Department of Mechanical and Aerospace Engineering

Project
Title

The creation of a tool to evaluate the feasibility and CO2 reductions of Hydrogen trains as an alternative to Diesel trains

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Abstract

A tool has been created in order to evaluate the technological feasibility as well as the CO2 emission reductions of using H2 as an alternative to diesel fuel for trains. The tool created is capable of producing outputs such as the volume of storage, energy and fuel consumption of both diesel and H2 fuels used, cost comparisons of fuels, range and number of times it would require refuelling over a given distance. The tool is also cable of showing the CO2 emissions that could be saved from the use of a H2 train. After the tool's creation several scenarios analysing different aspects of UK rail like passenger commuter trains, freight trains and high-speed passenger trains were carried out. Each of these different scenarios tested reacted differently when analysed through the tool. The tools outputs showed that the use of H2 was favourable for low power passenger trains, high-speed trains and short distance freight journeys for reducing CO2 emissions despite the high costs that would be incurred.

Acknowledgements

I would like to express my deepest thanks and gratitude to my project coordinator Professor Joe Clarke and Dr Paul Tuohy for their help and guidance throughout this report.

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1 Chapter 1: Introduction

Society today is dependent upon a readily available supply of energy in the form of fossil fuels especially when it comes to the transport of goods or people. Fossil fuels are a finite resource and the demand for transport is continuingly growing. Alternative energy sources must be found and utilized not only to meet transport demands and to reduce harmful emissions which have an adverse effect on the earth's climate as well people's health; but to create a more sustainable society for the future. There is little doubt that the prolonged continuation of fossil fuels in transport industries will lead to adverse environmental affect. This paper aims to create a tool that can test the benefits of the introduction of H2 trains in the UK against current diesel and electric rolling stock. Several scenarios effecting the different aspects of the current UK rail network will be tested by the tool and the results as well as the pros and cons of the adaption of H2 trains based around existing rolling stock to show the use of H2 as a primary fuel source would impact areas such passenger, freight and high-speed trains.

1.1 Literature Review

Transport emissions account for roughly around a quarter of greenhouse gas (GHG) emissions globally, emissions from this sector consists of fuels used for rail, road, air and marine. In the EU transport systems make up currently around 30% of GHG emissions and this figure is set to increase. World transport almost entirely relies on fossil fuels with 95% of transportation fuels coming from gasoline and diesel. Global transport emissions are continuing to grow even as vehicles become more efficient. Transport emissions are growing faster than any other sector which could lead to CO2 emissions more than doubling by 2050. Rail transport is one of the lowest emitting transport methods and one of the most efficient and most electrified transport methods. The UK government aims to reduce net carbon emissions by 80% which includes all six Kyoto greenhouse gases by 2050 based on 1990 levels. This equates to a reduction from 809 MtCO2e in 1990 to 161.9 MtCO2e by 2050. Levels in 2014 had dropped by 36% to 520.5 MtCO2e over 24 years however large infrastructure projects could adversely affect this. Transport emissions have not seen the same positive results in emission reductions as it is remained almost constant at 116.9 MtCO2e. Current annual rail emissions are 4.14 MtCO2e; 0.8% of total emissions and 3.6% of transport emissions.

However, in the UK around 36% of rail is electrified meaning that almost two thirds of the UK railways rely on diesel or diesel hybrids. When electric trains are compared to diesel there is clear reduction in CO2 emissions due to the reduced consumption of diesel which leads to an environmental benefit from the electrification of the rail tracks. Giovani et al produced a table which can be seen in Fig 1-1 showing the difference between CO2 emissions of diesel and electrical types of trains. It may seem as if the electrification of the remaining UK railway tracks may be the best solution to reduce CO2 emissions at first glance. However, this is not necessarily the case. The current rail split between UK rolling stock is roughly around a third electric and two thirds diesel. The UK also has over 15800 km of track that would require electrification to fully electrify the UK railways. Giovani et al state the mid-range cost of electrification of UK railway would be €840k per km, therefore, to electrify to full of the UK railway tracks would cost roughly €14.8 billion. The resulting CO2 emissions reductions over 50 years would be equivalent to 12 million tonnes of CO2. This works out as reducing one tonne of CO2 emissions would cost €1223. The electrification of the entirety of the UK's railway would not be cost effective, it would take several years to complete a project of this scale, creation of appropriate infrastructure would greatly impact passengers and freight operators, and it would only reduce CO2 output at the point of use as there would be greater demand placed on the grid and the majority of sources of electricity would not be from renewable sources. Electrification of the UK's rail network may not be the best solution.

Diesel trains			Electric trains	
gCO_2/litre	**2674**		**gCO_2/kWh**	**554** (2)
Fuel use (million liters)	463.7		Electricity consumed (GWh)	2820
Vehicle-km (million)	893		Vehicle-km (million)	1444
Liters/vehicle km	0.519		kWh/vehicle-km	1.95
gCO_2/vehicle km	**1389**		**gCO_2/vehicle-km**	**1082**

FIGURE 1-1 DIESEL VS ELECTRIC TRAINS

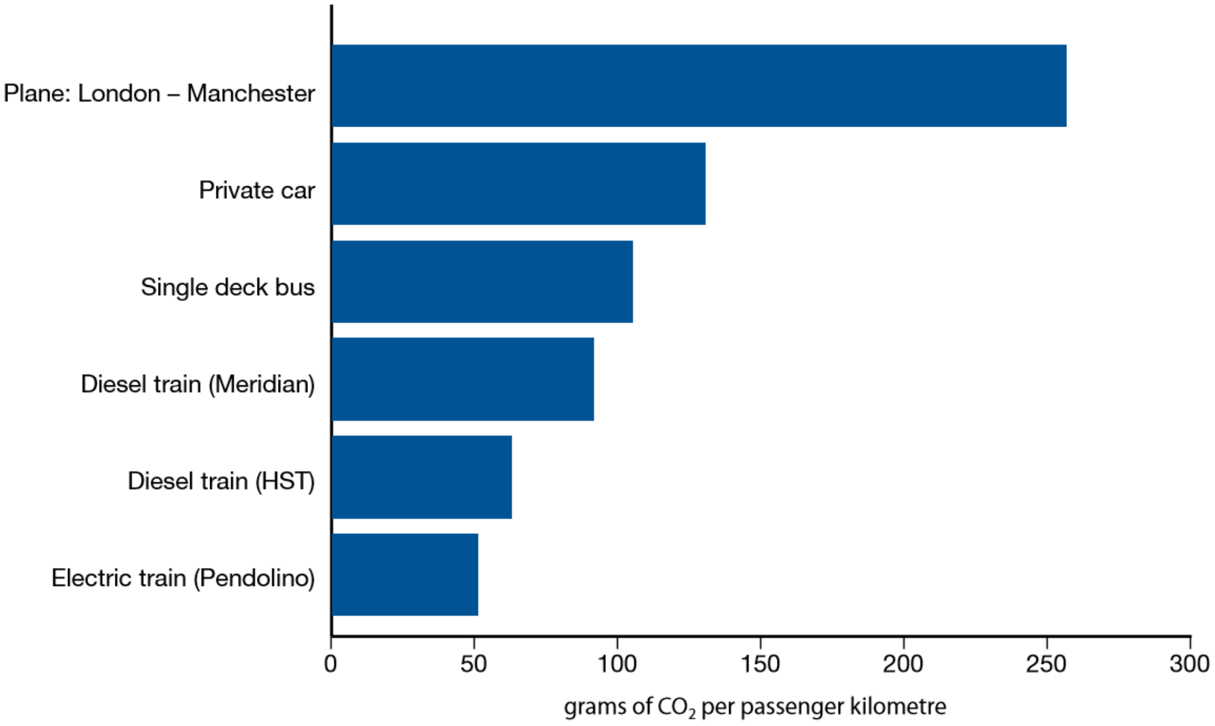


Figure 1-2 Transport mode emissions

The rail sector in UK has seen an increase in demand and in usage over the past two decades greater than that of any other method of transport, rail tends to be most commonly used for commuter journeys and freight use. Diesel trains have low efficiency engines and high maintenance costs and because of this Mwambeleko and Kulworawarichpong mention that diesel trains are still being used on heavy commuter routes to justify the high operating costs. Abramesko and Tartakovsky highlight that diesel trains are the standard option for train propulsion globally and in North America almost all of the rail transport is based around diesel trains. Due to grid connection, feasibility and economic factors the majority of electrified trains are used for short commuter journeys in urban areas, but electrified routes emit significantly less CO2 emissions as identified in Fig 1-1. Diesel trains are often used for longer cross country or rural journeys where electrification is not currently possible. Diesel engines are fuel efficient and as a result are used not only in rail sector but in many commercial transport sectors. They offer many benefits such as durability and good fuel economy. Despite this diesel engines are one of the main sources of air pollution, especially in cities and urban environments as they emit nitrogen oxide, sulphur oxide, carbon dioxide and carbon monoxide. Long term exposure to many of these gases can have adverse health impacts. There are methods available to reduce emissions such as emulsification and Nadeem et al show that water/diesel emulsified formulations are effective in reducing harmful emissions. Although this method only dilutes the emissions and does not remove them. Wood and Bauen mention that the use of first-generation biodiesel is available to use on diesel train engines and could save up to 60% carbon when it is compared to diesel. However, it can also be considered as not being a low carbon alternative due to its high land usage impacts as it will come into direct competition with food crops and also due to its poor fuel lifecycle carbon impacts. The inability of electrification for these journeys due to economic factors and feasibility, both passenger and freight routes, and limitations of technologies to reduce diesel emissions leads to the development of alternative energy solutions as a replacement for diesel fuel and an overall reduction of GHG emissions from rail transport. The UK’s Department for Transport (DfT) has made a U-turn since 2017 and there has been a loss of confidence in new electrification schemes. Three major rail electrification projects have been cancelled and were supposed to be in North of England, Midlands and Wales between Cardiff and Swansea so there is little prospect of further large-scale electrification projects in near the future.

The need for alternative fuel sources to replace diesel trains is increased by the UK Governments stance to phase out diesel only trains by 2040 which currently make up 29% of all UK rolling stock. With the current UK government’s decision to cancel several electrification projects and aims to phase out all diesel trains by 2040 there is a window of opportunity for the development of alternative fuels. Moriarty and Henry state passenger transport energy requirements globally will most likely fall and that freight transport energy requirements will dominate transport energy use. Their predictions mostly agree with the current trends in the transport and specifically rail sector in the UK. Moriarty and Henry also stated that the use of ICE will be continually phased out primarily in cities. The threat of climate change being caused by GHG emissions is a common issue faced globally and is posing a threat to human health and the health of the environment, as a result strategies to save energy and reduce emissions are growing, Mi et al. The growing demand for rail transport in the UK and the phasing out of diesel only trains and use of diesel engines in cities creates an opportunity for the development of alternative fuel sources such as biodiesel and H2. H2 would be favourable regrading emission reductions for the rail sector alongside the use of hydrogen fuel cells both do not emit GHG's at its point of use. There will be a large gap for the possibility of decarbonisation that cannot be met by electrification and the gap left by the phasing out of diesel only trains that will need to be filled.

The current presence of H2 in the global transport scene can be regarded as insignificant as it has not yet delivered or lived up to its predicted expectations. In 2003 the European Commission created a roadmap of integrated energy systems based on hydrogen fuels and how they would progress up to 2050. The European Commission's roadmap with its forecast of H2 use up to 2050 has failed thus far to come to fruition and Ajanovic and Haas state that some of the biggest barriers for wider use of hydrogen as fuel source in the transport sector are the economic feasibility due to the high cost associated with both its production and consumption technologies. Other challenges facing the future of hydrogen use for transport are its on board storage and its range. Despite this hydrogen is still a promising energy source due to several factors highlighted by Singh et al such as a reduction in GHG emissions, energy security and reductions in air pollutants. H2 can be used for nearly all application where fossil fuels are used therefore it is an extremely versatile fuel source. Its only by-product water and is emission free at the point of use. H2 is becoming increasingly popular and Zeng and Zhang identify three reasons for its growing use; it is seen as a clean fuel source emitting almost nothing but water, it can be produced from any available fuel source with renewable technologies being the favourable method and its compatibility with fuel cells. In comparison to internal combustion engines (ICEs), hydrogen fuel cells have higher conversion efficiencies with several sources giving different efficiencies ranging from 46% to 60% depending on the source, type of hydrogen fuel cell and its use. Although different fuel cells have varying efficiencies, they are still more efficient than IC engines which have efficiencies ranging from 33% to 37% and are unlikely to exceed 40%. Fuel cells are not restricted by the Carnot limit = $\frac{T1-T2}{T1}$ like ICEs and if there is no irreversibility's then they could achieve efficiencies of 100% as stated by Larmine and Dicks. H2 has a high gravimetric energy density and the highest specific energy content of conventional fuels. It also stores around 2.6 times more energy per unit of mass, has higher heating and calorific values when compared to gasoline. H2's lower volumetric density makes storage of H2 difficult for transport applications as it requires 4 times greater volume than gasoline engines to store the same amount of energy.

