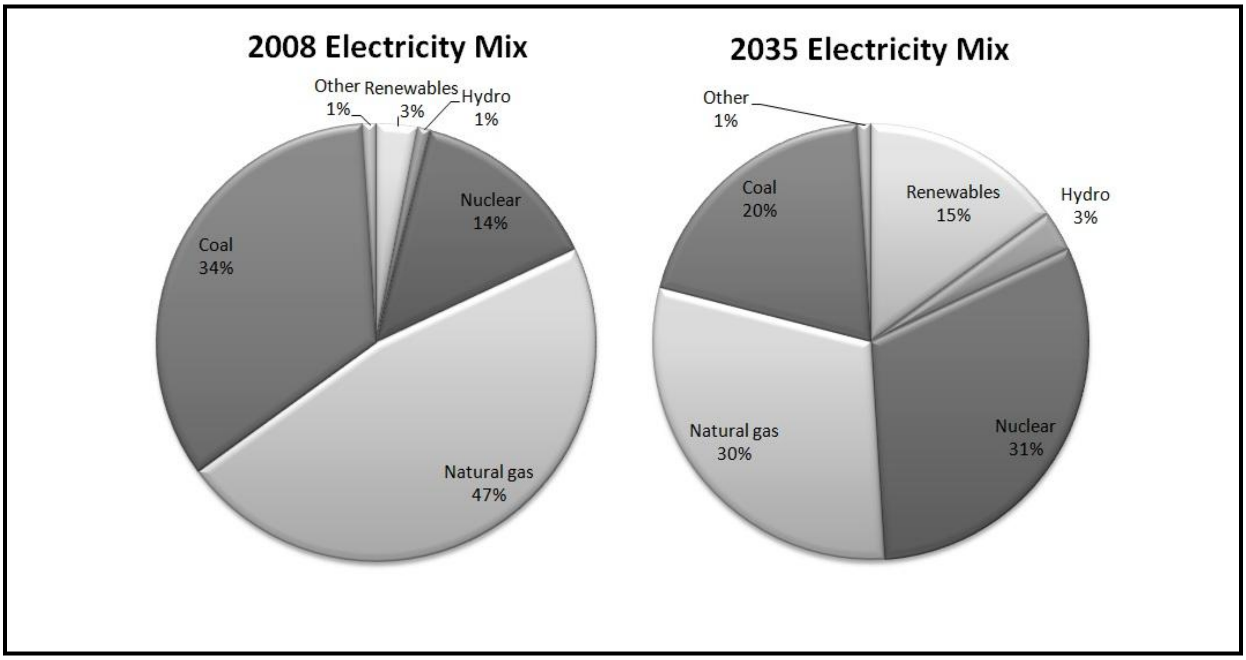


Figure 2: Pie charts comparing the 2008 UK electricity mix with a projected mix in 2035

3 FREIGHT SCENARIO ONE: HIGH SPEED CONTAINER TRAIN

3.1 The route

A substantial amount of container traffic entering the UK at East Coast ports, such as Hull, moves towards the North East of England and Scotland. Moving containers by rail along the electrified East Coast Main Line gives the opportunity for a high proportion of high-speed running.

This scenario simulates a train journey from Immingham Docks in East Yorkshire to the entrance of Mossend Freight Terminal near Glasgow. The route is 500 km in length and uses the East Coast Main Line between Doncaster and Edinburgh, allowing the train to run at speeds of up to 125 mph (200 km/h) for most of its journey.

The equivalent road route, calculated using the Google Maps journey planner, is 497 km long. This route uses motorways for the bulk of the journey; shorter alternative routes were possible (saving approximately 60 km), via the A66 or A69, but heavy vehicles are limited to 40 mph along single carriageways, making these routes an unlikely choice for a haulier.

3.2 The train

Each car of the train will be able to carry two Twenty-foot Equivalent Units (TEU), e.g. two twenty-foot containers or one forty-foot container, with a gross payload of 30 tonnes. The aerodynamic resistance is assumed to be that of a passenger train. This assumption requires improvements in dwell car design and an optimised loading pattern, as the inter-car gaps as well as the corrugated sides of the containers incur significant resistance to air. The use of smooth sided loading units, such as swap bodies would reduce skin friction. The more detailed engineering design plans have not been considered for this paper, but the authors believe that similar air resistance to passenger trains is possible.

The two possibilities for an outline train specification are: a four-vehicle electric multiple-unit and a four-vehicle articulated trailer rake hauled by an electric locomotive. Articulated means that the intermediate dwell cars share one bogie, as illustrated in Figure 3, thus reducing tare weight of the train and improving aerodynamic performance. A total load of four forty-foot containers was considered a sensible minimum for a trainload. Diagrams illustrating the two train formations and masses are shown in Figure 3 below. The locomotive hauled articulated formation assumes little reduction in weight compared to current practice. The more novel approach of multiple unit operation on the other hand is presented with the assumption of significant weight reductions, especially in the powered units, compared to multiple units in use today.

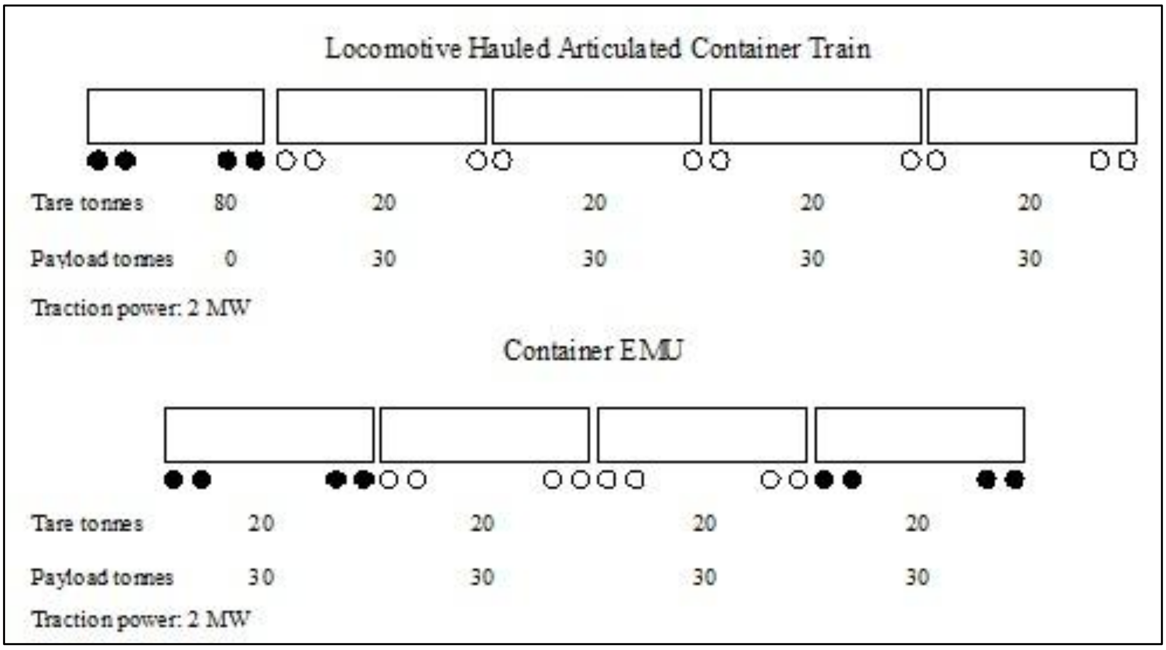


Figure 3: Container Train Diagrams

3.3 Results

Table 1 shows the results of the energy and CO_2 analysis for the container trains and equivalent lorry journeys.

Vehicle	Energy (kWh)		Well-to-Wheel CO_2 (kg)		
	Well-to-Wheel	At Tank / Line	Gross	Per container-km	Per tonne-km
Lorry x 4	7922.641	6806.393	2082.756	1.047	0.037
Locomotive hauled (2008 mix)	9554.766	3293.611	2035.452	1.018	0.034
EMU (2008 mix)	8421.765	2903.056	1794.089	0.897	0.030
Locomotive hauled (2035 mix)	10127.854	3293.611	1294.389	0.651	0.022
EMU (2035 mix)	8926.897	2903.056	1140.901	0.574	0.019

Table 1: Energy and CO_2 Emission Results for the High Speed Container Train

The results in Table 1 show significantly lower energy consumption at the line of the electrically propelled trains compared to the diesel powered lorries. This is because the main conversion losses occur at the chemical to other energy stage, i.e. in the diesel engine or at the power plants. This conversion stage is included in the tank energy figures for lorries as the diesel engine is on board, but not for the trains as the conversion is at the electricity generation station.

The well-to-wheel CO_2 emissions based on the 2035 electricity mix also show the train cases to be significantly lower that the road cases but for the 2008 electricity mix they are very similar. The reasons for this are:

Train

- The higher speed of the train;
- The higher mass of the train, due to relatively large tare masses, particularly in the case of the locomotive;
- The relatively short formation of the train, having just four wagons;
- The high acceleration rate of the train to allow for passenger line speeds;
- The relatively high carbon content of the electricity generation;
- In the case of the locomotive, the high power installed (a locomotive could haul more wagons without significantly affecting the energy consumption).

Lorry

- The relatively high fuel efficiency of the lorries;
- The lower tare mass;
- Limited route information, e.g. no gradients and speed limits are taken into account;
- No acceleration or braking is considered;
- The lorry is assumed to be fully laden.

Generally, the trains are designed to passenger train specifications to allow the same path allocation. This means a high power to weight ratio is necessary to have fast acceleration and high running speeds, both affecting energy use. The short formations of the train, especially in the locomotive hauled case, require a powerful locomotive, again leading to high energy demand. Adding a few wagons would not significantly increase energy consumption and therefore carbon emissions, so the per unit energy use and emissions would decrease; confirming that large volume flows are the traditional strength of railways.

4 FREIGHT SCENARIO TWO: PALLET NETWORK TRUNK ROUTE

A pallet network is a syndicate of small firms that share resources to provide an end-to-end solution comprising: local collection and delivery, consolidation, warehousing, and trunk movement. According to government-sponsored research [7], pallet networks move approximately 50,000 pallets around the country every night. The journey of a typical pallet might have the stages shown in Figure 4.

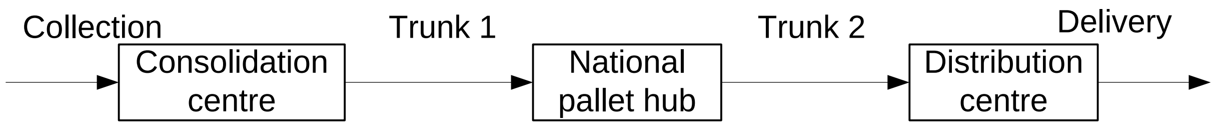


Figure 4: Pallet Journey Stages

Consolidation and distribution centres are located typically at access points to large urban areas. Barking and Carlisle were chosen as the consolidation and distribution points respectively. Each has a rail freight terminal and easy access to the national motorway network. In terms of distance, they represent the length of typical trunking legs – from the edge of the country to the Midland pallet hub.

4.1 The train

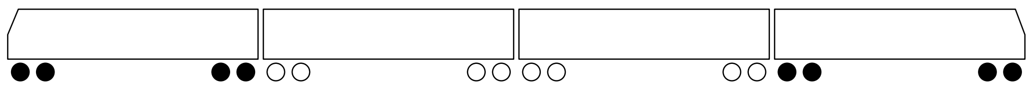
Each pallet network consists of a great many members situated around the country, running consolidation and distribution centres and carrying out trunk movements. There are therefore dozens of trunk pallet routes, meaning that the overall volumes on each route are not of comparable size to a traditional trainload of freight.

A short train was therefore considered a better option than a trainload. The multiple-unit train consist of four vehicles in this paper. These could easily be coupled into larger formations for the bulkier flows. Multiple unit traction is needed in order to provide sufficient acceleration capability for the trains to blend in with passenger services.

Modern multiple-unit vehicles can be up to 23 m in length; this would allow the vehicle to carry 38 pallets in a single layer at a payload of 28 tonnes. A single rail vehicle would, therefore, be capable of carrying the same number of pallets as a double-deck road trailer. Alternatively, it is also feasible to have a small amount of double-stacking or double-deck racking, as the floor to cantrail height of a passenger vehicle (the benchmark size) is around 2 m, enough to accommodate pallets stacked double if their individual height does not exceed 1 m.

The payload can then be set to be equivalent to the same road vehicle, at 28 tonnes, which is the largest practical payload for a lorry to carry, given a typical tare mass of 16 tonnes. The train consist is shown in Figure 5.