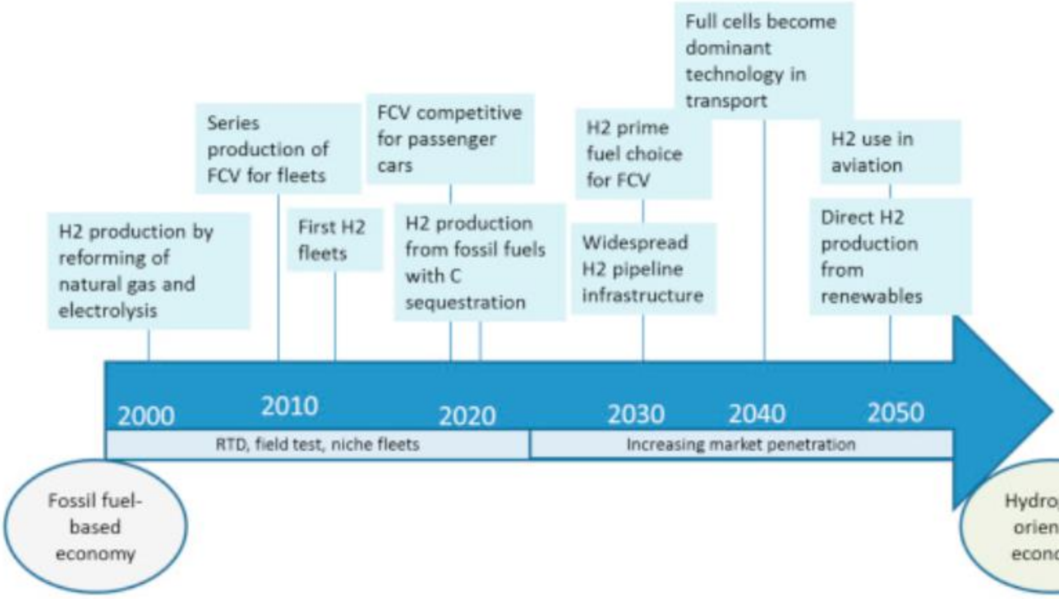


FIGURE 1-3 HYDROGEN ROAD MAP

There are several technologies available on the market that can be adapted to H2 as the fuel source, 3 examples of these technologies are H2 internal combustion engines (HICE), H2 fuel cells (HFC) and H2 fossil fuel hybrids. H2 fossil fuel hybrids may seem like an attractive alternative to purely diesel trains but they still emit GHGs and in order to reduce air pollution several cities are considering limiting the use of diesel engines and the times of day they can be used. For the purpose of this paper H2 fossil fuels hybrids will not be considered. H2 is not as energy dense as other fuels, therefore a lot H2 is required to do little work. The efficiency of an ICE is roughly one third, so when both are considered HICE is not the most efficient method. When H2 is combusted water is no longer the only emission, as well as water, NOx gas is emitted which is toxic. Therefore, HICEs are not a clean alternative to diesel which also emits NOx gas. The only remaining suitable technology that uses H2 as a fuel are fuel cell technologies, there are various types of fuel cells available but not all are suitable for transport applications. Fuel cells that make use of H2 as their fuel source are PEMs (Polymer Electrolyte Membranes), AFCs (Alkaline fuel cells), PAFC (Phosphoric Acid Fuel Cells), MCFCs (Molten Carbonate Fuel Cells) and SOFCs (Solid Oxide fuel cells).

AFCs were the first type of fuel cell technology to be widely used and were employed in the US space program to produce electrical energy and water onboard the space crafts. They are closely related to PEMFCs, but they use an alkaline membrane. They convert oxygen from the air and H2 into electricity and heat. It is chemically similar to a battery and its only by products are water and H2. Therefore, it has zero GHG emissions. The electrolyte, which is an important part of fuel cells, for AFCs is an alkaline liquid, potassium hydroxide. Hydroxyl ions of the potassium hydroxide move between the cathode and the anode creating a circuit and producing electricity to be extracted as be seen in Fig 1-4. AFCs are highly efficient with efficiencies of up to 60% when used in space applications and have a temperature range of $50 - 200^{\circ} C$.

However, AFCs are susceptible to poisoning from CO2, small amounts of CO2 in the air affect their durability and performance so are not ideal for use in transport systems like rail.

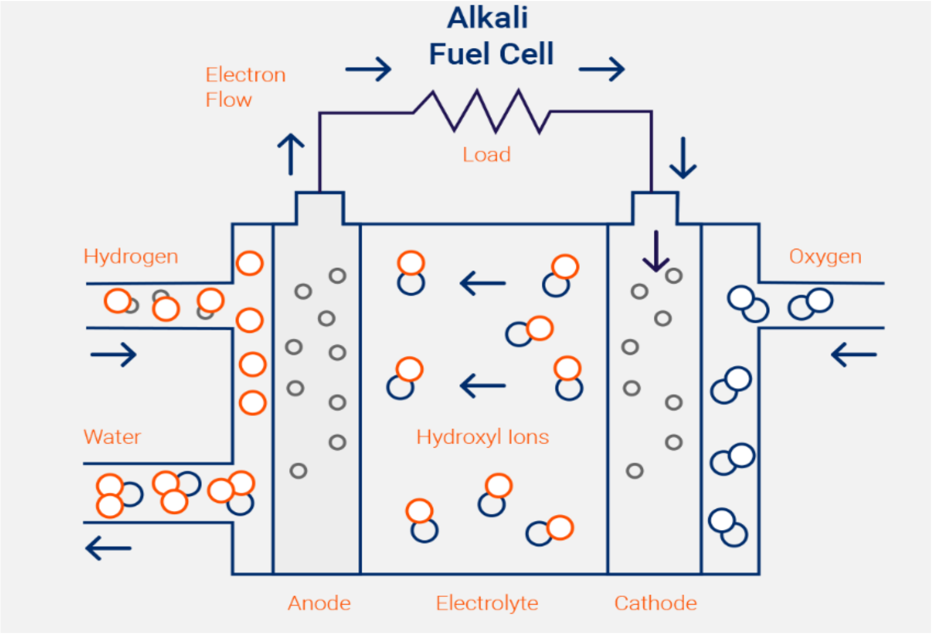


FIGURE 1-4 ALKALINE FUEL CELL

PAFCs were one of the first fuel cells to be adopted for commercial use and they are mostly used in stationary power applications but can also be used for large vehicles. The efficiencies of PAFCs are only marginally higher than that of ICEs with efficiencies ranging between 37% and 42%. They are also not as powerful as other fuel cells with the same weight and volume with operating temperatures as high as $220^{\circ}C$. PAFCs consist an anode and cathode that are themselves made of a platinum catalyst of carbon and silicon carbide structure using phosphoric acid as an electrolyte. Due to their low efficiencies and high operating temperature PAFCs are not considered for rail applications.

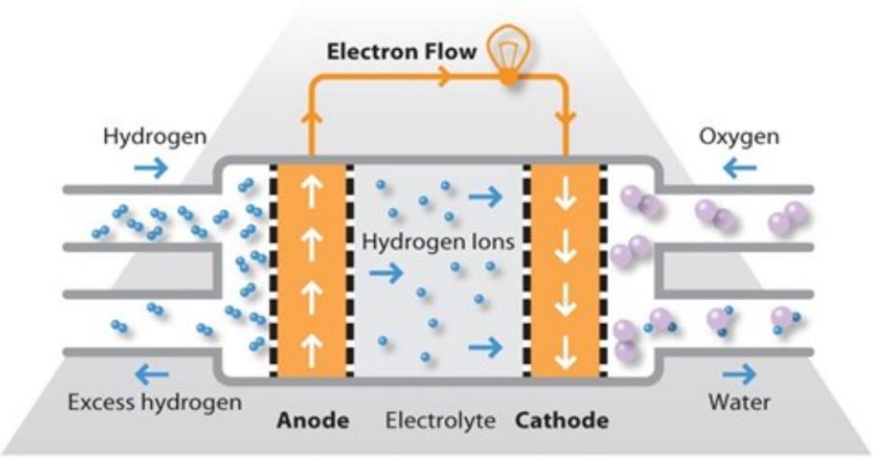


FIGURE 1-5 PHOSPHORIC ACID FUEL CELL

MCFCs electrolytes are molten carbonate salts that are suspended in a porous ceramic matrix, the salts that can be used are lithium carbonate, potassium carbonate and sodium carbonate. MCFCs have improved efficiencies when matched with a turbine reaching efficiencies of 65%. MCFCs are high temperature fuel cells that have an operating temperature of $650^{\circ} C$ and can convert fossil fuels to H2 in the fuel cell through the process of internal forming. However, the high temperatures at which they operate effect its durability and decrease the life of the cell life.

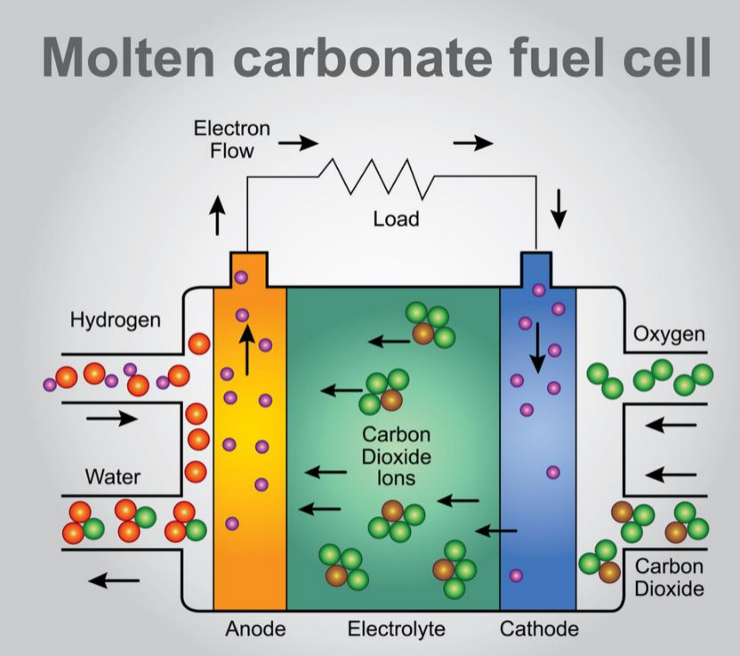


FIGURE 1-6 MOLTEN CARBONATE FUEL CELL

SOFCS have a solid ceramic electrolyte which is zirconium oxide stabilised with yttrium oxide and doesn’t have a liquid membrane. SOFCs are another type of fuel cell with high operating temperatures 50 – $100^{\circ} C$ and can reform fuels internally which means it can use a wide variety of fuels. A disadvantage of SOFCs is that they have slow start up speeds and require thermal shielding to retain their heat whilst protecting those around the fuel cell. It is also not suitable for transport applications and most commonly used for small- and large-scale stationary applications.