Pallet Carrying EMU



Pallets	38	38	38	38
Load tonnes	28	28	28	28
Tare tonnes	25	25	25	25
Gross tonnes	53	53	53	53

Figure 5: Pallet Carrying Train Diagram

A drive system of 2 MW rating was considered to be an appropriate balance between performance and energy efficiency. Overpowering the train would result in an excessive amount of energy being used in harsh acceleration. The latest UK four-car passenger EMUs rate at around 1.5 MW but are slightly lighter than this freight EMU. The amount of power provided for half of an HST passenger set is 2 MW, which consists of four lightweight coaches and a 70 tonne power car.

4.2 Results

Table 2 shows the results of the energy and CO_2 analysis for the pallet train and equivalent lorry journeys.

Vehicle	Energy (kWh)		Well-to-Wheel CO_2 (kg)		
	Well-to-Wheel	At Tank / Line	Gross	Per pallet km	Per tonne-km
Lorry x 4	8537.991	7335.044	2244.523	0.028	0.037
Freight EMU (2008 electricity mix)	8230.781	2837.222	1753.403	0.024	0.032
Freight EMU (2035 electricity mix)	8724.458	2837.222	1115.028	0.014	0.019

Table 2: Energy and CO_2 Emission Results for the Pallet Carrying Train

The results show significantly lower energy consumption at the line of the electrically propelled trains compared to the diesel powered lorries. This is because the main conversion losses occur at the chemical to other energy stage, i.e. in the diesel engine or at the power plants. This conversion stage is included in the tank energy figures for the lorries, as the diesel engine is on board, but not for the trains as the conversion is at the electricity generation plant.

5 Conclusion

The results of the studies suggest that the superior rolling efficiency of a railway vehicle can lead to some short-term reductions in CO_2 emissions if a modal shift from road to rail takes place, but that in some cases considered these reductions are marginal if the mix of energy sources in UK electricity generation does not significantly improve. However, should the electricity mix become less CO_2-intensive, then the reductions in emissions are significant, in some cases in excess of 50 %.

The case for a modal shift to rail is clearest for steady point-to-point flows, where a long road journey is replaced by a long rail journey at sustained high speed.

This study raises a number of questions, which are worthy of further research. Firstly, the vehicle parameters used here assume a level of technological progress over the next 25 years. Intensive research will be needed into vehicle design, in order to reduce vehicle tare masses to the levels assumed in this analysis.

Control strategies that optimise not only timetable constraints and speed limits, but also energy use should be developed and trialled in the simulator, replacing the generic control algorithm currently employed. Around the world, economic driving strategies have already been trialled [12], but could be developed further around an accurate model of a train driver as a controller.

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REVIEW AND ASSESSMENT OF HYDROGEN PROPELLED RAILWAY VEHICLES

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Abstract

The railway industry is under pressure to reduce emissions, and reduction of the dependency on petroleum oil products is desirable. Hydrogen powered trains are able to offer both. This paper shows the present hydrogen railway developments and the barriers to commercialisation.

Introduction

The increasing concern about global warming led to the response that a reduction of Green House Gases (GHGs) is necessary. The transport sector is one of the main sources of GHG emissions. Moving people and goods by rail has, in comparison to its competitors, low energy requirements and low emissions. It has additionally been recognised that the rail industry has further potential to reduce its emissions. Electric traction is one of the solutions, but the reduction in GHGs depends directly on the way in which the electricity is produced. When the electricity is produced mainly through regenerative sources such as hydro, wind and solar, the reduction is high, e.g. the impact of the railways in Switzerland on GHGs is very low as the network is almost 100% electrified and most of the electricity is generated by hydro power (75%) and the rest is nuclear (25%) [1]. When the electricity is generated by using natural resources such as coal or petroleum oil, the overall production of GHGs may increase with electrification.

The discussions concerning GHG reductions often do not take into account the fact that the main energy source for the transport sector (petroleum oil) is declining and production has already peaked in some parts of the world such as the United States [2]. Increasing demand for this energy source, coupled with decreasing availability, has led to price increases. It is generally accepted that these price increases will continue.

Railway administrations are in the fortunate position to be able to substitute diesel propelled trains with alternatives such as electric trains. The infrastructure required for electrically propelled vehicles is a major investment at the implementation stage. Railway administrations may not be able to afford to electrify very long distances or may be unwilling to undertake this investment; this is particularly true for lines which are not very busy such as branch lines where there may be no business case. An electric railway system has the further disadvantage that the electricity has to be generated at the same time as it is needed, which can lead to problems, for example: If the power supply fails, several lines and hence many trains can be affected, which is what happened in Switzerland on the 22. of June 2005, where on large parts of the network no trains moved, about 2,000 trains were affected and it took about 22 hours to fully restore usual operations [3].This was caused by a defect in the power transmission to the railway network.

Hydrogen powered railway vehicles offer the possibility of being independent from fossil fuels (such as petroleum oil) and they can reduce GHGs. The emissions incurred during production of hydrogen vary; when made from regenerative energy sources for example through electrolysis, no GHGs are incurred. Hydrogen can be stored, which eases the production and consumption relationship problem at the same time. This can be a considerable advantage if more regenerative energy sources are employed, e.g. If electricity for the electrified rail system is produced solely by wind power, trains could only run while the wind is blowing because the electricity has to be produced at the same time as the consumption occurs. Most railway administrations would consider this as undesirable.

Prototype hydrogen railway vehicles have been built in several countries, the major developments being in Japan and the United States. This paper reports first on those developments, then compares them and finishes with general issues concerning the commercialisation of hydrogen as an energy carrier with the focus on railways.

USA

The American railway network is mainly used for freight transport. The track is owned by individual companies, many of them operate their own trains. Most of the network is not electrified and building catenary over the long distances is costly. Private railway companies may not have the funds or are unwilling to spend the required money on electrification.

Emission restrictions depend on the state. California is committed to reduce GHGs and in some areas such as Los Angeles the local air quality is below average. The ports of Long Beach and Los Angeles (neighbouring each other) are the largest in the States and a considerable amount of the goods are transported to and from them by rail. The rail operators are under pressure to reduce pollution in California, especially in Los Angeles.

Fuel represents the largest single operating cost for some of the railroads. The US imports large amounts of petroleum oil and becoming more independent of that resource and its strong price fluctuations is desirable for the railroads and the country in general.

Fuel Cell Rail Development

Vehicle Projects LLC based in Denver, Colorado develops prototype fuel cell vehicles. In 2002 the company created the first hydrogen locomotive. It is a small engine that replaced a battery powered vehicle in a mine. Table 1 below shows the different performance of the battery and fuel cell vehicles [4].

Comparison of Battery and Fuel Cell Locomotives		
Parameter	**Battery**	**Fuel Cell**
Power, rated	7.1 kW (gross)	17 kW (gross)
Current, rated	76 A	135 A
Voltage at	94 V (estimated)	126 V
Energy	43 kWh	48 kWh
Operating time	6 h (available)	8 h
Recharge time	8 h (min)	1 h (max)
Vehicle weight	3,600 kg	2,500 kg (without ballast)

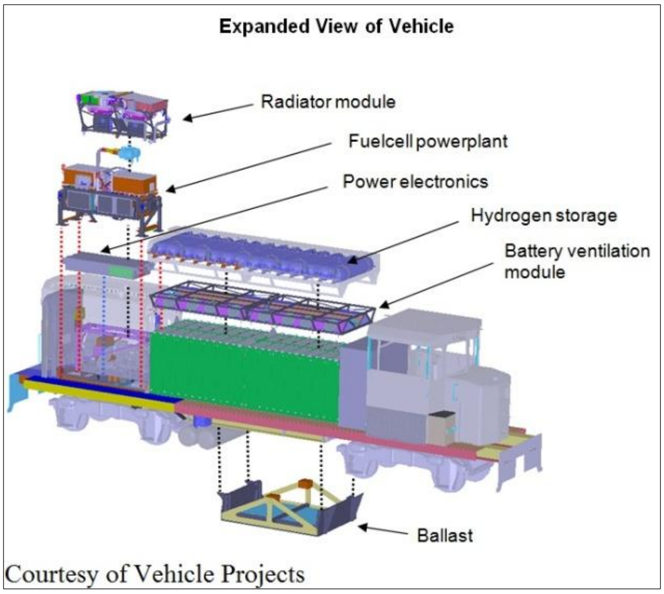
Table 1: Comparison of Battery and Fuel Cell Locomotive

Vehicle Projects has been developing a hydrogen-hybrid switcher (shunt) locomotive since 2006 [5]. In November 2009 it entered operational testing in the Los Angeles Basin with BNSF railway. The locomotive is meant to demonstrate that a hydrogen powered switcher is a feasible option for rail-yard operations and power-to-grid application is possible for emergency situations (it will be tested in a military base). The locomotive is built on the Green Goat™ platform and uses technology employed by the Citaro buses (tank and fuel cell power modules), the battery allows transients above one MW, see

Picture 1,

Picture 2 and Table 2. It does not make use of regenerative breaking. After the demonstrations are completed, the locomotive will be rebuilt to a road-switcher engine, comprising three times the hydrogen storage and twice the power (500 kW). Dr. Arnold Miller, president of Vehicle Projects, will give a more detailed description of the hydrogen-hybrid switcher locomotive at this conference.

Picture 1: Hydrogen-Hybrid Switcher Locomotive



Picture 2: Expanded View of Vehicle

The vehicle is powered by hydrogen which is supplied from Air Products. The company has a hydrogen distribution pipeline and production facilities in Los Angles. The pipeline supplies large industrial users in the area, such as petroleum refineries. The locomotive is fuelled from a hydrogen trailer as the vehicle is a prototype and will be in the area for operational testing for about three months. A more fixed supply from the pipeline was therefore considered to not be a viable option.

Japan

Japan is known for its high speed 'bullet' trains. The network is largely designed for passenger transport. Most of the population lives close to the cost and the railway lines there are mostly electrified. The more rural lines are usually not operated by electric traction. The traditional gauge used in Japan is narrow (1.067 m), but the high speed network is build to standard gauge (1.435 m). About 65% of the total network is electrified. Japan is committed to reduce its GHGs and the country imports large quantities of petroleum oil. Due to the large percentage of electrification, the dependency on imported resources for the railways is limited, but becoming more independent is desirable. The railway sector is working on the reduction of its environmental impact and propulsion of trains by hydrogen is one possibility.

The Railway Technical Research Institute (RTRI) and East Japan Railway Company (JR East) have each developed a hydrogen hybrid railcar; both are presented in more detail below.

JR East [6]

JR East has been exploring several possibilities to reduce their environmental impact, including the visual intrusion form catenary equipment. One of them is the development of the New Energy Train (NE Train), which started in 2002.

Picture 3: JR East Railcar

The first step was the creation of a diesel-hybrid railcar which has been in commercial operation since 2004; it is the KIHA-E200 series. The second step was to replace the diesel engine with a fuel cell power plant. The fuel cell hybrid railcar was finished in 2006 and in 2007 test runs have been conducted on commercial lines. The vehicle is shown in Picture 3 [7] and a drawing of the main components in Picture 4 [7], for the specifications please see Table 2.

The tests have been successful. The development team stated that the main issues to commercialisation are:

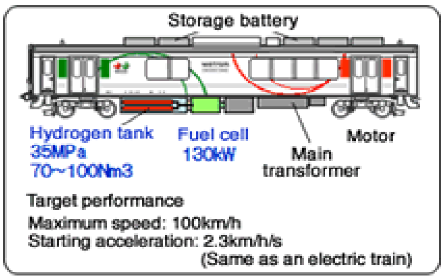
- Carrying larger amounts of hydrogen on board the vehicle,
- Supply chain of hydrogen including infrastructure requirements,
- Cost reduction,
- Increasing the useful life of fuel cells.

RTRI [8]

From 2001 onwards the RTRI conducted tests with fuel cells to power railway vehicles. The most recent vehicle is a two car hydrogen-hybrid train. It does not have any space for a payload (passengers, mail etc.) yet. The specifications of the two car train are given in Table 2, please see Picture 5 for an outside view of the vehicle. The institute hopes to reduce the GHG emissions of the industry and to increase efficiency. Both targets can be achieved with fuel cell trains according to the RTRI.

The development started with powering one motorised bogie in 2003 to establish that fuel cells are suitable for railway applications. The next step was the implementation of a fuel cell powered railcar, which was demonstrated in 2006. This railcar was powered solely by fuel cells, but the auxiliaries were dependent on the transmission of electricity from the catenary [9]. The tests of that railcar show that a fuel cell power pack alone is able to power a train. In 2008 the present two car hydrogen-hybrid railcars were demonstrated [8]. This train was operated solely by the fuel cells, including auxiliaries and hotel power such as air-conditioning. The data presented in Table 2 is based on this two car train. The main problems which have to be overcome for commercialisation of fuel cell hybrid railway vehicles are, according to the RTRI:

- Reducing equipment size so that it can be fitted outside the car enabling space for a payload,
- Implementation of a hydrogen supply infrastructure,
- Modification of relevant laws.