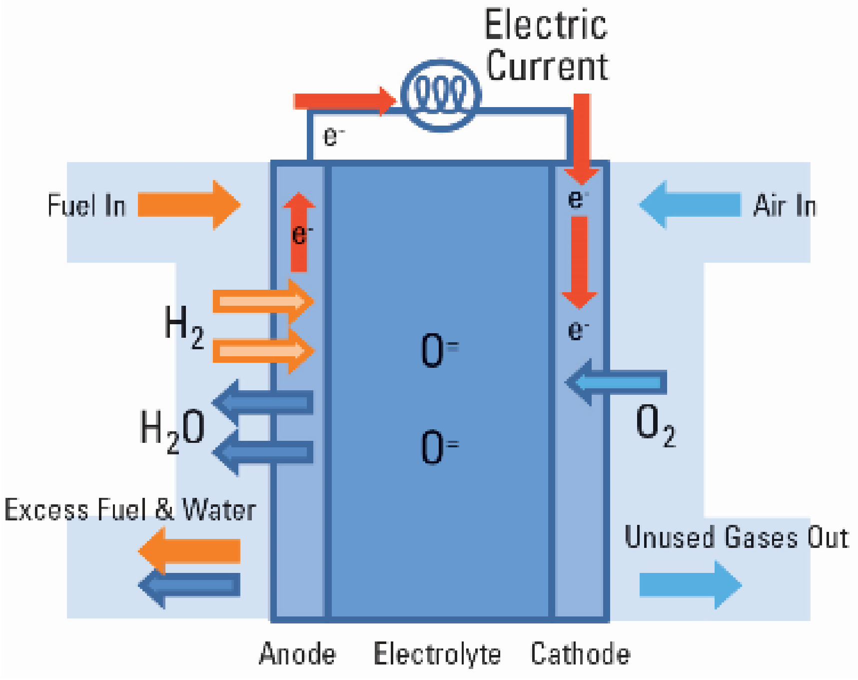


FIGURE 1-7 SOLID OXIDE FUEL CELL

PEMFC electrolytes are water based, using an acidic polymer membrane and platinum-based electrodes. They operate on pure H2 alone due to their electrodes which are precious metal based. The anode separates the H2 electrons from the protons on the surface of its platinum-based catalyst. The protons then move across the membrane to the cathode on the other side of the cell and the electrons travel to an external circuit which generates the electrical output. PEMFCs can deliver high power densities and are low weight and with small requirements when compared to other types of fuel cells. PEMFCs have low operating temperatures $30 - 100^{\circ}\,C$ which allows them to have to have quick start times and therefore better durability. They are mainly used for transport applications due to their good power to weight ratios making them particularly useful for use in trains. PEMFC are preferred for transport and are made up of many layers sandwiched together to provide the desired power output.

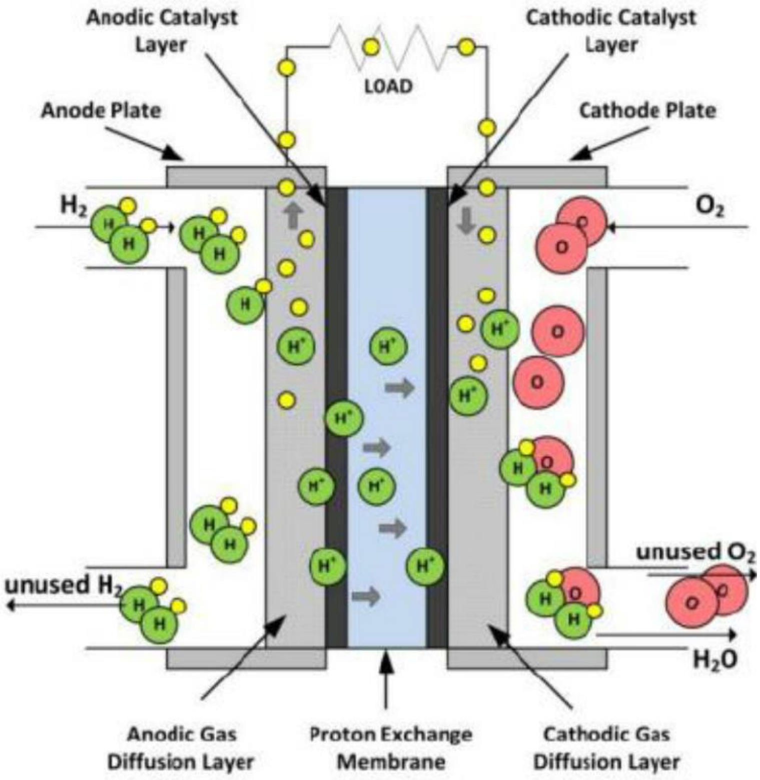
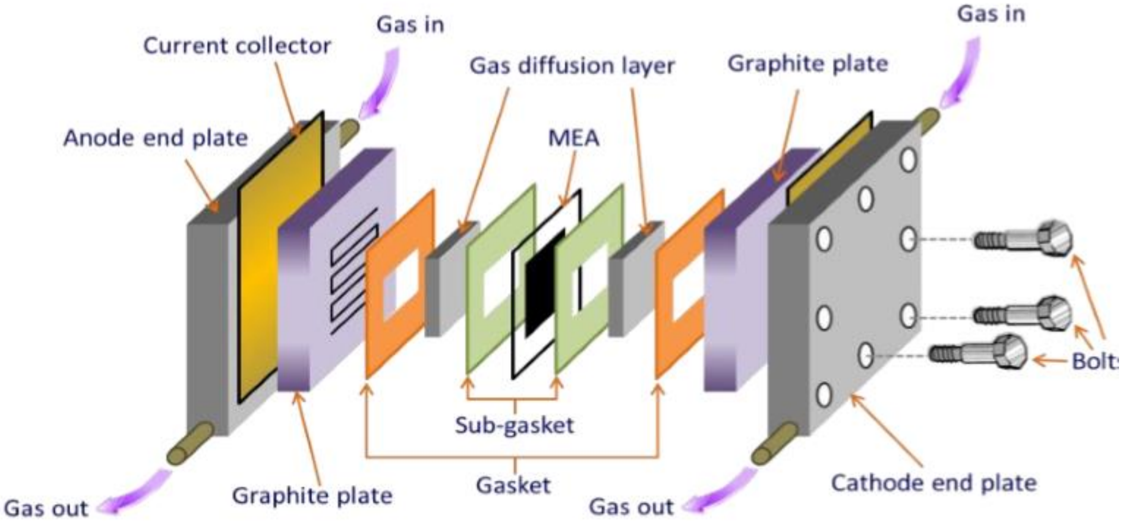


FIGURE 1-8 PROTON EXCHANGE MEMBRANE FUEL CELL



PEM fuel cell assembly

FIGURE 1-9 PEMFC ASSEMBLY

The storage of H2 for use in the PEM fuel cell is one of the most challenging areas due to the previously mentioned volumetric density of H2 which makes it difficult for use on board vehicles like trains. Hwang and Varma highlight the main challenges facing the use of compressed H2 storage for use on board vehicles as being able to achieve a good range of 300 or more miles in one tank and some of the other constraints it faces are safety, weight, volume, efficiency and cost. They also highlight that compressed has storage is not the only available method of H2 storage other methods are cryogenic and liquid H2 sorbents, metal hydrides and chemical hydrides which are seen as either reversible on board or regenerable off board. However, material-based methods like the ones mentioned have material-based values of efficiency that have not been noted and have yet to be used in vehicles. No technology as of yet meets the current targets set by the US department of energy but despite this the most commonly used method is the use of compressed H2 storage. The most important factor for the compressed H2 storage is the material the tank is made of. Some of the requirements the storage tank should ideally meet are the material should be lightweight, cheap and strong. Another requirement of the material is that it must have a high thermal conductivity so that it can cope with the exothermic heat during the filling of the tank. A promising material based on these requirements that can be used for the tank material is Carbon Fibre Reinforced Plastic (CFRP) as it is a lightweight and durable material but despite this it does not have a high thermal conductivity and is expensive especially the carbon fibre composite.

Commercial H2 trains have already been introduced into service in other countries across Europe and in the German state of Lower Saxony they have been adopted. The two Coradia iLint trains are the first H2 fuel cell passenger trains and were designed to work on a non-electrified route which will replace the existing diesel trains on a 62-mile route with a refuelling station placed on the route. A new hydrogen train is being designed for the UK market by Alstrom and Eversholt Rail which will be named the breeze train. The new hydrogen train could potentially be introduced to the UK by 2022. The Breeze train will be based around an adapted and retrofitted already exiting class 321 electric train and is currently undergoing testing. The class 321 is considered one of the most reliable trains in the UK’s rolling stock fleet and retrofitted to create a zero-emission clean train. Despite the introduction of new technologies that aid the use of H2 in trains and the introduction and testing of H2 trains in several countries there is still very little information available showing the differences and benefits of H2 as a primary fuel source over diesel for rail transport. Even though some of the main driving factors for H2 trains are decarbonisation there is little information showing the clear differences between existing diesel rolling stock and the specifications of H2 trains being introduced and developed. This may be due to the some of this data regarding this could be commercially sensitive information and that it is too early to make statements on this as it is still a relatively new technology. This paper aims to address this issue and create a model that can show emissions, diesel and H2 fuel consumption, their costs, energy consumption, range and the number of refuelling stations that would be required over a given distance. This will be done by creating a mathematical model which makes use of the appropriate equations, relationships and existing technical information such as some of the examples already found from analysing the literature.

2 Chapter 2: Development of Tool

The creation of a tool to equate a diesel train with varying power outputs to a hypothetical H2 train will be detailed and explained in this chapter, the tool will provide several outputs such as volume of H2 that can be stored in the same space taken up by the diesel engine with the space of the fuel cell also taken into account, the range of the tank in miles, number of times it will need refuelled, the cost of both fuels compared and the energy requirements of both fuels. The cost comparison of both the fuels diesel and H2 will be produced by the tool for the same journey and the emissions produced for a given journey will also be an output of the tool to highlight the emission reductions from the use of H2. The tool will be created in excel with several inputs being required to allow the calculations to produce the outputs previously stated. The methodology for the tool's algorithm will be presented through the use of a flowchart which a pictorial method of representing the sequences taking place within the algorithm. Before the tool can be created and implemented, a flowchart must be made clearly highlighting all the inputs, decisions that will be made, processes and outputs. The flowchart is created to help split up all calculations and processes needed and show how they are all connected. The tool will consist of 3 inputs which will be the power output of the train in kw, the speed in miles per hour and the distance in miles. The H2 train will use a PEMFC as identified previously and depending on the power output of the train more than one may be required.

The tool will also make use of the volume requirements of a passenger and freight trains engines as well the power requirements for these two types of trains. Two of the most commonly used types of passenger and freight diesel trains currently in the UK rolling stock are the Class 158 passenger train and Class 66 freight train. Class 158 is a regional passenger train usually made up of 2 or 3 carriages and has a max speed of 90 mph and engine dimensions of 2.055m in length, width of 0.99m and height of 1.535m and also an engine weight of 1410kg. The Class 158 is predominantly used for long distance rural routes and many short distance commuter routes. The Class 66 is a diesel electric freight locomotive and is one of the most widely used freight trains in the UK and across Europe with a max speed of 75 mph and its engine dimensions are 4.597m in length, width of 1.75m and a height of 2.75m with an engine weight of 14600kg. The dimensions of these two types of trains engines will be important in the tool as the fuel cell and storage tank will be required to fit within this volume as the H2 train should be able to retrofitted around existing rolling stock or not require excessive amounts of storage making it more costly. Two additional engine volumes will be added to the train to accommodate high-speed passenger trains. The H2 train will run on a PEMFC with the power output to match that of the passenger or freight trains engine output.

TABLE 2-1 CLASS 158 SPECIFICATIONS

Type	Passenger
Class	158
Length	22.57m
Width	2.7m
Height	3.805m
Volume of Carriage	$231.9m^3$
No. of carriages	2 or 3
Weight	Two car 77 tonnes. Three car 115.5 tonnes
Max Speed	90 mph
Engine Output	Cummins: 350 bhp 250 kw
Engine Dimensions	Length 2.055m, Width 0.99m, Height 1.535m
Engine Volume	$3.12m^3$
Engine Weight	1410kg
Fuel Consumption	65 Litres/Hour
Fuel Capacity	1387 L

FIGURE 2-1 CLASS 158

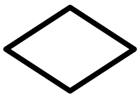
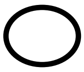
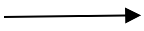
TABLE 2-2 CLASS 66 SPECIFICATIONS

Type	Freight
Class	66
Length	21.4m
Width	2.65m
Height	3.9m
Volume	221.2m^3
No. of carriages	1
Weight	142 tonnes
Max Speed	75 mph
Engine Output	3300 bhp 2460 kw
Engine Dimensions	Length 4.597m, Width 1.75m, Height 2.75m
Engine Volume	29.22m^3
Engine Weight	14600Kg
Fuel Consumption	318.5 Litres/Hour
Fuel Capacity	6400 L

FIGURE 2-2 CLASS 66

2.1 Flowchart

A flowchart is a pictorial representation of a process showing the sequence of events with different shapes having different meanings and instructions. The symbols used are a standard set of symbols which represent instructions. The flowchart method will ease the breakdown of tasks and identify how they are connected. To distinguish between an output and input as they both have the same symbol outputs will be highlighted in red and inputs highlighted in blue.