Picture 4: Diagram JR East Railcar

Picture 5: RTRI Railcars

Comparison Table

	Vehicle Projects Switcher Locomotive 2006-present	JR East Railcar 2005-2007	RTRI Railcars 2001-2008
			
Type	Locomotive (hybrid)	One carriage railcar (hybrid)	Two passenger railcars (hybrid)
Weight	127t	-	70t (both cars together)
Max. Operating Speed	64 km/h (40 mph)	100 km/h	45 km/h (limited by test track length) 104 km/h at rolling stock test facility (one car under FC-Inverter direct connected condition)
Fuel Cell Type	PEM	PEM	PEM FC
Power of the Fuel Cell Plant	250 kW (2 x 125 kW) max. rated	130 kW (2 x 65 kW)	100 kW class
Hydrogen Tank Capacity	70 kg at 35 MPa (350 bar) 2870 litres 14 tanks	10 kg at 35 MPa (350 bar) Approx. 410 litres	18 kg at 35 MPa (350 bar) 720 litres 4 cylinders
Cylinder Type	Type III, Composite cylinder (aluminium liner reinforced with carbon fibre)	Seamless steel	Type III, Composite cylinder (aluminium liner reinforced with carbon fibre)
Battery Type	Dry-cell Lead-acid	Lithium-Ion 19 kWh	Lithium-Ion 360 kW
Tractive Effort	Starting Tractive Effort: > 356 kN (80,000 lbs) Continuous Tractive Effort: 356 kN (80,000 lbs) to 6 mph	-	-
Braking Characteristics	No regenerative braking	Regenerative braking	Regenerative braking
Vehicle Efficiency	N/A (testing in progress)	-	57.8% (with air conditioner) to 72.4%(without air conditioner)
References	[5]	[6, 7]	[8, 9]
NOTE	All vehicles are prototype test vehicles		

Table 2: Comparison Table

France

The development of hydrogen vehicles in Europe has a focus on road transport. In some countries there have been projects associated with hydrogen trains, one example is Denmark. No prototype vehicle exists however. In France the Platform for Energy- Efficient and Environmentally Friendly Hybrid Trains (PLATHEE) programme is investigating different new technologies and their potential application for the railways [10]. Part of that programme is a consideration of fuel cells. A shunting locomotive of the series BB 63000 of the SNCF is being rebuilt into a hybrid locomotive. It has two prime movers, a 235 kW diesel generator and a 50 kW fuel cell. The generated power is transferred into batteries and ultra capacitors, which will provide power to the traction motors. It is hoped that the project identifies possibilities to reduce GHG emissions and lower fuel consumption.

Conclusion

Hydrogen as a power carrier has been explored in several rail applications, the most recent being the hydrogen-hybrid locomotive developed by Vehicle Projects. All projects concluded that fuel cells and respectively hydrogen as a fuel are feasible for railway applications. The main hurdle to be overcome in Japan which applies equally to Europe, is the implementation of the hydrogen supply infrastructure. This only applies in a limited way to the greater Los Angeles area in the US as hydrogen could be supplied from the Air Products pipeline. Additional barriers to commercialisation are the high cost of the vehicles, the life span of fuel cells, and the storage capacity of hydrogen. For railcars, the size of the equipment required is an issue, as at the moment only limited space for a payload is available. A locomotive does not have this problem as it does not carry a payload directly; a commuter train system which uses unpowered coaches and a locomotive is therefore a viable option. Loco hauled trains of this kind are used in Switzerland (Electric) and the USA (Diesel).

The UK has some main lines which are not electrified at the moment and several less busy lines which are unlikely to be electrified in the future. Britain has, therefore, potential demand for hydrogen powered railway vehicles. The UK railway network is mainly used for passenger transport, and multiple unit trains are popular. The Japanese developments are therefore of particular interest.

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WELL-TO-WHEEL ANALYSIS FOR ELECTRIC, DIESEL AND HYDROGEN TRACTION FOR RAILWAYS

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ABSTRACT

This paper derives the energy efficiencies and CO_2 emissions for electric, diesel and hydrogen traction for railway vehicles on a well-to-wheel (WTW) basis, using the low heating value (LHV) and high heating value (HHV) of the enthalpy of oxidation of the fuel. The tank-to-wheel and well-to-tank efficiency are determined. Gaseous hydrogen has a WTW efficiency of 25 % LHV, if produced from methane and used in a fuel cell. This efficiency is similar to diesel traction, 26 % LHV, and electric traction in the UK 26 % LHV, USA 25 % LHV, and California 28 % LHV, considering the generation mix in 2008. A reduction of about 19 % in CO_2 is achieved when hydrogen gas is used in a fuel cell compared to diesel traction, and about 3 % reduction compared to US electricity. It has been shown that producing hydrogen from electrolysis via hydro or wind power leads to lower efficiencies than transmitting the energy through an electric grid. Further, hydrogen produced through a solar thermo-chemical process, and electricity generated from solar power, have similar efficiencies.

Keywords: well-to-wheel; railway traction; CO_2 emissions; railroad; hydrail; fuel cell

1 INTRODUCTION

Railways all over the world have to reduce their environmental impact; focus is usually given to reduce greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2).

In the UK 63 % of all rail related CO_2 emissions are produced through traction, where 26 % are contributed from electric- and 37 % from diesel traction (Rail Safety and Standards Board Ltd., 2010). Autonomous vehicles have, therefore, the largest single impact on GHG emissions.

In the USA railways have the highest share of the freight transportation market with about 40 % measured in ton miles. To propel trains 3.9 billion gallons of diesel fuel are consumed annually by US railways. This represents approximately 99.5 % of their energy use for traction; the rest is electricity (U.S. Department of Transportation - RITA Bureau of Transportation Statistics, 2011).

A change in railway traction technology could have a significant impact on diesel fuel consumption and on carbon emissions. Additionally, petroleum based fuels are likely to become more expensive in the future as demand is increasing and supply decreasing, affecting railway operating costs.

Emissions and energy consumption are often measured at the point of use. This does not, however, account for the overall emissions and energy consumption. To evaluate the impact of fuels and energy carriers the whole supply chain has to be considered (Bossel, 2003; Wang, 1999). Well-to-Wheel studies have been conducted for various modes of transport, with a general focus on road transportation. Compared to other modes, railway vehicles have different duty cycles, power requirements, and useful lives. Furthermore, electricity is often used to propel railway vehicles, particularly in Europe, whereas for road vehicles this is not common, and in the air and maritime industry almost unheard of. This paper is one of the first applications of the Well-to-Wheel (WTW) methodology to the railway sector, considering the main railway fuels diesel and electricity. It, additionally, evaluates hydrogen as a potential energy carrier for railway vehicles.

This paper considers electric, diesel, hydrogen fuel cell, and hydrogen internal combustion engine (ICE) propulsion systems. Additionally, the supply chain of the fuel and its carbon content are presented. Electricity generation data are used for the United Kingdom (UK), United States of America (USA, US) and the state of California (CA). These areas have been chosen for the following reasons:

- The UK has mainline railways that have not yet been electrified, and has ambitious CO_2 reduction targets;
- The USA has very little electrification, as the distances covered by railway lines are long, making electrification less likely;
- CA has stringent emission standards, as well as a high contribution of renewable sources to the electricity generation mix (a similar level is planned to be achieved in many European countries in about 15-20 years time).

The calculations were repeated for the renewable sources: hydro, wind, and solar, to show how railways can reduce their impact and ensure their energy security.

1.1 Energy Consumption

A reduction in energy consumption of railway vehicles will lead to a lower environmental impact of the system. Cost savings for the railway operators may be possible, since the energy to propel trains has to be bought.

The energy consumption of a railway vehicle results from several factors; major elements are the efficiency of the various system components and the duty cycle. The overall energy efficiency is dependent on the vehicles drive train and the supply chain of energy, but not on the traction work provided by the vehicle, which is dependent on the physical characteristics of the vehicle, such as mass and its resistance to motion.

2 METHODOLOGY

The WTW analysis is an approach that considers the energy consumption and greenhouse gas emissions associated with production pathways and drive train systems. A WTW analysis includes the energy use and GHG emissions at every stage of the process from the original source (well) to energy delivery at the wheels (wheel). It is usually split into two stages: the well-to-tank (WTT) or fuel cycle stage, and the tank-to-wheel (TTW) or vehicle efficiency stage (TIAX LLC, 2007). This split allows the comparison of different vehicle drive trains, which are powered by the same fuel.

In contrast to heat engines, the natural form of energy to consider for electrochemical power devices, such as fuel cells, is the Gibbs free energy, ΔG. This notwithstanding, because most of the data in the literature are in terms of enthalpy, the energy calculations in this paper are based primarily on the change in enthalpy, ΔH. As indicated by the Gibbs equation, $\Delta G = \Delta H - T\Delta S$, where T is the absolute temperature at which the reaction occurs, we can calculate ΔG from ΔH if we know or can estimate the entropy.

The approach of using the low heating value (LHV) in WTW comparisons is commonly used and recommended by Wang (1999), the Department for Environment, Food and Rural Affairs (Defra), as well as the Department of Energy and Climate Change (DECC), (AEA, 2009). Calculations in LHV can lead in some instances to efficiencies above 100 %, e.g. 105 % for some condensing boilers, which is physically impossible (Bossel, 2003). The use of the high heating value (HHV) is consistent with the laws of thermodynamics and calculations have, therefore, also been presented in HHV. The conversion has been carried out on the basis that the quantity of fuel (mass, volume) does not change. The energy content of the different fuels has been taken from the U.S. Department of Energy (2008), and the carbon content of fuels has been based on information provided by the Department of Energy and Climate Change (AEA, 2009).

2.1 Assumptions

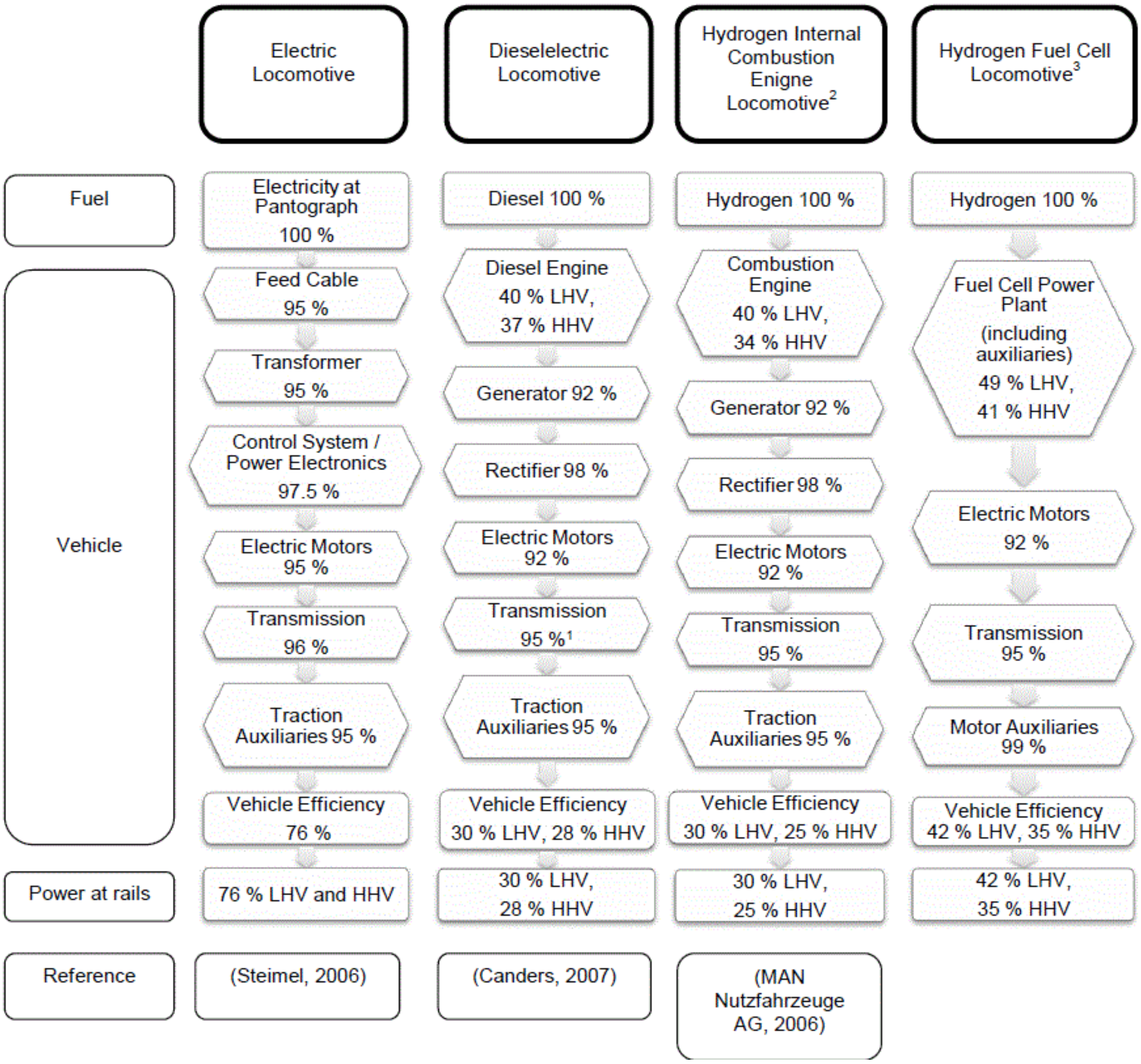
Carbon Dioxide (CO_2) emissions and high-level nuclear waste are considered emissions, any other GHG emissions are not considered. The CO_2 content of the fuels is based on UK data. It has been assumed that all regions use the same fuel types. The efficiencies of UK electricity generation power plants have been used for the USA and California. The diesel fuel cycle (WTT) and the natural gas based hydrogen cycle (WTT) are based on American data and has been used for the UK. The calculations are based on input data from various years. It is assumed that these figures are still representative. Regenerative braking is not considered, because it is not utilised widely. It could however be included by adjusting the vehicle efficiency. The vehicle efficiency for diesel and electric traction has been calculated with data obtained from literature. The ICE (diesel and hydrogen) is assumed to work at its highest efficiency. The hydrogen vehicle efficiency is based on the operational tests of the hydrogen hybrid switcher locomotive during trials in Los Angeles. The renewable mix in California is determined with the assumption that the efficiencies for biomass and geothermal power are based on the LHV. Electrical transmission losses in the power grid are based on the UK and have been used for the US and California.