	Start/Stop symbol. Put at the beginning or at the end of a flowchart.
	Process symbol. An instruction or command.
	Decision symbol. A yes or no decision.
	Input/output symbol. Input data into the tool. Output produced by the tool.
	Connector. A move from one point in a sequence to another.
	Arrow. Direction of flow and connects the symbols.

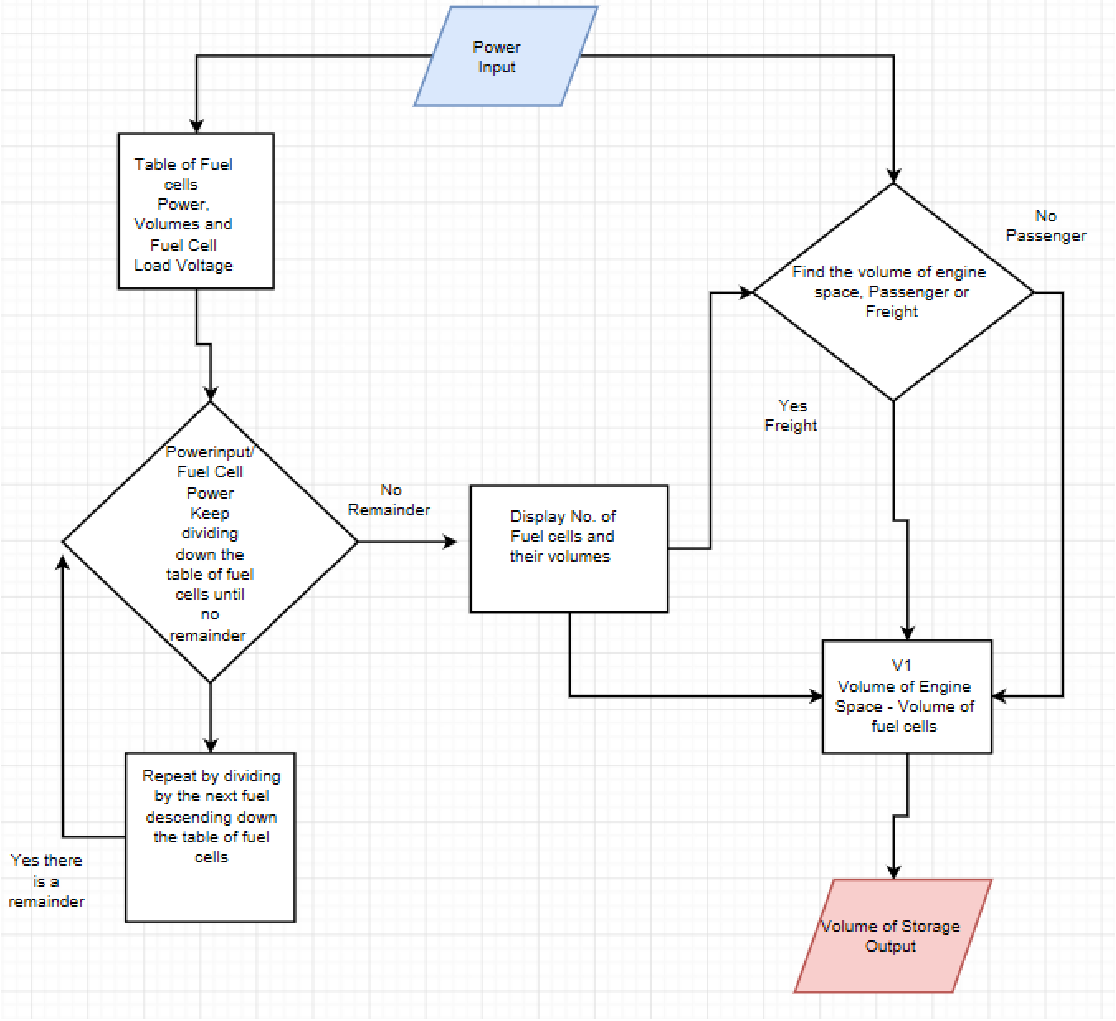


FIGURE 2-3 FLOWCHART PART 1

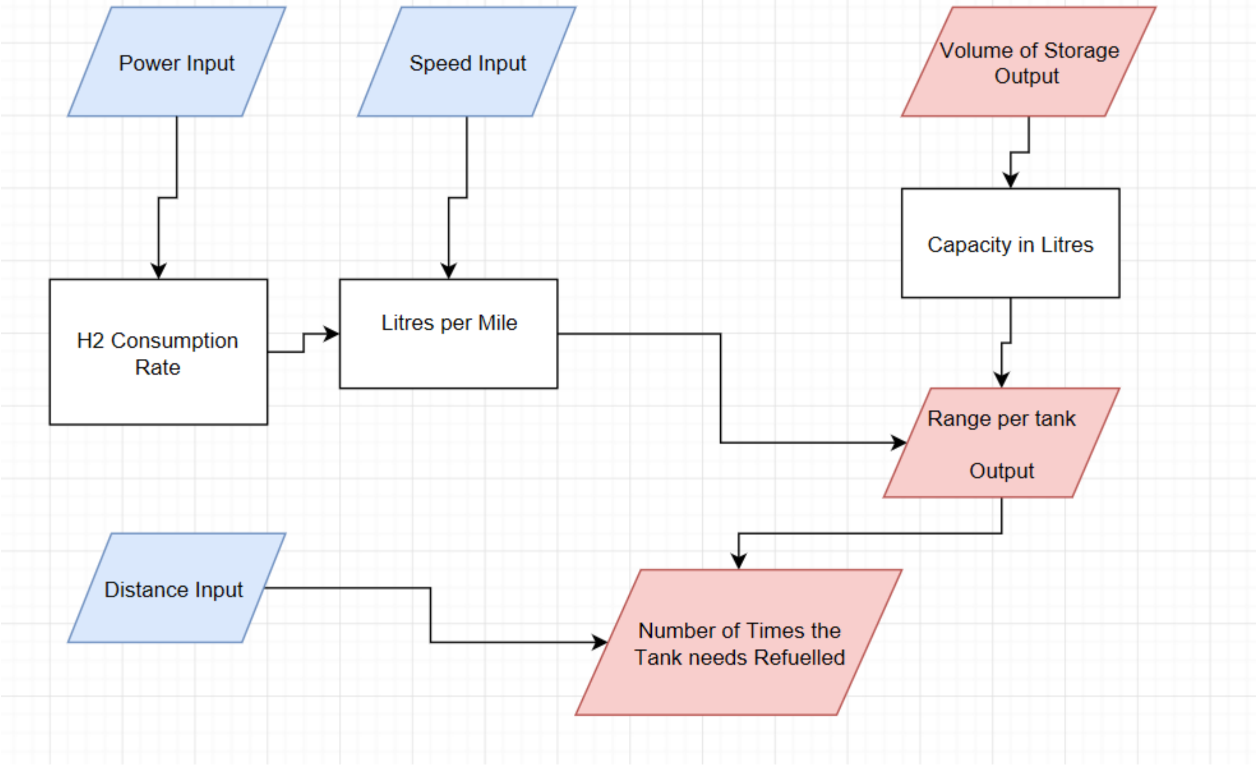


FIGURE 2-4 FLOWCHART PART 2

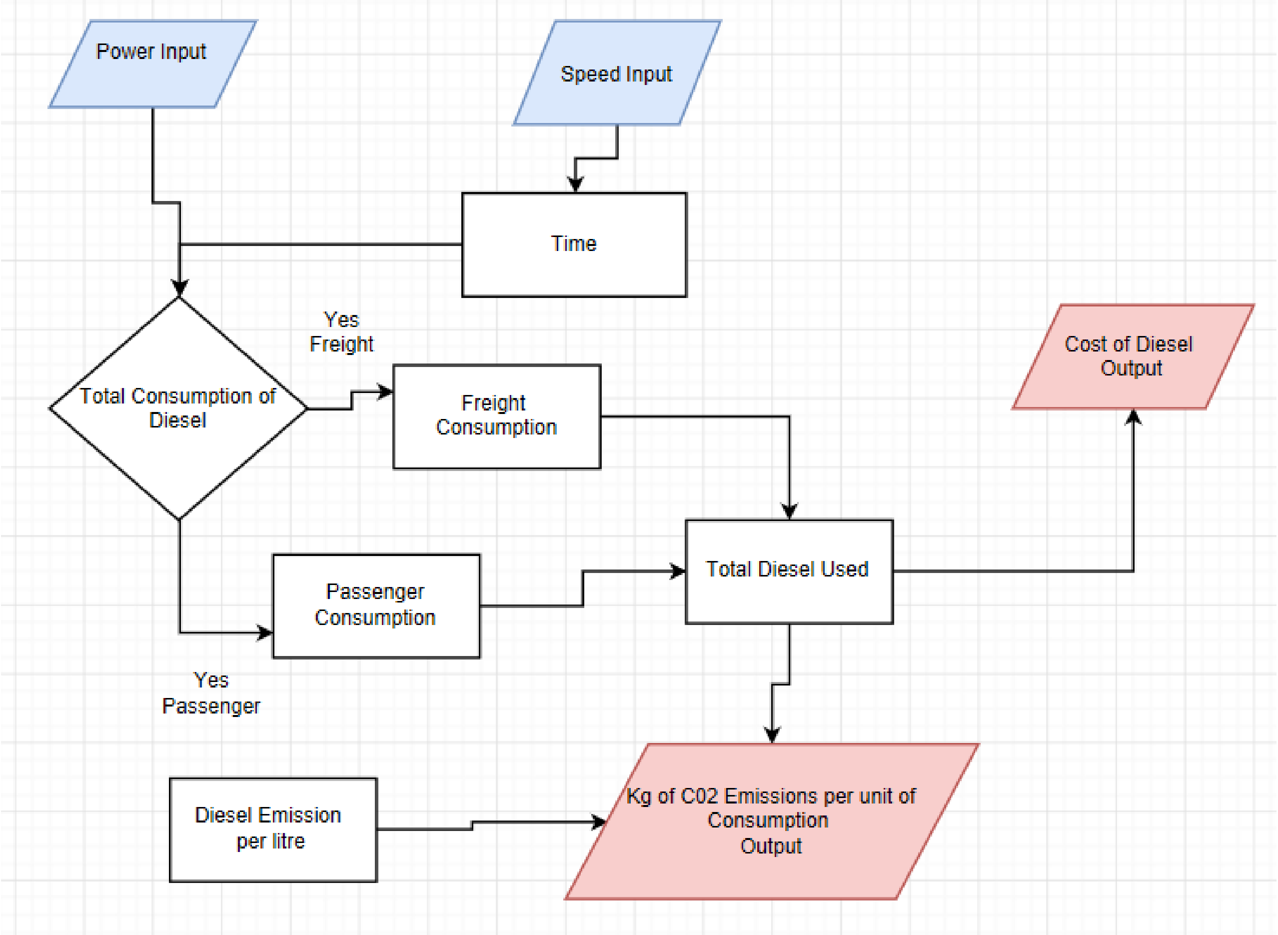


FIGURE 2-5 FLOWCHART PART 3

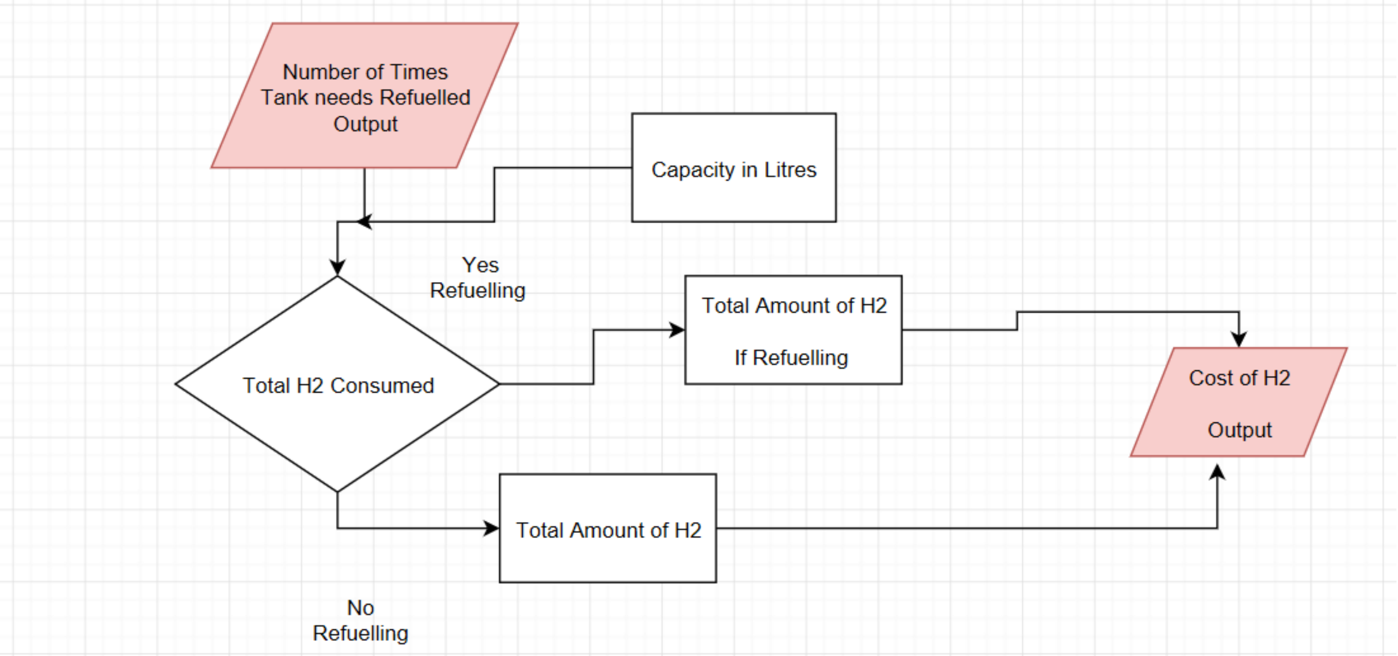


FIGURE 2-6 FLOWCHART PART 4

2.2 Flowchart Breakdown

For each of the inputs there are several processes and calculations being carried out in the background. The 3 inputs will be power, speed and distance. To simplify the flowchart and how it works it will be split into 4 parts where each step will be broken down and explained clearly to show how the tool will operate.

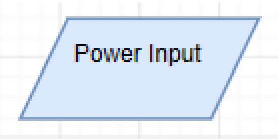


FIGURE 2-7 POWER INPUT

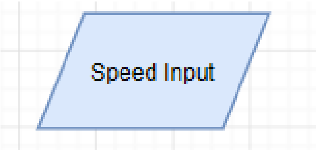


FIGURE 2-8 SPEED INPUT

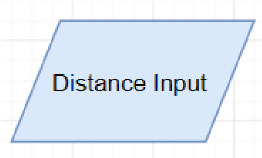


FIGURE 2-9 DISTANCE INPUT

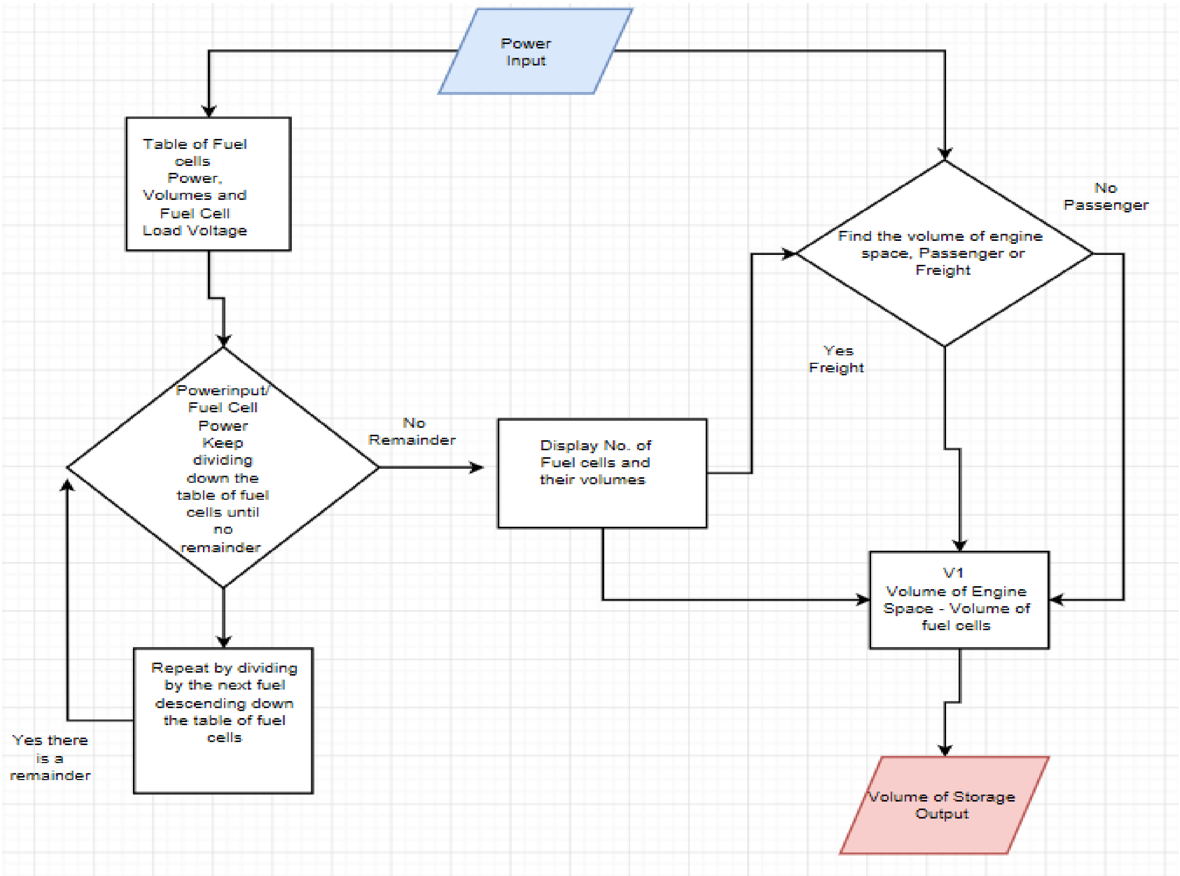


FIGURE 2-10 FLOWCHART PART 1 BREAKDOWN

All of the inputs lead to one or more of the outputs and depend upon certain equations and therefore certain variables. The tool will allow the user to find important information about a H2 to train which will be the volume of the storage tank in m^3, range of the tank in miles, number of times the tank will be refuelled to travel the distance in miles, cost of diesel and H2 fuels and energy requirements of fuels and also the emission produced by an equivalent diesel train. The inputs will all lead to processes and decisions within the tool. The power input will lead to a process within the tool of determining the type of fuel cells and the decision of how many of them are required for the given power output of the train as well their volumes and fuel cell load voltage.

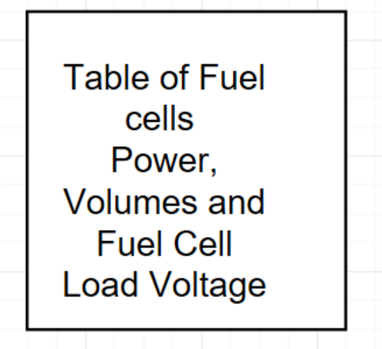


FIGURE 2-11 TABLE OF FUEL CELLS

A list is stored in the tool of all fuel cells and their power outputs as well as the fuel cells load voltage and the volume of each of the fuel cells in m^3. An assumption is made that all fuel cells will have identical fuel cell load voltages. The power input will allow the tool to determine the volume of the fuel cell and the volume left in terms of engine space taken up by the equivalent diesel train engine.

TABLE 2-3 PEMFC SPECIFICATIONS

Power of Fuel Cells kw	Volume m^3	Fuel Cell Load Voltage V
250	1.52	0.68
180	1.2	0.68
100	0.621	0.68
90	0.59	0.68
10	0.053	0.68
5	0.048	0.68
1	$1.8\text{x}10^{-3}$	0.68