3 VEHICLE EFFICIENCY

The vehicle efficiency of a traction unit is determined by how the energy that enters the vehicle is converted into traction work (TTW). Electric traction is based on an electric locomotive that is fed from a catenary line. Diesel traction is based on a diesel electric locomotive. Hydrogen can either be burned in an ICE or used in a fuel cell. Most existing rail vehicle prototypes use Proton Exchange Membranes (PEM) fuel cells (FC). Below are the vehicle efficiencies for both types. Fuel-cell traction employs fuel cells as the vehicle's prime mover. The fuel cell power plant efficiency has been established by the hydrogen hybrid switcher locomotive of Vehicle Projects Inc (Miller et al., 2010). This locomotive does not use regenerative braking, like electric and diesel traction in this paper, and has therefore been chosen. The efficiencies have been established in full service operation over a period of several months. Its power plant efficiency is 49 % LHV and 41 % HHV. Based on Gibbs free energy, the respective power plant efficiencies are 51 % and 50 %.

The company MAN built hydrogen ICEs for trucks that principally work like an Otto engine. The best efficiency of such an engine is 40 % (LHV) (MAN Nutzfahrzeuge AG, 2006). The tank-to-wheel chain is considered to be the same as for a diesel electric locomotive where the diesel engine is the prime mover. Figure 1, shows the efficiencies for electric, diesel, hydrogen fuel cell, and hydrogen ICE traction.

Figure 1: Vehicle Efficiencies



[1] Canders (2007) does not consider auxiliaries; the auxiliary value from Steimel (2006) of 95 % has been added.

[2] The Hydrogen ICE Locomotive does not exist. MAN produced a hydrogen internal combustion engine for a truck. In this comparison this engine substituted the diesel engine.

[3] For the fuel cell locomotive only the fuel cell power plant efficiency was determined. It is built from a diesel-electric locomotive, therefore, the efficiency chain from diesel has been used. Auxiliaries are already included in the power plant efficiency, so the auxiliary value at the end of the chain is motor specific.

The main conversion loss of energy occurs in the transfer from chemical energy into a different form. The vehicle efficiency of the electric locomotive is in comparison high, as the conversion from chemical to electrical energy already occurred at the electricity generation plants. The high efficiency of the fuel cell can directly be seen in the energy efficiency of the fuel cell locomotive.

4 WELL-TO-TANK ANALYSIS

The well-to-tank analysis establishes the losses from the original energy source (well) to the tank of the vehicle. The main stages in the WTT path are: (1) recovery, extraction and transport (RET); (2) refining or electricity generation; and (3) transport to the vehicle.

The WTT efficiencies in LHV, for electricity, and associated the CO_2 emissions per kWh delivered are: UK 34 %, with 0.61 kg CO_2 and 0.005 g of radioactive waste, USA 33 % with 0.648 CO_2 and 0.007 g of radioactive waste, CA 36 %, with 0.422 kg CO_2 and 0.005 g of radioactive waste. The WTT efficiencies in HHV, for electricity, and the associated CO_2 emissions per kWh delivered are: UK 32 %, with 0.61 kg CO_2 and 0.005 g of radioactive waste, USA 31 % with 0.651 CO_2 and 0.007 g of radioactive waste, CA 34 %, with 0.422 CO_2 and 0.005 g of radioactive waste. These figures have been calculated from information provided by (AEA, 2009; Barbier, 2002; Department of Energy and Climate Change, 2008a, b; E.ON AG, 2010; Evans et al., 2010; Muyeen et al., 2008; Nyberg, 2008; Seitz, 2010; U.S. Department of Energy, 2008; U.S. Energy Information Administration, 2008; Wang, 1999, 2003).

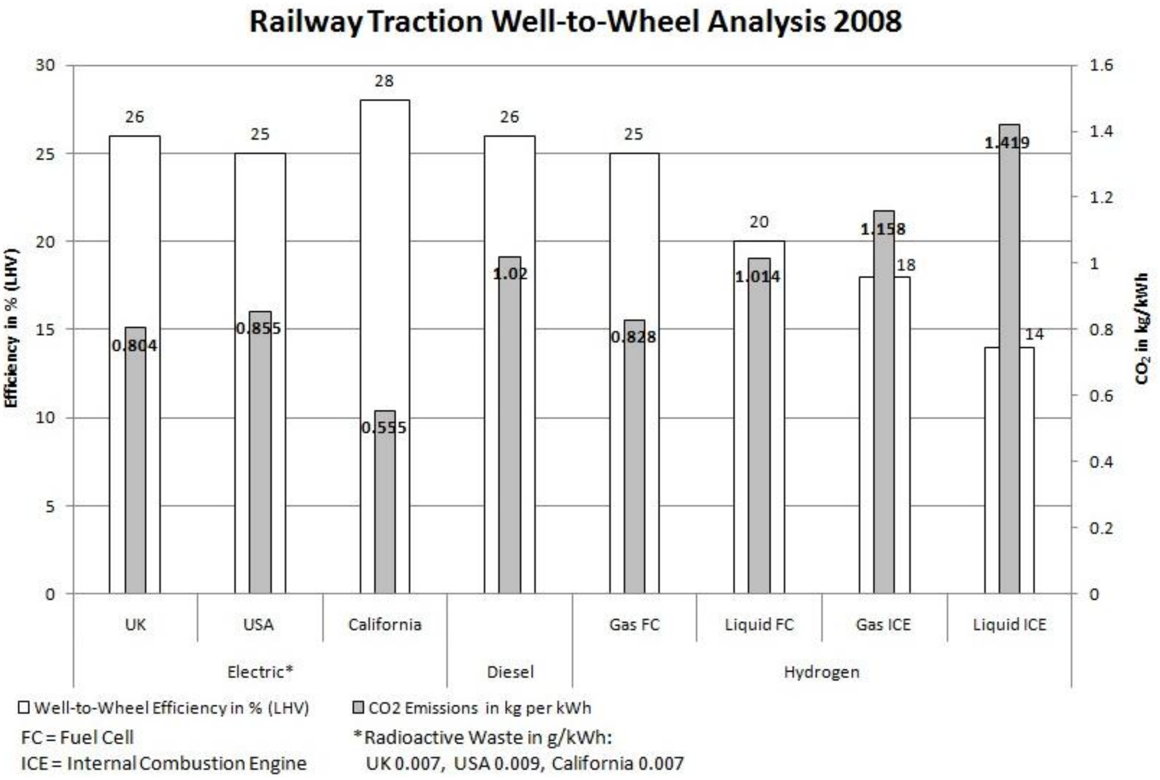
The diesel WTT efficiencies, first in LHV then in HHV, and the associated CO_2 emissions per kWh at the tank are: 86 % with 0.306 kg CO_2, and 86 % with 0.285 kg CO_2 (Wang, 1999, 2003, 2008).

The hydrogen WTT efficiencies and the associated CO_2 emissions per kWh at the tank are in LHV hydrogen as a gas 58 %, with 0.348 kg CO_2, hydrogen as a liquid 48 %, with 0.426 kg CO_2; and in HHV hydrogen as a gas 62 %, with 0.294 kg CO_2, hydrogen as a liquid 51 %, with 0.36 kg CO_2 (Wang, 1999, 2003).

5 WELL-TO-WHEEL

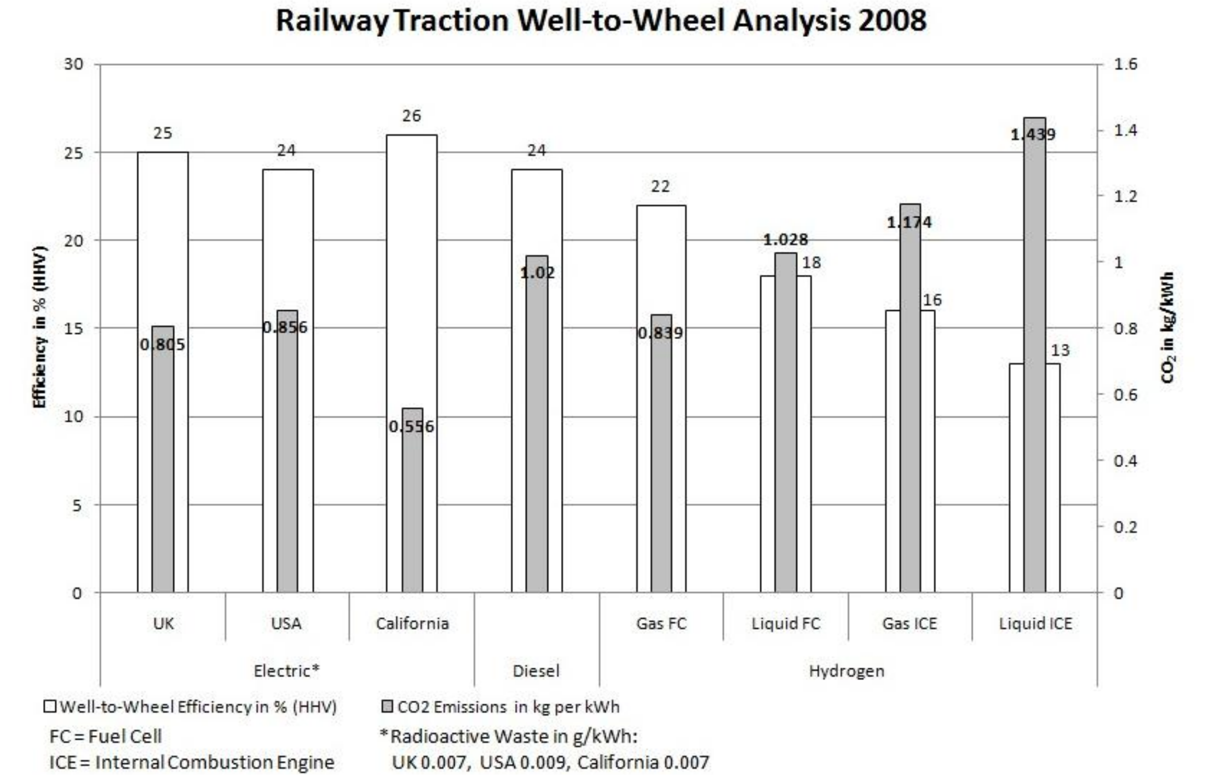
The combination of the vehicle efficiency (TTW) and the WTT figures give the WTW efficiency. Figure 2, LHV, and Figure 3, HHV, show the efficiencies and the emissions for electric, diesel and hydrogen systems, with electricity generation data from 2008.

Figure 2: Railway Traction Well-to-Wheel Analysis 2008 based on the LHV



Sources: (AEA, 2009; Barbier, 2002; Canders, 2007; Department of Energy and Climate Change, 2008a, b; E.ON AG, 2010; Evans et al., 2010; International Union of Railways and Community of European Railway and Infrastructure Companies [UIC], 2008; MAN Nutzfahrzeuge AG, 2006; Muyeen et al., 2008; Nyberg, 2008; Seitz, 2010; Steimel, 2006; U.S. Department of Energy, 2008; U.S. Energy Information Administration, 2008; Wang, 1999, 2003, 2008)

Figure 3: Railway Traction Well-to-Wheel Analysis 2008 based on the HHV



Sources: (AEA, 2009; Barbier, 2002; Canders, 2007; Department of Energy and Climate Change, 2008a, b; E.ON AG, 2010; Evans et al., 2010; International Union of Railways and Community of European Railway and Infrastructure Companies [UIC], 2008; MAN Nutzfahrzeuge AG, 2006; Muyeen et al., 2008; Nyberg, 2008; Seitz, 2010; Steimel, 2006; U.S. Department of Energy, 2008; U.S. Energy Information Administration, 2008; Wang, 1999, 2003, 2008)

The WTW efficiencies range from 14 % to 28 % (LHV), 13 % to 26 % (HHV). The 14 % and 13 % are for liquid hydrogen in an ICE and the 28 % and 26 % are achieved in California's electric system. The second highest WTW value is 26 % LHV, achieved with diesel traction and 25 % HHV is achieved with the UK electric system. The high efficiencies in California are due to the large contribution of natural gas and hydro generation. The CO_2 emissions range from 0.555 kg/kWh to 1.419 kg/kWh (LHV), 0.556 kg/kWh to 1.439 kg/kWh (HHV). The lowest CO_2 values (0.555 kg/ kWh LHV, 0.556 kg/kWh HHV) are achieved in California, due to the substantial utilisation of low and non carbons source for the electricity generation, such as large scale hydro, renewables, nuclear, and natural gas. The second lowest values (0.804 kg/ kWh LHV, 0.805 kg/kWh HHV) are achieved in the UK electric system. The high contribution of non- and low carbon sources, such as nuclear and natural gas are the reason for this. The comparison of diesel and hydrogen gas in a fuel cell, show that the WTW efficiency of diesel traction is higher but hydrogen traction would result in lower emissions. The use of ΔG for the efficiency calculations would lead to higher efficiencies and lower emissions of the hydrogen system, especially on the HHV basis. The high carbon content of a fuel is not necessarily offset by a high WTW efficiency; this can be seen in the example of diesel traction, where the WTW efficiency and the CO_2 emissions are high. The highest efficiency and lowest emissions can be achieved with electrification, if the electricity is produced with non- and low carbon sources, such as hydro, nuclear and natural gas.

Substitution of diesel traction with fuel cell vehicles using hydrogen-gas leads to a reduction of about 19 % LHV and 18 % HHV in CO_2 emissions. Hydrogen gas in a fuel cell vehicle yields a reduction in CO_2 of about 3 % LHV and 2 % HHV compared to the US electric system. The carbon reduction is, therefore, greatest in the US when the existing diesel fleet would be replaced by hydrogen gas fuel cell vehicles. In the UK the CO_2 emission of hydrogen gas fuel cell traction are about 3 % LHV and 4 % HHV higher than the electric system. In California the CO_2 emission of gaseous hydrogen in fuel cell traction would be about 30 %, LHV and HHV, higher than those in an electrified railway network. It should be recognised that this assumes that all the hydrogen is produced via steam methane reforming, whereas the electricity generation mix includes in all cases renewable and non carbon sources.

The development of more efficient fuel cells and improvements in the hydrogen supply chain, such as pressure drop pipelines, will increase the WTW efficiencies and lower the emissions of hydrogen traction.

5.1 Renewable Sources

The desire to become more independent from fossil fuels and to lower CO_2 emissions calls for renewable sources. Wind, hydro and solar sources are considered in this paper. The energy carriers investigated are hydrogen and electricity. Many renewable sources produce electricity; hydrogen can be generated with water and an electrolyser. In this paper the electrolyser efficiency is 71.5 % LHV, 84.6 % HHV (Wang, 2002).

Water flow can be used to generate electricity with an efficiency of about 90 %. These plants are an opportunity to produce hydrogen, as water and electricity for the electrolysis are present.

Wind turbines have a high theoretically efficiency, but the regularity with which the wind blows has to be considered, the load factor is 35 % (Muyeen et al., 2008).

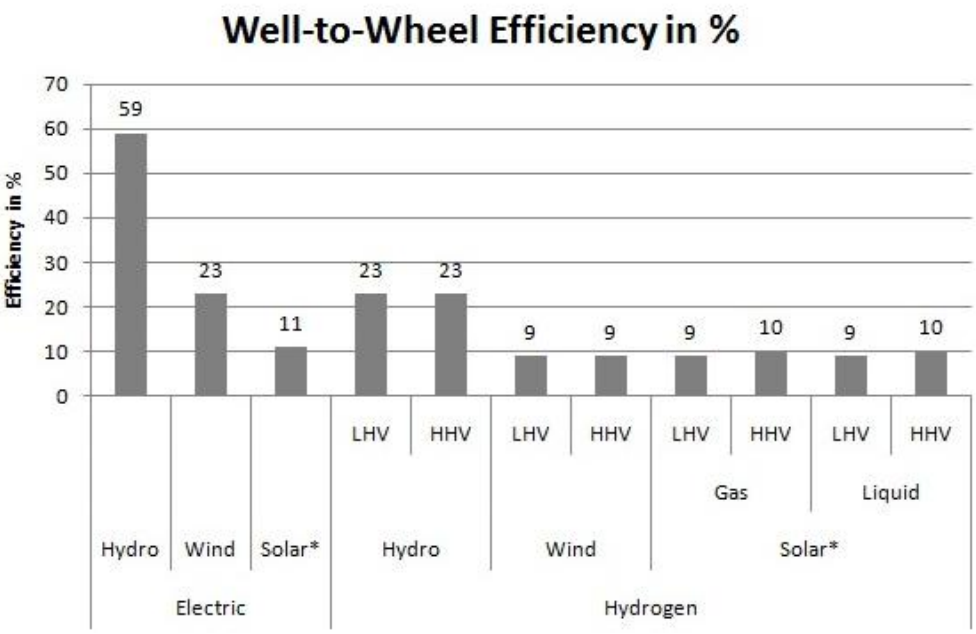
The energy return on a given piece of land is highest when the sun is directly converted into the required energy (Bossel, 2008). A 20 % conversion efficiency on about 0.1 % (approximately 500 km x 500 km) of available land, can provide the energy required by all people (Meier and Steinfeld, 2002). Solar to electricity power plants can achieve a year round efficiency of about 15 % (Solar Millennium AG, 2008). These power plants are located in Spain; sunnier areas will result in a higher efficiency, so the year round efficiency has been increased to 20 %. Large solar power plants are often not close to main demand centres, so the created electricity has to be transported. Long distances power lines, 1000 km and above, are usually HVDC to minimise losses. HVDC lines lose are about 3.5 % per 1000 km (Siemens, 2009) and losses for conversion from and back to AC are around 1.5 % (Grad, 2008).

Solar thermolysis of water will create hydrogen as an energy carrier (the necessary heat could also be provided by a nuclear reactor). A two-step thermo-chemical process using zinc and water has been developed. The conversion efficiency form sunlight to hydrogen is about 42 % (HHV). It is expected that this can be raised to 57 % (HHV) in the near future (Steinfeld and Weimer, 2010). Long distance distribution of hydrogen is likely to be by pipeline. Pumps are often installed approximately 160 km (100 miles) apart, per pump the efficiency is lowered by 1.5 % (Liu, 2003). Pipelines with pressure drops up to a distance of about 1600 km have been suggested, not requiring pumps and therefore having an efficiency of 100 %.

Liquid hydrogen distribution by ship is likely to be adopted to overcome oceans. For every 1000 km the efficiency is lowered by about 0.4 % (Wang, 1999, 2003).

Long distance overland transportation of liquid hydrogen is assumed to have a similar efficiency to ocean tankers. Figure 4 shows the WTW results for renewable sources.

Figure 4: Railway Traction Well-to-Wheel Analysis for Renewables



*The solar case includes long distance transport of 3000 km

Sources: (Canders, 2007; Department of Energy and Climate Change, 2008a; E.ON AG, 2010; Grad, 2008; International Union of Railways and Community of European Railway and Infrastructure Companies [UIC], 2008; Liu, 2003; MAN Nutzfahrzeuge AG, 2006; Muyeen et al., 2008; Siemens, 2009; Solar Millennium AG, 2008; Steimel, 2006; Steinfeld and Weimer, 2010; U.S. Department of Energy, 2008; Wang, 1999, 2002, 2003)

In the case of hydro and wind the losses of the electric system are significantly lower than in the hydrogen system. The available areas to build new hydro power plants are limited. Hydro electricity may, therefore, not be available for electrification plans of railways. The solar efficiencies over a distance of 3000 km are similar between the electric- and the hydrogen systems.

A key issue with wind and solar power is the intermittence of solar radiation and of winds. Storage mediums can cover the fluctuations and provide dependable and uninterrupted energy output. No large scale, longer term electricity storage system, except for pumped hydro and some air pressure storage, does exist.

The current electricity production system has base load power plants that cannot react quickly to a change in demand. At low demand times, e.g. at night, production exceeds demand. The generated electricity is then often ‘stored’ in pumped hydro plants to be released a peak demand time. This can be utilised to balance the unpredictable power production from renewable sources, like wind and solar. The available locations for pumped hydro plants, and air pressure storage, are however limited. Hydrogen as a storage medium is for this reason very useful and is already utilised to make wind power more dependable (Aklil, 2010).

The relatively unpredictable production of electricity through wind turbines and the inflexibility of the present electricity generation can lead to electricity prices below zero, which happens frequently (Woitas, 2010), and for this reason hydrogen production to stabilise the power generation from wind turbines becomes increasingly important. The use of hydrogen as a storage medium reduces the need for backup power plants, usually gas fired, to stabilise the grid. Hydrogen has the additional advantage that it can be sold as a valuable product in its own right, e.g. as a transportation fuel; the lower overall efficiency less of a concern.

The distribution of solar hydrogen over long distance, such as 3000 km and above, may be as a liquid. Solar electric and liquid solar hydrogen distribution systems have the same efficiency between 5000 km and 7100 km, any longer and hydrogen becomes more efficient. The most efficient mode of hydrogen distribution up to a distance of 2.500 km is in gaseous form via pipelines. Pressure drop pipelines would make the solar hydrogen gas system more efficient than the solar electric version.

6 CONCLUSION

The paper shows that a high WTW efficiency reduces the amount of energy needed from the original source and that a reduction in overall emissions is possible.

The case of Diesel traction demonstrates that a high WTW efficiency does not automatically lead to lower emissions. Hydrogen as an energy carrier to provide power for railway vehicles is a suitable solution on an efficiency and emission basis, if a fuel cell is used. The WTW efficiency is similar to electric and diesel systems, but the CO_2 emissions are lower than for diesel traction. If electricity is largely produced from high carbon fuels, a reduction of CO_2 is possible through the utilisation of hydrogen when produced from natural gas; the USA case shows a reduction of 3 % in CO_2. Hydrogen production from renewables reduces the CO_2 emissions further. Compared to diesel traction the CO_2 emissions are reduced by about 19 % if hydrogen gas is produced from steam methane reforming and used in a FC vehicle.

Hydrogen can be used to ‘store’ electricity, and can therefore increase the supply dependability of renewables. The created hydrogen can be converted back into electricity or can be sold as a valuable product for direct use, e.g. as a transportation fuel. No other storage medium for electricity offers this possibility. High losses through the use of electrolysis do lower the overall efficiency and it should only be used if the main objective is electricity storage.

The WTW efficiency of sun radiation into electricity or hydrogen are similar. Liquid hydrogen becomes the most efficient on a WTW basis, compared to hydrogen gas and electric transmission, for distances longer than 7100 km. Liquefaction requires large amounts of energy and should be avoided when the distances are shorter.

In regions were large amounts of hydro power are available and the distances are short, electrification may be the preferred choice. However the large initial investment to carry out electrification may prohibit future schemes especially over long distances. Hydrogen is able to provide a sustainable alternative.

This article has not considered other benefits of hydrogen, such as lower noise levels and no particle emissions compared to diesel traction, and reduced visual impact compared to electrification. In urban areas, such as Los Angeles, these factors are significant; hydrail vehicles would contribute considerably to the improvement of local air quality, especially along busy rail corridors. Further work will be carried out in determining the most suitable railway services for hydrogen traction and the cost of implementation.