The power input by the user will determine the number of fuel cells used. This is calculated by the power input being divided by the highest rated power output of the fuel cell which will be 250 kw. If there is a remainder then the tool will able to make decisions and calculate what other fuel cells are needed and how many there will be. To accurately calculate the number of fuel cells needed the round down function will be used within excel. The answer of the first calculation will be rounded down to nearest integer. Within the tool the formula to carry out this instruction will be =Rounddown(F2,0). To display the remainder in the correct terms the mod function, =mod(B2,C2), displaying the remainder.

Number of 250 kw Fuel cells = $\frac{Power\ Input}{250}$

Number of 250 Fuel Cells rounded down to the nearest integer = Roundown(Number of 250 Kw fuel cells,0)

Remainder of $\frac{Power\ Input}{250}$ =Mod(Power input,250)

If there is a remainder after the power output is divided by the highest rated fuel cell, then the tool will be required to make a decision which will allow it to select the following fuel cell in Table 2-3. The decision in the tool will be in the form of an IF statement and if the answer to power input divided by the fuel cell power does not equal an integer then the tool will divide the remainder by the following fuel cell power but if the answer of the logical test is an integer then it will display the answer of the division. The IF statement carried out in the function will be =IF(F2<>INT(F2),(F4/C4),0). This process will be repeated for all the fuel cells and will determine how many of them are needed based on the power input by the user. So even if the power input by the user is perfectly divisible by the power output of the first fuel cell the tool will carry out the procedure for all the other fuel cell ratings and display that the answer would be zero. The IF statement and the tool is designed to always check all of the power ratings of the fuel cells.

Number of Fuel cells =IF($\frac{Power\ Input}{250}$ <>INT($\frac{Power\ Input}{250}$), $\frac{Power\ Input}{180}$,0)

This process and the above calculations will repeat for all the fuel cells in Table 2-3.

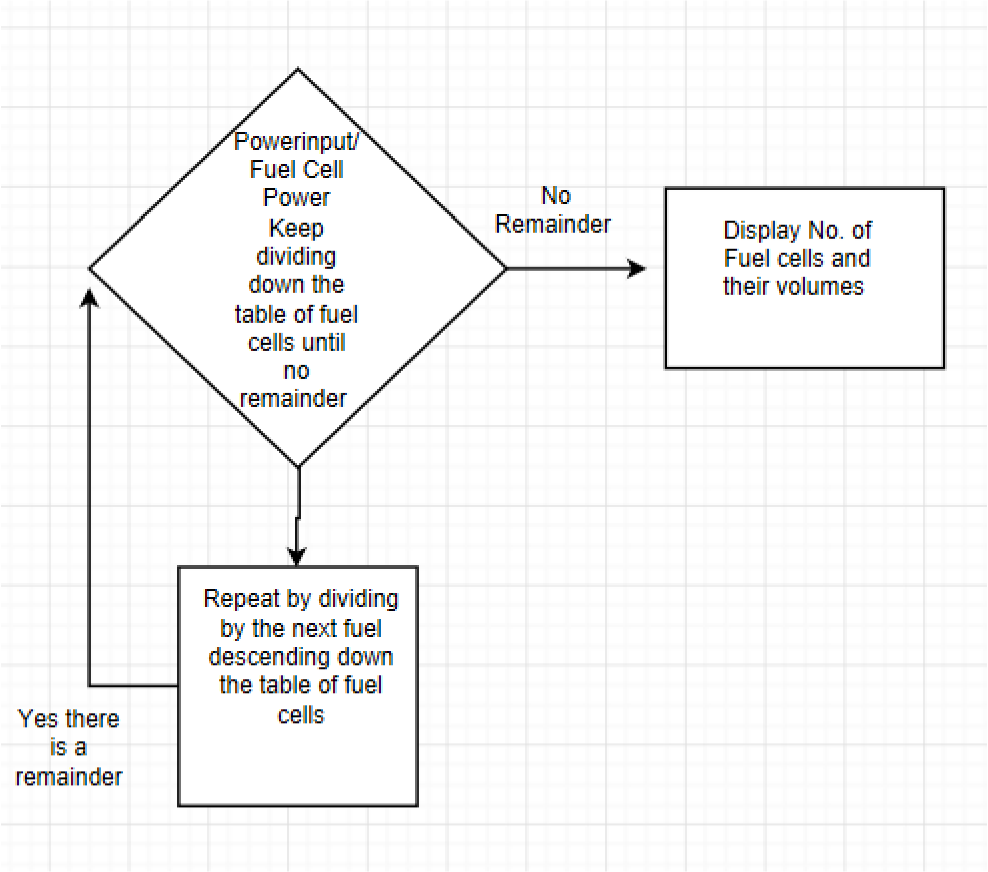


FIGURE 2-12 NO. OF FUEL CELLS AND VOLUMES

The volume of storage will also be dependent on the power input by the user and the calculations above. The tool will contain another table with the power output of the fuel cells, number of fuel cells and volume each fuel cell takes up. The answers from the previous calculation will fill in the number of fuel cells column and the volumes column will have the volume of one fuel cell for each type multiplied by the number of cells previously calculated. The total volume taken up by the fuel cells will be the sum of the volume's column.

TABLE 2-4 PEMFC REQUIRED

Power Output of Fuel Cells Kw	Number of Fuel Cells Calculated	Volume m^3
250	X	=x*1.52
180	X	=x*1.2
100	X	=x*0.621
90	X	=x*0.59
10	X	=x*0.053
5	X	=x*0.048
1	X	=x*1.8x10^{-3}

Volume of Fuel cells = Sum(Volume column)

Boyle's law, PV = k so P_1V_1= P_2V_2, with the assumption of constant temperature will be adopted for the volume of storage of the H2 tank calculation. The equation will be rearranged for the volume of storage $V_2 = \frac{P_1V_1}{P_2}$. P1 will be taken as atmospheric pressure P_1 = 101.325 Kpa, P_2 will be tested with a high pressure and low pressure to show the comparison, V_1 will be equal to volume of engine space minus volume of fuel cells. Due to the engine space of a passenger, high-speed and freight train being different as they have different power outputs a decision must be made within the tool and the amount of H2 will be dependent on the space that is left after the volume of the fuel cells has been subtracted. The volume of the space is the volume of the engine and therefore is dependent on the power input. An IF statement is created to establish the volume of engine space whether it is the volume of a freight or passenger train engine and within this there will be two additional engine space's available that are both high-speed train engines. These are both passenger trains and will be considered that in the tool. This will add an extra two conditions to the if statement to accommodate the high-speed passenger train engines space. The IF statement will state that if the power input is greater than 1500 then the greater engine volume the freight engine will be selected and if not then the passenger engine volume will be displayed, =IF(Power Input>=2460,Freight,IF(Power Input>=1340, High Power High Speed Passenger Volume, IF(Power Input >=560, Low Power High Speed Volume, Passenger Volume)))). From the IF statement V_1 is found by taking the answer from the conditional statement answer and subtracting the volume taken up by the fuel cells. This allows for the calculation of the first output V_2 the volume of storage tank in m^3.

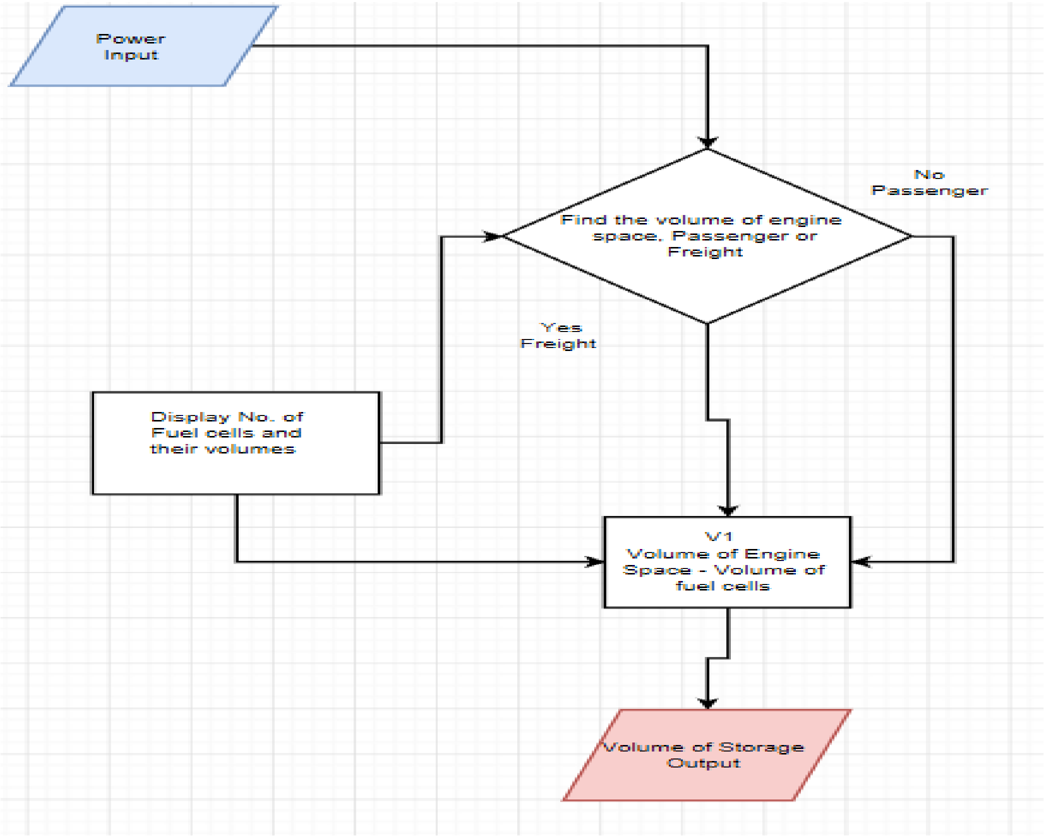


FIGURE 2-13 VOLUME OF STORAGE

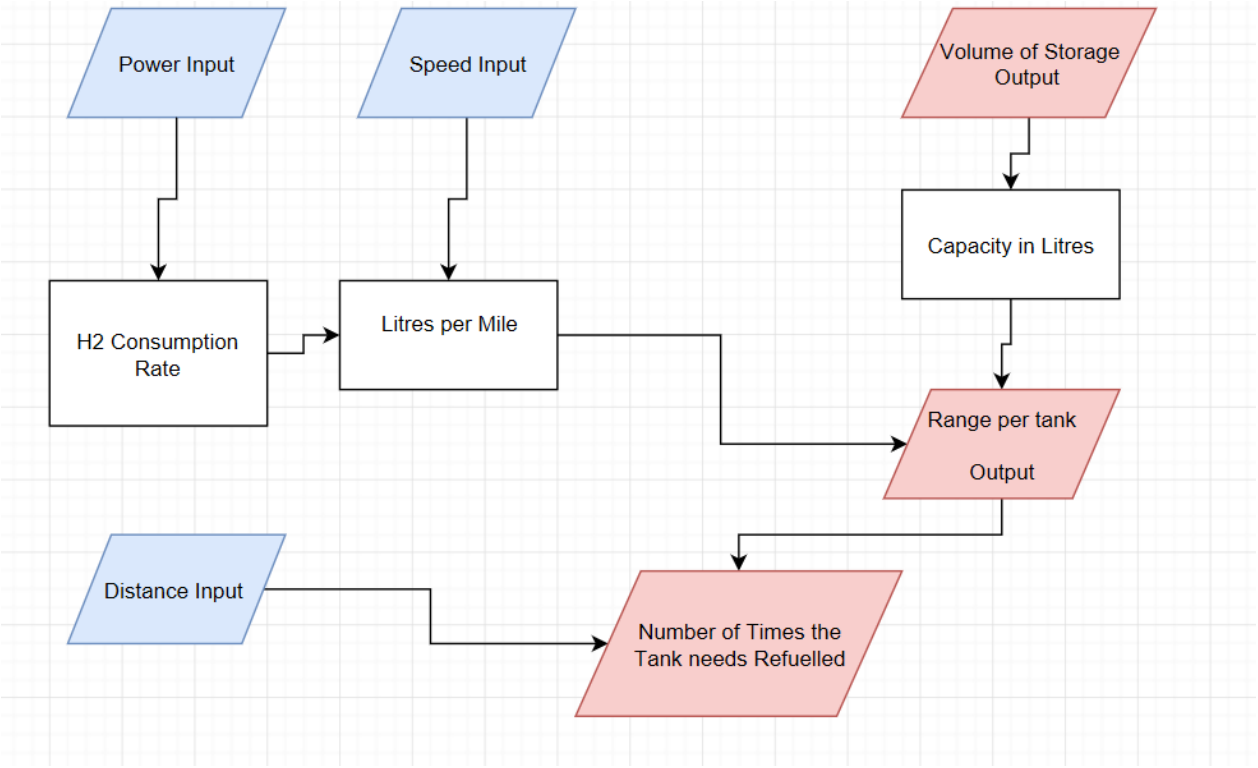
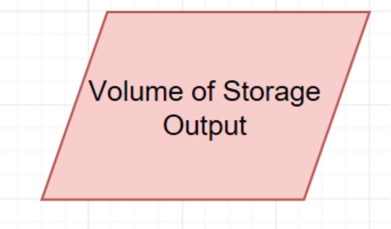


FIGURE 2-14 FLOWCHART PART 2 BREAKDOWN

The volume of the storage tank will be converted from m^3 to litres to give the capacity of the tank and allow for future calculations to be carried out within the tool.



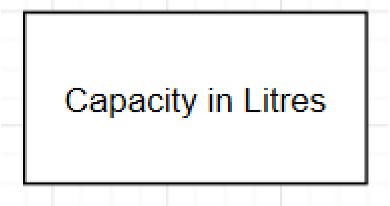


FIGURE 2-15 VOLUME OF STORAGE OUTPUT

FIGURE 2-16 CAPACITY IN LITRES

The power input by the user also allows for the calculation of the H2 consumption rate and the equation identified for H2 usage = $1.05\text{x}10^{-8}\text{x}\,\frac{Pe}{Vc}\,\text{kg}s^{-1}$ by Larmine and Dicks will be used within the tool. To calculate the H2 consumption rate of the fuel cells used the fuel cell load voltage and the power input are needed for the equation H2 usage = $1.05\text{x}10^{-8}\text{x}\,\frac{Pe}{Vc}\,\text{kg}s^{-1}$. For the solution of this equation to be implemented it must be converted from kgs^{-1} into litres/hour. This is done by dividing the answer by the density of H2 gas 0.084kg/m^3 which gives the consumption rate in m^3/kg. The final steps of the conversion are to multiply this answer by 1000 to give litres/second then multiply by 3600 to give the desired H2 consumption rate in litres/hour of the fuel cells.

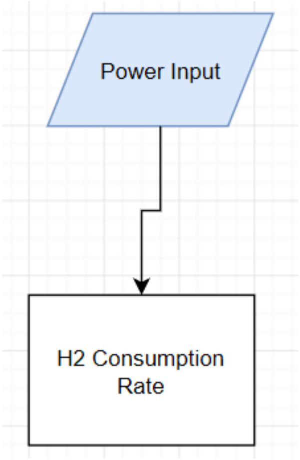


FIGURE 2-17 H2 CONSUMPTION RATE

An important feature of the tool will be its ability to determine how far the H2 train will be able to travel per tank of H2 in miles. In order for the tool to be able to find the distance travelled per tank of H2 output the speed input is required. The previously established H2 consumption rate alongside the speed input which aids the calculation of the tanks range in miles. Before the range is able to be found in the tool litres per mile of the tank must be found first. This is found by dividing the H2 consumption rate by the speed input.

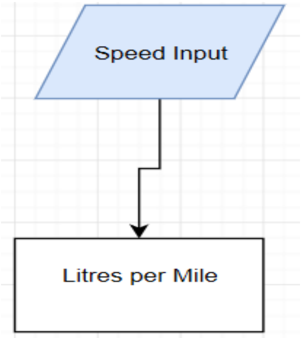


FIGURE 2-18 LITRES/MILE

The litres/mile of the H2 train is then used by taking the capacity in litres and dividing it by the litres/mile solution to give the output range per tank in miles. Although this output is greatly dependent on the speed input by the user it is also connected to and dependent on the power input and the calculations that follow this input.