In this paper a WTW analysis for a number of different fuel and vehicle combinations has been conducted. This method is essential for meaningful comparisons. If comparative analysis does not use WTW, then there is a possibility of the not using common boundaries on the energy chain, and therefore the results may not be comparable, and bias towards specific results may be introduced. It has been demonstrated that hydrogen is a suitable energy carrier for railway vehicles on an efficiency and emission basis. These vehicles offer a reduction in GHG emissions and WTW efficiencies are similar to electric and diesel traction. Hydrail vehicles contribute, therefore, to achieving GHG reduction targets.

7 ACKNOWLEDGEMENTS

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Feasibility of Discontinuous Electrification on the Great Western Main Line Determined by Train Simulation

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Abstract

Britain has a number of main line railway routes that are not yet electrified. Some of these routes are under consideration for electrification and the UK Government has announced the electrification of the Great Western Main Line (GWML). Railway electrification requires a large capital investment in infrastructure. Areas with limited clearances, such as tunnels and sections through overbridges, are particularly expensive to electrify. For this paper the authors have modelled train performance on the GWML, from London Paddington to Cardiff and vice versa, for three cases: no electrification, full electrification and electrification that does not include tunnels, most notably the Severn Tunnel. The trains modelled were: the High Speed Train (HST) hauled by pairs of Class 43 diesel-electric locomotives, the 9-car Class 390, and the Intercity Express Programme consists formed as straight electric and bi-mode multiple units. Bi-mode trains combine electric and diesel traction in the same train. IEP will include both 5-car and 8-car bi-mode options. Journey time, energy consumption, and CO_2 emissions were determined in each case. Electrification of the route will result in a reduction in energy consumption, carbon emissions and journey time, with the longest trains offering the greatest benefit. Under normal conditions, all modelled trains were able to complete the journey under discontinuous electrification. However, a small reduction in entry speed into the Severn Tunnel resulted in stalling of the wholly electric trains. Bi-mode rail vehicles complete the journey in all cases and, as to be expected, also when tunnel entry speed is reduced; journey time, energy consumption, and carbon emissions are not majorly impacted compared to exclusively electric operation.

Keywords: Bi-Mode Train, Discontinuous Electrification, Great Western Main Line Electrification, Inter City Express Programme,

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1 Introduction

The electrification of their routes allows railway administrations to increase capacity, eliminate emissions at the point of use and reduce energy consumption. In Britain, only about 40 % of the railway network is electrified, which is low compared with other European countries [1]. All the same, about 60 % of passenger kilometres (pkm) on Britain's railways are provided by electric trains. There is a general agreement in Britain that more railway lines should be electrified, including the Great Western Main Line or GWML [2]. However, railway electrification requires a large investment in infrastructure [3-5] and areas with limited clearance, such as tunnels, are especially costly to electrify, particularly in the case of overhead electrification [6]. This is predominantly the case where additional clearance for the electrification equipment is needed, thus requiring extensive civil engineering works, e.g., lowering the track level or increasing the height of the structure. The high capital cost of electrification schemes may prevent implementation, particularly in times where capital funding is either not available or available only on unfavourable terms. Most rail electrification schemes around the world have been financed, or financially supported, by governments. However, many governments, including that of Great Britain, need to reduce their expenditure, which threatens rail electrification schemes.

The purpose of the studies presented in this paper was to investigate the effect on train performance and service quality of leaving limited clearance areas without electrification, in order to reduce the overall cost of an electrification project thereby increasing the chances of implementation; the studies in this paper are based on GWML, which is going to be electrified. The scope of the investigation was limited to the performance of Inter City trains under three different scenarios for the GWML: (1) No electrification, which is the present situation and the base case; (2) Full Electrification; and (3) Electrification except for tunnels. The changes to the financial cost of electrification infrastructure fall outwith the scope of the paper, as the focus is technical feasibility, rather than financial viability. The effect of on-board energy storage systems has also been excluded, as the purpose was the evaluation of running unmodified trains across gaps in the electrification power system.

Discontinuous electrification in this paper refers to gaps of any length in the railway electrification infrastructure, the shortest being 89 m and the longest 7012 m. Therefore, it includes Network Rail's [7] definitions of discontinuous electrification as well as discrete electrification. A similar study, considering regional services and an option with energy storage devices on the hilly Trans-Pennine route in the North of Britain was conducted by Silmon and Hillmansen [8].

In the first part of the paper, the authors briefly outline existing electrification systems where the power supply to the trains is not available at all times. In the second part they show the method that was employed to study the different scenarios, including a brief description of the University of Birmingham's Single Train Simulator, information about the GWML route, and information about the modelled trains. In the third part the results and discussions are presented, and finally conclusions are provided. The research for the paper was conducted as part of an MSc dissertation project at The University of Birmingham.

2 Existing Discontinuous Electrification Systems

2.1 3rd Rail Electrification Gaps in Britain

Gaps in railway electrification infrastructure are not a new issue, and are indeed unavoidable in 3rd rail electrification systems, both in junction areas (see Figure 1) and at level crossings [4]. The world's largest 3rd rail mainline network exists in Britain, covering about 14 % of the total national railway infrastructure [9]. It is an area in South encompassed by the Thames, the English Channel, Weymouth, and Reading. The top-contact 3rd rail is placed on the side of the running rails and is operated at 750 V DC (Volts direct current).

The gaps are typically overcome by means of coasting or, with multiple unit operation, by providing several traction power pick up points along the train. In general these gaps are relatively short, extending to between 2 meters and 15 meters, and do not cause operational problems, except in rare circumstances where a train stops without any pick-ups contacting the 3rd rail. Class 70 hybrid locomotives, designed primarily for freight service, were utilised by the Southern Railway (SR) in the South of England in the 1940s to overcome the gaps. The locomotives had motor-generator sets with flywheels that stored the necessary kinetic energy [4].

Figure 1: Gap in 3rd Rail Electrification Infrastructure (Hoffrichter 2011)

2.2 Overhead Electrification Gaps in the Netherlands

In the Netherlands overhead electrification is used on the main line railway network supplying trains at 1500 V DC. A continuous electrification infrastructure could not be provided over some bridges that have to open for shipping traffic and, therefore, these were left without overhead wires, i.e., leaving a gap, see Figure 2.

Figure 2: 75 m Gap in Overhead Electrification Infrastructure at Alphen aan den Rijn in the Netherlands[1]

The height limited pantograph expands into open space and contact with the conductor wire is only re-established once the gap is overcome. The principle is the same as on 3rd rail electrification systems. This type of discontinuous electrification can only be used if space for the maximum deployment of the pantograph is available. In underpasses and tunnels it is not practical as some additional clearance is required.

[1] Photos in Figure 2 courtesy and © Ferry van Schagen

2.3 Energy Storage Trams to Overcome Electrification Gaps in City Centres

Historic city centres are particularly affected by the visual impact of overhead electrification and this lead to the development of alternatives. One of these alternatives is vehicle that store energy onboard. Alstom has developed and tested several energy storage devices for trams: flywheels, batteries, and super capacitors [10]. Battery storage trams, developed by the company, are in commercial operation in Nice since 2007. The non-electrified sections are relatively short, usually up to 500 m, but flywheel test, conducted in Amsterdam, allowed up to 2 km autonomous traction [10].

Energy storage trams are in revenue service and their main power is supplied form overhead electrification, as would be the case on the GWML. Even though the power demands of trams are lower and the pantograph can be lowered at a stop, these vehicles show that the principle of operating railway vehicles from energy storage devices over gaps in overhead electrification infrastructure is feasible.

2.4 Neutral Sections in Alternating Current Overhead Electrification Systems

Overhead Alternating Current (AC) railway electrification systems often use the public power grid for the provision of electricity. In most cases, grid power at industrial frequency is transmitted and distributed as three phase AC. However, all modern railway electrification systems use single phase AC power supplies. In order to balance loading of the supply in this situation, the rail electrification infrastructure is often connected across different phases of the grid. To avoid electrical phase problems, neutral sections are inserted in the rail power infrastructure [11]. These sections are normally earthed, that is, they are connected to the earth return.

In Germany, neutral sections for phase separation must be a minimum of 402 m long, according to Kiesling, Puschmann, Schmieder and Schneider [11]. This length is determined by the train configurations to be used and other local factors. The circuit breaker on the train is usually opened before entering the neutral section to prevent power surges, then the train coasts through the neutral section. The circuit breaker is closed once the train has re-entered the powered section. The pantograph does not lose physical contact with the overhead infrastructure in these cases. In Britain, trains coast through the 50 m long neutral sections in the overhead line [7]. The entry and exit points of neutral sections feature insulating material or very short physical gaps in the electrification infrastructure, but the latter are arranged in a way that does not allow the pantograph to rise. No power for propulsion is available once the pantograph has entered the neutral sections.

This type of unpowered infrastructure can be used in tunnels and underpasses although it must be ensured that the transition of the pantograph from the powered section into the neutral section does not result in the overhead line, through the constrained area, being temporarily energised at line voltage. Since the contact wire is earthed through the constrained area, clearances can be kept to a minimum, which ensures that the pantograph cannot touch the tunnel ceiling or bridge parapet.

2.5 Bi-Mode Trains

Bi-mode or dual-mode, trains have two separate main power supplies, e.g., an electrical supply provided by the infrastructure and a diesel-generator set. They may be, therefore, described as a type of hybrid train, even though they do not feature an energy storage device in most cases. The two power supplies can provide the energy required to propel the train either separately or together. Bi-mode trains can take advantage of electrification infrastructure without compromising the flexibility to reach non-electrified parts of the network. The Class 73 locomotive is an example of a bi-mode railway vehicle in Britain, as it can operate either from the 3rd rail electrical power supply or from the onboard diesel-generator set [12]. In the greater New York area of the United States, bi-mode trains have been used for several decades to comply with the city's regulations. Dating back to the days of steam traction, these by-laws do not allow smoke emissions from locomotive diesel engines within the city limits and, especially, not in tunnels. An example of a locomotive built to overcome this restriction is the EMD FL9 built, from 1956 onwards for the New York, New Haven and Hartford Railroad [4]. A modern version that allows operation from overhead electrification or from a diesel-generator set is the ALP-45DP dual-mode locomotive built by Bombardier from 2010 onwards [13].

The examples above show that operation of electric trains over gaps in railway electrification infrastructure is possible. However, the gaps must be relatively short of necessity, if the use of bi-mode vehicles is to be avoided. By contrast, the GWML discontinuous electrification arrangements will involve non-electrified sections that are much longer than described above and it cannot be concluded, therefore, that discontinuous electrification is feasible without a further analysis. The assessment of the feasibility of discontinuous electrification for the GWML, as well as the performance of trains for the other two scenarios, was determined with the use of computer simulation software.

3 Methodology

3.1 Single Train Simulator

The University of Birmingham's Single Train Simulator has been utilised to model the performance of trains. It uses distance-domain numeric integration to solve differential equations to model train behaviour and to estimate train performance. The simulator has been used extensively for train operation modelling [14, 15]. For the present project it was modified to take account of gaps in the electrification infrastructure and to include the higher resistance to motion encountered in tunnels, in accordance with values provided by Sachs [16]. The simulator requires route and vehicle information for its operation. Details of the simulated route and vehicles are presented below. For all vehicles, except the High Speed Train, regenerative braking has been included, making the assumption that the electrification infrastructure is always receptive.

3.2 Simulation Scenarios

Simulation was carried out for three scenarios on the Great Western Main Line: (1) Base Case, present condition, no electrification; (2) Full Electrification; and (3) Discontinuous Electrification, i.e., electrification of the line except for tunnels. Only intercity passenger train services were simulated.

The performance indicators in this study are: (a) Completion of Journey without Stalling, (b) Journey Time, (c) Energy Consumption, and (d) Carbon Emissions.

Journey completion is the strongest indicator for the feasibility of discontinuous electrification, as an incomplete journey shows that the proposed system is not feasible. Journey time is second priority, as a large increase in time due to unavailable traction power in certain sections may not be tolerable.

Energy consumption and carbon emissions are related to the propulsion technology employed and have been included to show the effect on the environment and the sustainability of railways. The results are shown on a well-to-wheel basis, using the methodology of Hoffrichter, Miller, Hillmansen and Roberts [17], to ensure fair comparison between the existing diesel technology and electrification. The vehicle efficiency for electric traction has, however, been increased to 85 %, in accordance with measurements of Class 390 trains [18] and other recent electric trains [19].

3.3 Great Western Main Line

The Great Western Main Line (GWML), see Figure 3, is one of the major non-electrified rail routes in the UK, but it is going to be electrified [2].