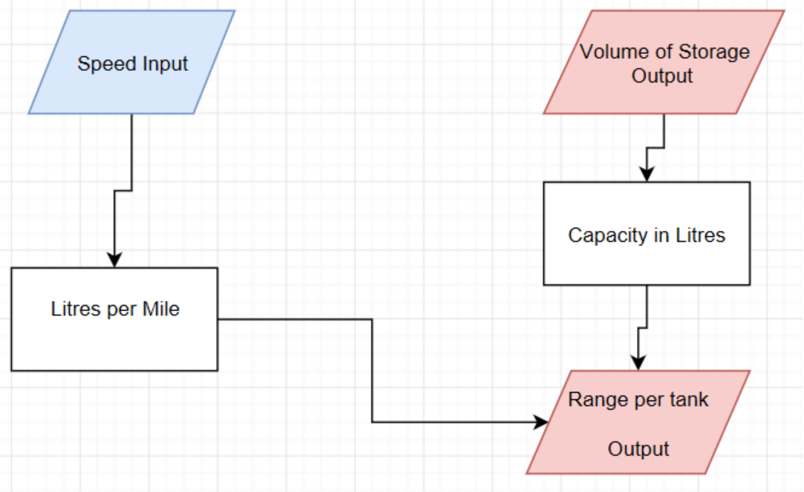


FIGURE 2-19 RANGE PER TANK OUTPUT

Another important output that the tool will produce is the number of times the fuel tank may need to be refuelled over a given distance. To know this the tool requires an additional input from the user which will be the desired distance in miles the train should be able to travel. Due to volume restrictions of the both passenger and freight trains engine space, the volume of H2 storage will be limited meaning that if the range is too far the tank will need to be refuelled allowing the user to know how many fuelling stations the train would require and how far it can go between refuelling's. To find the output number of refuelling's the H2 train requires the distance input from the user which will be divided by the range of the tank to produce this output.

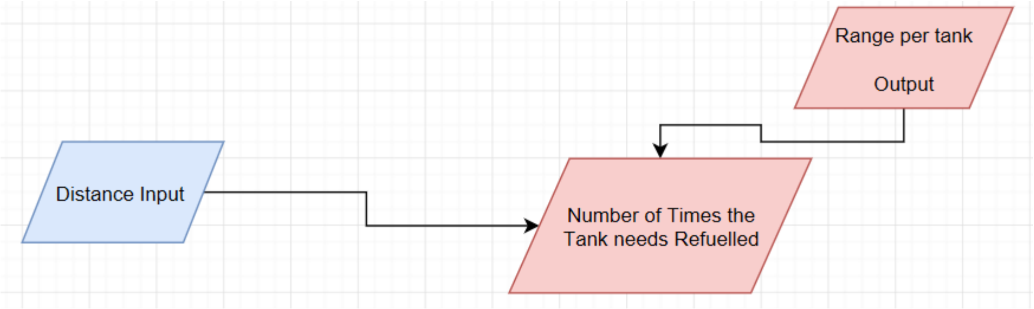


FIGURE 2-20 NUMBER OF TIMES TANK NEEDS REFUELLED OUTPUT

An additional output will be produced by the tool to show the potential for CO2 emission savings for the same journey on both a passenger, high-speed and freight trains. More outputs regarding the cost comparisons for a freight, high-speed and passenger train journeys will be produced using diesel compared to the H2 trains and its cost of using H2. The rail industry measures CO2 emissions per litre per person km and this is roughly 0.06 per person per km but this does not provide a great of information about the type of train, fuel or engine being used. However, the fuel capacity and diesel consumption of both the Class 158 and Class 66 alongside the standard emissions per litre of diesel can. The per person km is not accurate for freight CO2 emissions as it carries goods not people. In order to have CO2 emissions of both trains in the same units to show a clear comparison for the same journey the kg of CO2 unit of consumption of diesel will be utilized which is 2.68 per litre. The information regarding the two types of trains fuel capacity will be added in the tool to allow the algorithm to determine the CO2 emissions that would be produced by the equivalent diesel passenger or freight train which is dependent on the power output. The H2 train produces no CO2 emissions at point of use so the emissions from the H2 train will be zero. To produce the equivalent CO2 emissions of a passenger and freight train the fuel consumption of both will be implemented into the tool, which is for a passenger train is 65 litres/hour and for a freight train 318.5 litres/hour. To fully estimate each type of trains emissions the time the journey would take must be found within the tool which is equal Time = $\frac{Distance\ Input}{Speed\ Input}$. From this the fuel consumption in litres/hour will be multiplied by the solution to the above equation which gives the tool amount of diesel consumed for a given journey and then with the CO2 emissions of diesel per kg will be used. The total amount of diesel consumed by the train passenger or freight train is multiplied by the 2.68 kg of CO2 emissions per litre of diesel fuel. This provides the user with two outputs CO2 emissions of a passenger train or freight train, meaning the H2 trains journey will show how the amount of CO2 emissions that would have been emitted from diesel alternatives and how much CO2 emissions would be reduced.

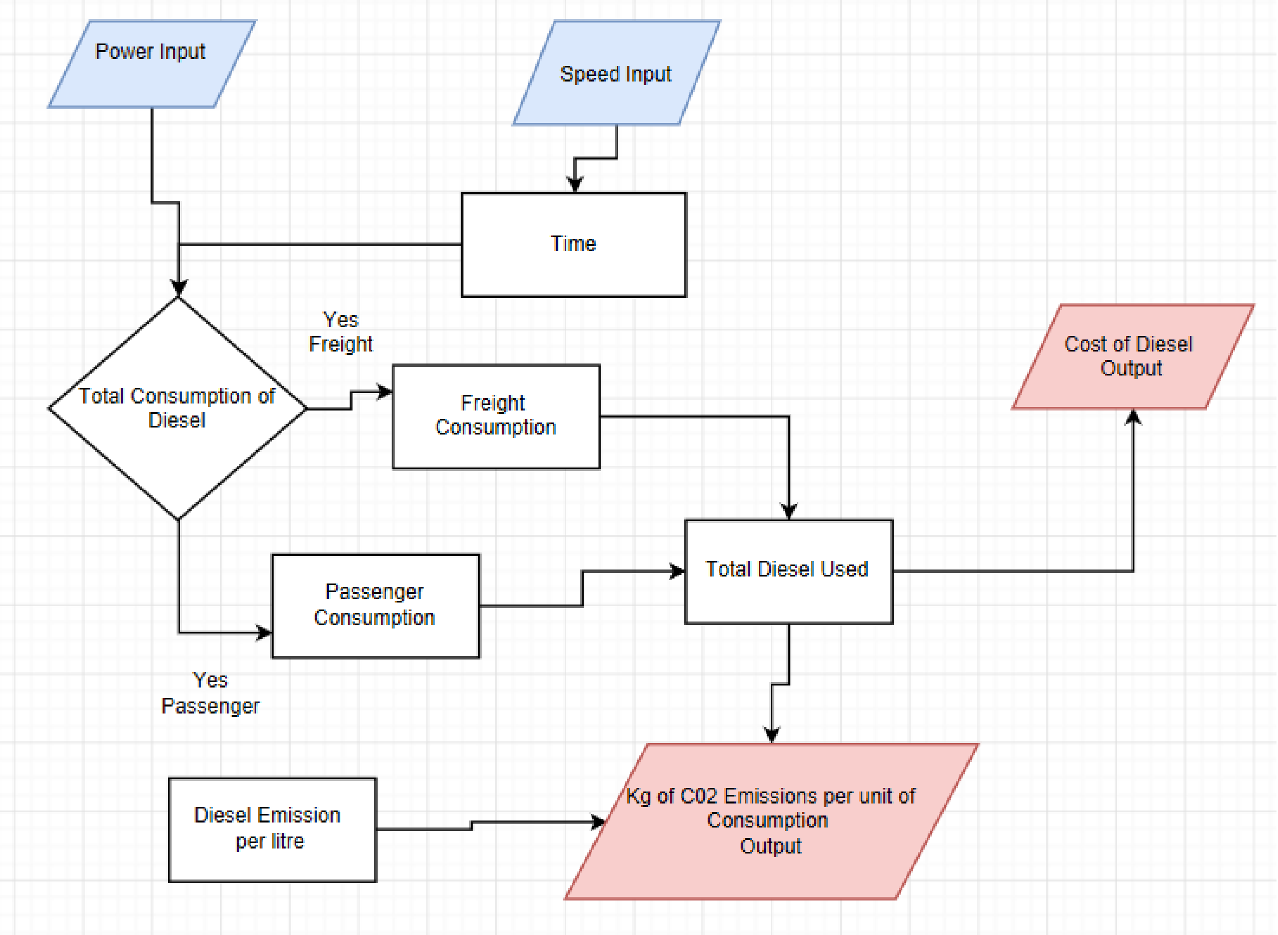


FIGURE 2-21 FLOWCHART PART 3 BREAKDOWN

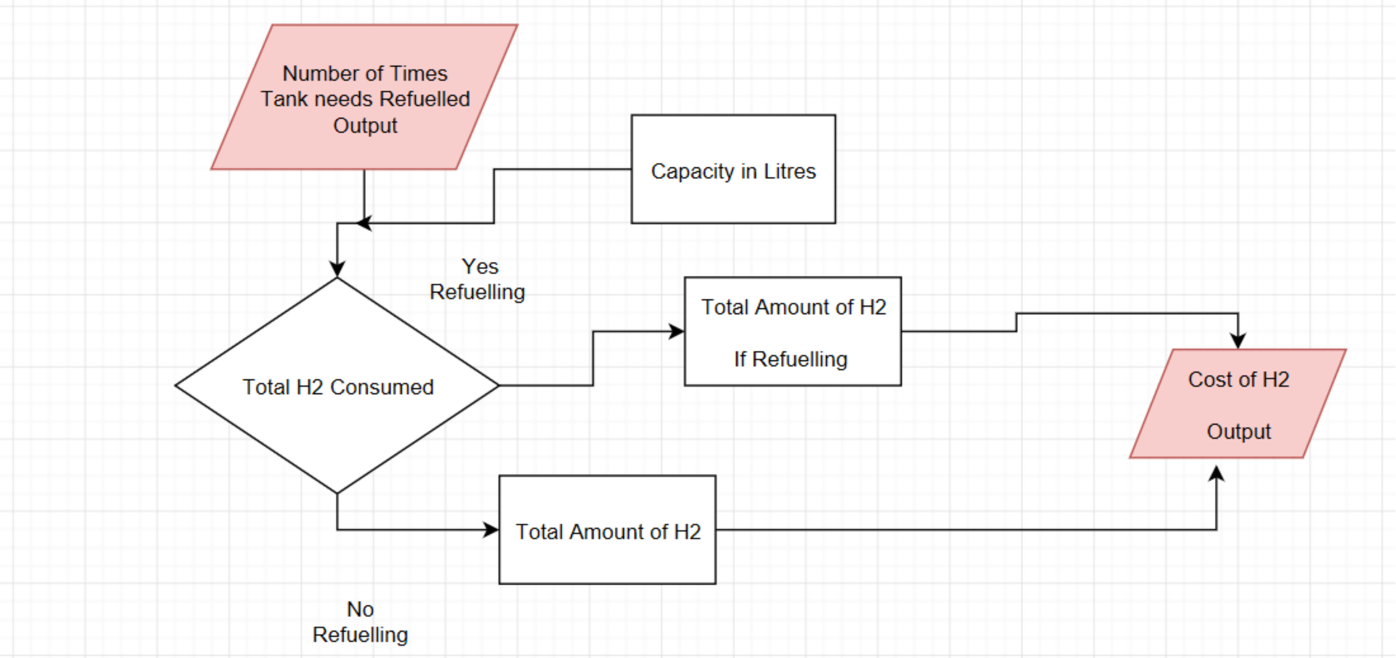


FIGURE 2-22 FLOWCHART PART 4 BREAKDOWN

Freight Diesel Consumption = 318.5 litres/hour

Passenger Diesel Consumption = 65 litres/hour

Diesel CO2 Emissions Kg of CO2 per unit of Consumption = 2.68 per litre

Time = = $\frac{Distance\ Input}{Speed\ Input}$

Freight Diesel Consumed in litres = 318.5 litres/hour x Time

Passenger Diesel Consumed in litres = 65 litres/hour x Time

Kg of CO2 Emissions per Unit of Consumption Output = Total Diesel Used x Diesel Emissions per Litre

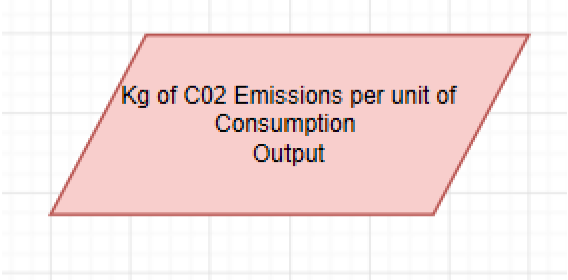


FIGURE 2-23 DIESEL TRAIN EMISSIONS

The final two outputs produced by the tool will be the price of the fuels, H2 and diesel for the given journey. The price of both H2 and diesel per litres is found to be in the UK £2.69 per litre of H2 and £1.32 per litre of diesel. For the tool to work out the price of each fuels over a given route the capacity in litres for both H2 and diesel are required as well as two separate IF statements for both are needed. The IF statement for the cost of H2 is dependent on two variables within the tool that have been previously calculated, the number of times the tank needs refuelled and the capacity of the tank in litres. The logical test of the IF statement will be that if the cell containing the number of times the tank needs refuelled is greater than one then the product of capacity is multiplied by the price of H2 per litre and should be multiped by the number of times the tank needs refuelled. If this statement isn’t true and the number of times the tank needs refuelled is less than or equal to 1 then the statement will display the answer to capacity multiplied by the price of H2 per litre. The IF statement will be =IF(F25>1,((E22*B19)*F25),B19*E22).