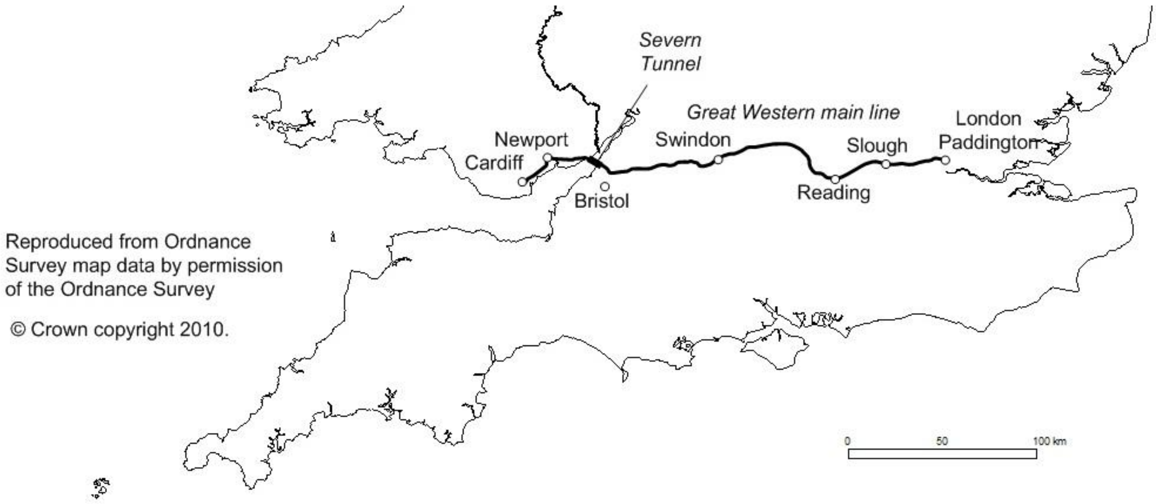


Figure 3: Great Western Main Line Route

The line connects London Paddington with Cardiff Central and has long stretches of relatively straight track with high speed limits and several tunnels of various lengths, as shown in Table 1. The river Severn is traversed by means of a 7 km sub-sea tunnel, before approaching Newport and Cardiff. The length of the Severn Tunnel presents a serious challenge for any train attempting to transit it without power.

Table 1: Tunnels on the Great Western Main Line

Name	Length in m	Max. Speed Limit (km/h)
Spring Bridge Road Car Park Tunnel	121	200
Alderton Tunnel	463	177
Chipping Sodbury Tunnel	4065	193
Patchway Tunnels New (Up tunnel)	1609	145
Patchway Tunnels Old (Down Tunnel)	1139	145
Patchway Tunnels Short (Down Tunnel)	57	145
Ableton Lane Tunnel	89	113
Severn Tunnel	7012	113
Newport Tunnels	704	97

The route information has been compiled using Trackmaps [20], Network Rail's Sectional Appendix [21], and Network Rail's GEOGIS gradient database. The tunnel exit speeds, for the electric trains under discontinuous electrification, have been based on increases of the speed limit applied to the tunnel in 20 km/h intervals until the present maximum limit was reached. On the journey from Paddington to Cardiff the authors used the New Patchway

Tunnel as it is longer than the two old tunnels combined and therefore presents a more severe case for discontinuous electrification.

3.4 Railway Vehicles

In this section the authors give details of the trains simulated. After the description of the train the corresponding layout is shown and at the end of the section the vehicle characteristics of all trains are presented.

3.4.1 High Speed Train

The High Speed Train (HST) is a diesel-electric intercity train with a maximum speed of 200 km/h. For many years it has been one of the major main line passenger trains in the UK. It has two power cars (locomotives) of Class 43, one at each end, and a number of intermediate unpowered coaches. For the simulations, the train has been modelled with two power cars and eight coaches. The HST is currently used on the GWML and its simulated performance is taken to be the base case. The vehicle information for the HST has been sourced from the Traction Recognition guide [12] and the resistance to motion parameters were taken from the University of Birmingham's archives and Sachs [16] as mentioned.

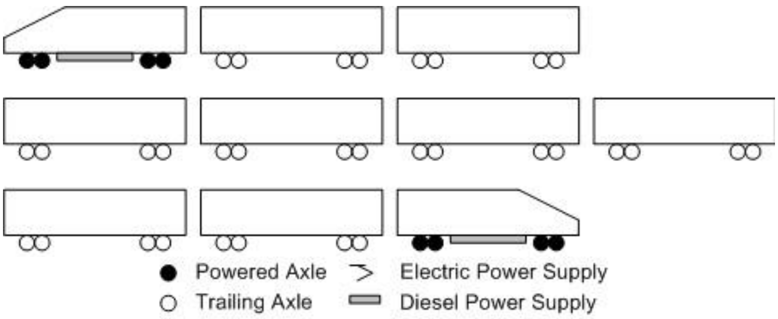


Figure 4: High Speed Train Layout

3.4.2 Class 390, Pendolino

The Class 390, a Pendolino, is a tilting electrical multiple unit train used on the West Coast Main Line. It is a modern train, built between 2001 and 2005. The train operates at up to 200 km/h, and is capable of 225 km/h; it utilises regenerative braking. The Pendolino has been chosen to represent a modern existing electric train, which could run over an electrified GWML. The performance characteristics of the Class 390 have been sourced from literature [12, 22] and the resistance to motion coefficients are based on experimental tests with a Class 390 train, suitably modified for operation in tunnels using values reported by Sachs [16] as mentioned earlier.

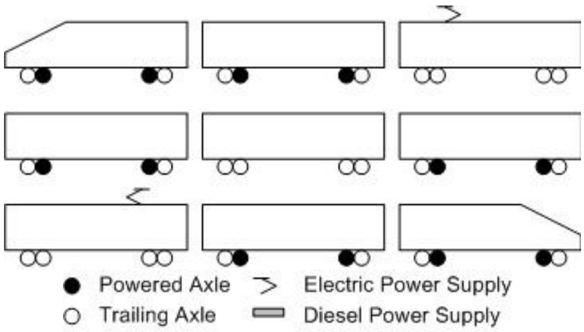


Figure 5: Class 390, Pendolino, Train Layout

3.4.3 Intercity Express Programme Trains

The Intercity Express Programme (IEP) is a government initiative to replace the aging intercity fleet in the UK, and it is intended that the resulting train will replace the HST on the GWML [23, 24]. The train will be built as a multiple unit train, and comes in various consist arrangements [25]. The specifications of the IEP have changed several times since the original document was published by the Department for Transport, and the train characteristics used in the simulations are based on numerous publications and the authors' best knowledge and interpretation of the information available in early 2012.

The most numerous IEP trains will be the five car bi-mode, the eight car bi-mode, and the eight car electric consists [24]; for this reason these have been simulated.

The electric train is assumed to have four traction units (powercars), giving the same ratio as in the original specification [25], and one under-floor diesel engine for emergency and shunting moves [26]. It is assumed that the under-floor engine is not used in regular service.

The five car bi-mode version will have three diesel power plants and an electric power train for three traction units, according to Clifton [26]. The eight car bi-mode is assumed to have four diesel power plants, giving the same ratio as in the original specification [25], and an electric power train, resulting in four traction units. The bi-modes can be operated using electricity from overhead infrastructure, or diesel on non-electrified routes, or can use both power sources on electrified routes. In the simulations it is assumed that the diesel engines are only operated if power from the electrification infrastructure is unavailable. It is also assumed that the electric drive train is able to provide all the power required in electrified sections, as suggested by Foster [27].

The train specification data for the IEPs has been sourced from literature [23-29]. The mass data for the trains has been based on Clifton [26] and attributed to the train consists according to the number of cars. The tractive effort data is based on the original concept trains, as released by AgilityTrains [25], and has been adapted according to the number of cars. The resistance to motion is determined using the Davis Equation [30, 31]:

$$R=A+BV+CV^2 \tag{1}$$

Where R is the resistance to motion, A, B, and C are constants, and V is speed (velocity). The Davis coefficients are based on experimental tests with the Class 390, so-called run-down tests. The A and B values, which are mass related, are scaled according to the train mass, the C term is assumed to be the same as that of the 9-car Class 390. This is a conservative assumption

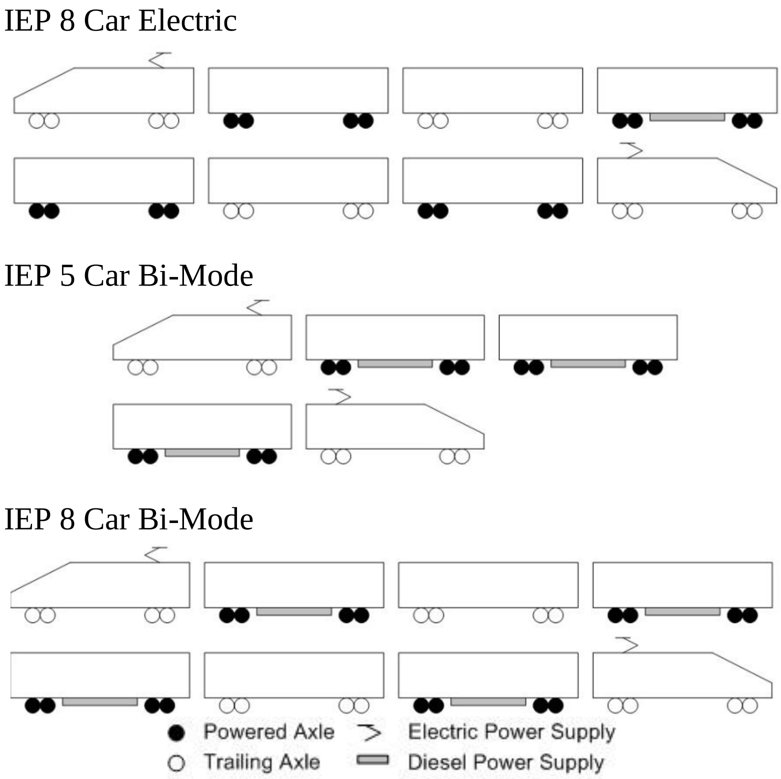


Figure 6: Intercity Express Programme Layout

3.4.4 Vehicle Parameters

Table 2 shows the vehicle parameters. The authors assume that the trains travel as fast as possible and have a dwell time of two minutes at each station.

Table 2: Vehicle Parameters

Vehicle Type	Mass (t)	Effective Mass (t)*	Power (MW)	Max. Speed (km/h)	Tractive Effort (kN)	Resistance to Motion, Davis Coefficients A (kN)	B (kN s/m)	C (kN s^2/m^2)
HST, 8 passenger cars	498	612.54	2.6	200	160	3.2217	0.1128	0.0078
Class 390, 9 passenger cars	456	560.88	5.1	200	204	5.4216	0.069	0.0121
IEP 8 Car Electric	389.3	478.84	3.2	200	320	4.6286	0.0589	0.0121
IEP 5 Car Bi-Mode	256	314.88	2.4	200	240	3.0437	0.0388	0.0121
IEP 8 Car Bi-Mode	405.2	496.01	3.2	200	320	4.8176	0.0613	0.0121

*A rotational allowance of 0.08 and a load value of 0.15 were used to determine the effective mass, except for the IEP 8 Car Bi-Mode where the same load as for the IEP 8 Car Electric was used

Journeys for the trains in Table 2 were simulated for the roundtrip from London Paddington Station (PAD) to Cardiff Central Station (CDF). To ensure comparability, operation with and without regenerative (dynamic) braking was modelled. The power mix assumed for the calculation of the well-to-wheel energy flow and the CO_2 production is based on the UK's 2008 electricity mix and the well-to-wheel study of Hoffrichter, Miller, Hillmansen and Roberts [17], which applies this mix.

4 Results and Discussion

The simulation results of the trains travelling over the GWML from Paddington to Cardiff are shown in Analysis of Results of Journeys in Either Direction

Table 3 and the return journey results are presented in Table 4. A discussion of the performance indicators follows the results table, while observations valid for both travel directions and comments about tunnel exit speed are provided at the end of the section.

4.1 Analysis of Results of Journeys in Either Direction

Table 3: Performance Results for a one-way trip from Paddington to Cardiff on the GWML

Railway Vehicle	Journey Time in minutes	Vehicle Energy Consumption in kWh*	Well-to-Wheel Energy Consumption in kWh	Well-to-Wheel CO_2 emissions in kg	Lowest Speed in Severn Tunnel (km/h)
(1) Non-electrified:					
High Speed Train	112	8607	10008	2634	
(2) Fully Electrified:					
Class 390 Pendolino, no regenerative braking	100	4101	12062	2502	
Class 390 Pendolino	100	3164	9306	1930	
IEP 8 Car Electric, no regenerative braking	104	3660	10765	2233	
IEP 8 Car Electric	104	2965	8721	1809	
(3) Discontinuous Electrification:					
Class 390 Pendolino	103	3122	9182	1904	25
IEP 8 Car Electric	107	2909	8556	1774	14
IEP 5 Car Bi-Mode	105	2691	7982	1712	94
IEP 8 Car Bi-Mode	105	3064	9029	1946	95
(4) Discontinuous Electrification with electrified Severn Tunnel:					
Class 390 Pendolino	101	3140	9235	1915	
IEP 8 Car Electric	105	2913	8568	1777	

* Diesel in vehicle tank, or electricity at pantograph, or a combination of both

In scenario (3), all trains are able complete their journey without stalling, regardless of composition. However, the relatively low minimum speeds of the exclusively electric vehicles under discontinuous electrification in the Severn Tunnel indicate that this solution may not be dependable enough for regular service train operations. For this reason scenario (4) has been simulated, where all tunnels are left non-electrified except for the Severn Tunnel.

A journey time reduction is achieved with electrification, i.e., use of the Class 390 reduces the journey time by 12 min, compared to the non-electrified base case, 9 min under discontinuous electrification, and 11 min in scenario (4). The time difference between full electric operation with the IEP 8 Car Electric and operation under discontinuous electrification is 3 min and 1 min compared to scenario (4). Bi-Mode vehicles, compared to the electric IEP, reduce the journey time with discontinuous electrification to a difference of 1 min, compared to electrification throughout.

The increase in energy consumption between the 8 car IEP electric and 8 car bi-mode is 201 kWh. This shows that the bi-mode does not consume a significant amount of additional energy compared to the electric train, despite being heavier and operating partially on diesel traction power. The IEP 5 car bi-mode consumes 419 kWh less energy than the IEP 8 car bi-mode, per car: 5 car layout 538 kWh, and 8 car layout 389 kWh. From these figures it can be seen that adding additional coaches to a train does not affect energy consumption in the same way as running an additional train. This is because, at high speeds, the largest component of the resistance to motion is the aerodynamic resistance dominated by the front of the train [32]. Adding coaches has less of an effect on energy consumption.

Table 4: Performance Results for a one-way trip from Cardiff to Paddington on the GWML

Railway Vehicle	**Journey Time in minutes**	**Vehicle Energy Consumption in kWh***	**Well-to-Wheel Energy Consumption in kWh**	**Well-to-Wheel CO_2 emissions in kg**	**Lowest Speed in Severn Tunnel (km/h)**
(1) Non-electrified:					
High Speed Train	113	8517	9903	2606	
(2) Fully Electrified:					
Class 390 Pendolino, not utilising regenerative braking	100	4113	12097	2509	
Class 390 Pendolino	100	3268	9612	1993	
IEP 8 Car Electric, not utilising regenerative braking	105	3642	10712	2222	
IEP 8 Car Electric	105	3035	8926	1851	
(3) Discontinuous Electrification:					
Class 390 Pendolino	102	3190	9382	1946	37
IEP 8 Car Electric	107	2959	8703	1805	31
IEP 5 Car Bi-Mode	105	2772	8212	1752	97
IEP 8 Car Bi-Mode	105	3087	9173	1966	98
(4) Discontinuous Electrification with electrified Severn Tunnel:					
Class 390 Pendolino	101	3210	9441	1958	
IEP 8 Car Electric	106	2984	8776	1820	

* Diesel in vehicle tank, or electricity at pantograph, or a combination of both

Again, in scenario (3), all trains are able complete their journey without stalling, regardless of composition. However, the relatively low minimum speeds of the exclusively electric vehicles under discontinuous electrification in the Severn Tunnel indicate that this solution may not be dependable enough for regular service train operations, so as with the previous journey a scenario with an electrified Severn Tunnel, but leaving the other tunnels non-electrified, was simulated The lowest speeds in the Severn Tunnel in this travel direction are higher than from Paddington (PAD) to Cardiff (CDF), the reason for this is the slightly lower gradient on the English side of the tunnel.

The electric Class 390 reduces the journey time by 13 min, compared to the non-electrified base case, 11 min under discontinuous electrification, and 12 min in scenario (4). The time difference between fully electric operation of the IEP 8 electric and operation under discontinuous electrification is 2 min and 1 min in scenario (4). The 8 car bi-mode version achieves them same journey time as the electric version under full electrification.

The increase in vehicle energy consumption between the 8 car IEP electric and 8 car bi-mode is 205 kWh. This shows that the bi-mode does not consume a large amount of additional energy compared to the electric train, despite being heavier and using partial operation of diesel traction power. The IEP 5 car bi-mode consumes 392 kWh less energy than the IEP 8 car bi-mode, per car: 5 car layout 554 kWh, and 8 car layout 396 kWh. From these figures it can be seen that adding additional coaches to a train does not affect energy consumption in the same way as running an additional train, as already shown on the journey from Paddington to Cardiff.

4.2 Summary of Results for Both Travel Directions

Discontinuous electrification reduces journey time compared to the non-electrified base case (1), however the reduction is not as high as with full electrification, but there is relatively little time difference between full and partial electrification.

The largest difference in vehicle energy consumption can be seen between the diesel powered HST and the electric, or partially electric, operated trains. The reason for this is that the largest losses of energy occur from the chemical to the other energy stage, which takes place in the diesel engine or, for electric railways, at the power station; e.g., chemical energy in the diesel is changed to mechanical energy, where during the combustion of the fuel pistons are moved, which results in the rotation of the drive shaft.

The well-to-wheel energy consumption of the electric vehicles not utilising regenerative braking is the highest, followed by the HST. One reason for this is the higher power to weight ratio of the electric vehicles compared to the HST; a shorter journey time is the positive consequence. Regenerative braking for the electric and bi-mode layouts reduces the well-to-wheel energy consumption to a level below the Base Case.

The largest difference in CO_2 emissions is between the diesel-powered HST, which has the most carbon emissions, and the electric trains utilising regenerative braking, if regenerative braking is not utilised the carbon emissions between the HST and the electric trains is similar. Carbon emissions are related to energy consumption, and it can again be seen, particularly when comparing the 5 and 8 car IEP bi-mode, that additional coaches on a train do not increase energy consumption and carbon emissions as much as running a separate additional train. The 8 car IEP bi-mode train emits more carbon than the electric version; this is due to the partial operation, in tunnels, with diesel power. The 5 car IEP bi-mode has nearly the same carbon emissions as the 8 car electric IEP, again making the case for long trains.

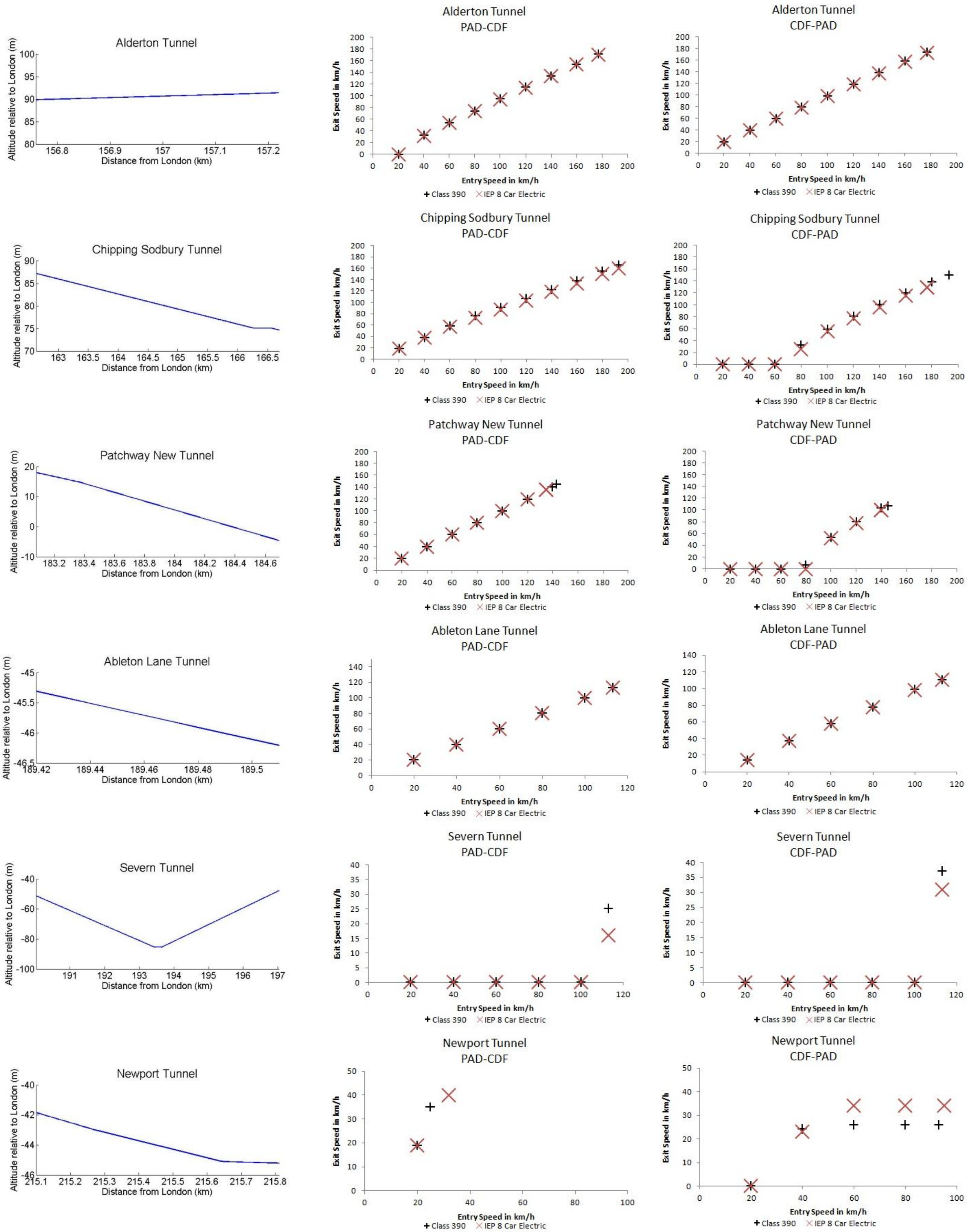
4.3 Speeds of Fully Electric Trains on Entering and Leaving Tunnels

The general operating patterns of the Class 390 and the IEP 8 Car Electric through the tunnels are similar if these are left non-electrified, see Table 5. The Severn Tunnel forms the greatest challenge and a small reduction in entry speed prevents both fully electric trains from completing their journey without stalling. As mentioned above, the lowest speeds in the Severn Tunnel in travel direction CDF to PAD are higher than from PAD to CDF and the reason for this is the slightly lower gradient on the English side.

The figures of Table 5 use different types of crosses to indicate the type of train, with Class 390s shown as ‘+’ and IEP Electric as ‘×’. It can be observed that, in general terms, the behaviours of trains are the same where the gradient profile is the same for both directions of travel.

Table 5: Entry and Exit Speeds for Class 390 and IEP Electric in Non-Electrified Tunnels

Altitude	Travel Direction PAD-CDF	Travel Direction CDF-CAD



Newport Tunnel is traversed at low speed because of the 32 km/h (15 mph) speed restriction in Newport station, which is adjacent to the tunnel. The effect of the gradient can be seen in the Patchway Tunnel, Chipping Sodbury Tunnel and, to a lesser extent, in Alderton Tunnel, as in the travel direction CDF-PAD the trains are not able to complete the journey with lower entry speeds, whereas in the direction PAD-CDF they do. From these results it can been seen that the length of the tunnels, gradients in these, speed on entering the tunnels and the speed limits are the main factors that determine the feasibility of running electric trains through non-electrified tunnels of any route.

5 Conclusion

The GWML has been taken as an example route to evaluate the feasibility of discontinuous electrification. Modelling has been undertaken to obtain the performance values. These include the binary journey completion indicator, journey time, energy consumption, and CO_2 emissions. The base case was the present situation without electrification and train service operation with HSTs (pairs of Class 43s). Other vehicles modelled were the Class 390 and the IEP train in the 8 car electric, 5 car bi-mode, and 8 car bi-mode configurations.

The research has shown that the GWML electrification will result in lower energy consumption and carbon emissions from train operation. Trains with many coaches offer the greatest benefit. Discontinuous electrification is possible, but a small reduction in entry speed into the Severn tunnel will result in non-completion of the journey of the fully electric trains and, therefore, this is not a robust solution. IEP bi-mode trains will complete the journey with a small increase in journey time compared to full electrification. It has been possible to demonstrate that, in general, relatively short gaps in the electrification infrastructure do not affect the ability of trains to complete their journeys without stalling.

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