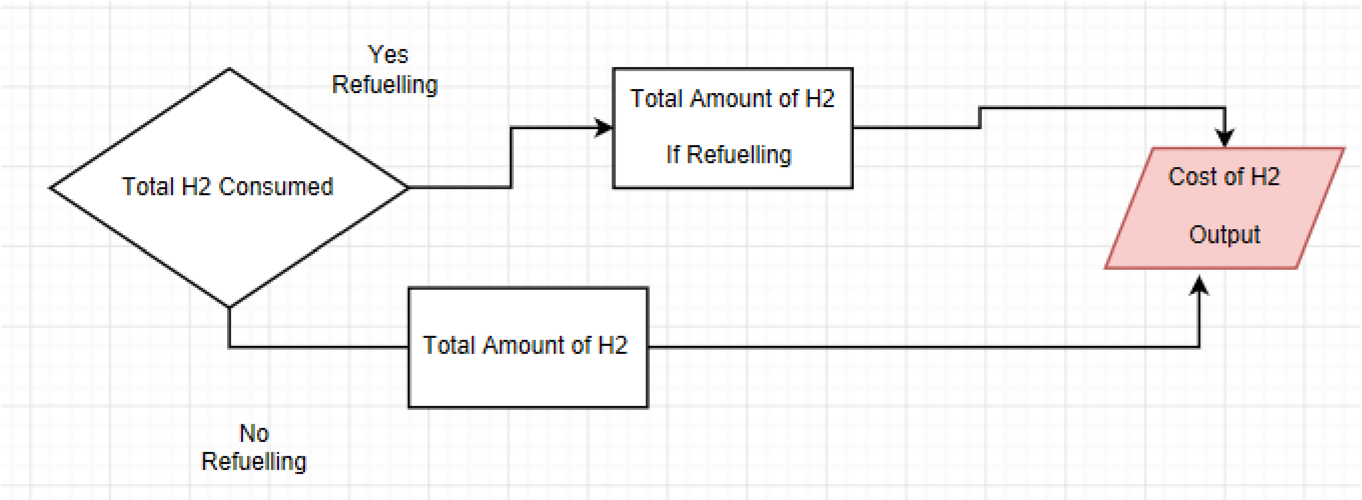


FIGURE 2-24 COST OF H2

The final output the cost of diesel for the same journey again will be based on a conditional IF statement. The previous answer of diesel consumed in litres for the freight and passenger train will be adopted in the statement as well the price of the diesel and the power input by the user. The condition in the IF statement will be based on the power input and determines whether it should take the diesel consumption of a passenger or freight train. The condition will be that if the power input is greater than 560 kw then the consumption of diesel for a freight train is multiplied by the price of diesel and if this condition isn’t true then the consumption of the passenger train will be multiplied by the price of diesel per litre. The conditional statement in the tool allows it to distinguish between the different type of train that would be used based on power requirements and the IF statement will be =IF(B2>560,J25*B18,B18*K25).

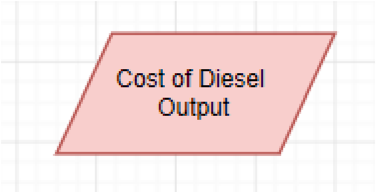


FIGURE 2-25 COST OF DIESEL

2.3 Validation

The processes, decisions, inputs and outputs will be created within the tool and the displayed in a flowchart to show the flow of events and logic behind each connection or calculation so that it is represented clearly. A crucial aspect of the tool is its validity as it must be validated to show its accuracy and that it works. There a various ways to prove its validity before going on to test future scenarios and making predictions on their likelihood or outcome based on the answers found in the tool. A way in which the tool will be validated will be to find information that is already known and use the tool to get this same known answer. This will give an indication of how accurate the tool is based on already established information known. Validation at this stage is an important activity and it can be attempted in several different ways but for the present work given the resources available an intermodal comparison approach will be adopted for the emissions output The emissions produced by the tool for a passenger and freight train based on the emission factors from locomotives data from London Research Centre (LRC 1998) which provides emissions data for class 37, 47, 56, 58, 60, 66, 66, 67, 158 and many other diesel trains. The tool used in this work does not take into account all the emissions of these different types of trains but only selects the one freight class 66 and one passenger train the class 158. The tool only calculates the CO2 output of the different types of trains whereas the LRC provides the CO2, S02, VOCs, PM10 and N0X outputs produced. The emissions are in kg/km allowing the tool to easily calculate the emissions over a given distance.

TABLE 2-5 EMISSIONS KG/KM

Train Type	CO2	S02	V0Cs	PM10	N0X
Class 66	19.147	0.0244	0.0173	$2.9\text{x}10^{-3}$	0.12
Class 158 2 Carriages	2.793	$3.6\text{x}10^{-3}$	$2.7\text{x}10^{-3}$	$9\text{x}10^{-4}$	0.0284
Class 158 3 Carriages	3.723	$4.7\text{x}10^{-3}$	$3.6\text{x}10^{-3}$	$1.2\text{x}10^{-3}$	0.0379

However, there are other sources that show different emission factors Giovani et al 2009 state that the CO2 emissions of diesel trains in 2006/07 are 1.389 kg/km and is based on the emissions of a diesel passenger train. Whereas the emissions used are in a tool based on an individual train emission for the class 158 is higher. If emissions are compared the percentage of error produced can be seen.

Passenger train emissions kg of CO2 from the tool = 3.723 kg of CO2

Passenger train emissions in kg of CO2 1.389 x 48.27 = 1.389 kg of CO2

Percentage of error = $\frac{3.723-1.389}{3.723}$ x 100 = 63%

This percentage of error between these two values seems large and may appear that compared to emissions of a passenger train from Giovani et al to tool is inaccurate this may be because the emission of CO2 per km is more up to date but the emissions factor for a passenger train is based on a train that is currently in service. When the emission factors of several currently operating diesel trains are averaged and compared to the emission factor of from the tool the percentage of error is significantly reduced. There are over 20 diesel passenger train emission factors to choose from but only the trains with 3 carriages will be selected so that the emission factor will be higher so that the tool may on average slightly over estimated the amount of CO2 emitted per passenger train but the decision was made to slightly over estimate rather than under estimate the CO2 emissions.

Averaged CO2 emissions in kg/km = 3.461kg/km

Passenger train emissions kg of CO2 from the tool = 3.723 kg of CO2

Percentage of error = $\frac{3.723-3.461}{3.723}$ x 100 = 7%

Even though there is still a percentage of error it is significantly smaller than the percentage of when the emissions of CO2 per kg/km is compared to the one by Giovani et al, it is also more representative of diesel passengers trains currently in use when compared to the averaged CO2 data emissions of passenger trains from the LRC. To assess the validity of the passenger train emissions of CO2 in kg/km the benchmark for comparison is set at the averaged emission of CO2 for all the diesel train emissions of CO2 of 3 carriage trains. The tools CO2 emission in kg/km for a passenger train takes the class 158 data as it is one of the most DMU’s used and when compared to the benchmark figure the percentage of error is only 7% which is relatively small as the tool slightly overestimates so it was predicted not be 100% accurate and as it be seen they are not too far removed from agreement. Given the available data for the CO2 emissions in kg/km for diesel passenger train these results are found to be acceptable but they may be several aspects that could increase the percentage of error such as retrofitted diesel trains with regenerative braking, improved energy efficiency through driving techniques and reduced diesel train engine idling but information regarding how these aspects could improve emissions in terms of CO2 in kg/km is not yet readily available.

TABLE 2-6 EMISSIONS KG /KM 3 CAR PASSENGER DMU'S

Train Type	CO2 Emissions
Class 144	2.606
Class 158	3.202
Class 156	2.904
Class 158	3.723
Class 159	3.723
Class 165	2.979
Class 166	2.979
Siemens future 3 car diesel unit	5.570

Approximately around 90% of the tonne-km’s moved on the UK rail network are transported by diesel freight trains. A similar approach will be taken for the emissions factor of a diesel freight train as majority sources measure freight CO2 emissions in gCO2/tonne-km. NAEI show that from 1990 to 2004 the CO2 emissions factor has remained constant at 49 gCO2/tonne-km. However, the emissions factor from the rail transport operations is 22 gCO2/tonne-km and McKinnon adopts an emission factor of 20 gCO2/tonne-km which is based on many varying emission factors from several sources. This is not fully representative of the rail freight industry as it takes into account multiple factors split between diesel and electric haulage, average carbon intensity of the electrical power source, average energy efficiency of the train engine and assumption of the average train load factors. Emissions factors measured in CO2/tonne-km from a multitude of literature sources vary widely and due to this they will not be used in the tool or as benchmark for comparison with the tool. The emission factor of the class 66 will be used as the benchmark for comparison against the average emission factors for all diesel freight trains which are taken again from the LRC’s model where another Intermodal comparison will take place , the class 66 is roughly 11% more energy efficient than the Class 56/58.

TABLE 2-7 EMISSIONS KG/KM FREIGHT DMU’S

Train Type	CO2 Emissions
Class 37	11.27
Class 47	16.723
Class 56	21.441
Class 58	21.441
Class 60	20.154
Class 66	19.147
Class 67	9.277

Averaged CO2 freight emissions in kg/km = 17.06 CO2 kg/km

Class 66 train emissions in kg of CO2 from the tool = 19.147 CO2 kg/km

Percentage of error = $\frac{19.147-17.06}{19.147}$ x 100 = 10.9%

The percentage of error from the tools emission factor values is slightly larger than that of the percentage of error of the passenger train emission factor as it 10.9% greater than the average emission factors for all the diesel freight trains. This again overestimates the amount of CO2 released into the atmosphere, but this does not consider the most commonly used train which is the class 66. Despite the 10.9% difference between emission factor used in the tool and the average emission factors of diesel freight trains the emission factor from the LRC model it is still representative of the typical emissions of a diesel freight train. Even though both diesel passenger and freight trains have emission factors slightly above the averaged emission factor across all types of diesel trains available from the model it is compared against the results produced from the tool regarding CO2 emissions on kg/km are still valid even if they are slightly above average emissions factor.

Given time constraints and resources available a simpler approach was adopted for the validation of the following outputs the costs of both H2 and diesel fuels and the energy consumed for each fuel. For the costs of fuels outputs validation there will be two separate explanations as they are two separate outputs, but the methodology used will be almost identical. As the cost diesel per litre will be constantly fluctuating the source of its cost will be directly from the source which displays the value from the commodities market which shows the average annual price of diesel of £1.14. However, when this value is compared to the average retail price of H2 taken from the across the UK from multiple sources there is a notable difference as the average price is £1.32 per litre. There may be a certain degree of inaccuracy at any given time as it is an average price per litre and this degree of error may increase further in the future due to market unpredictability, price fluctuations and is averaged across all regions of the UK but currently this price for diesel is relatively accurate and representative of the current period in time. Due to the use of H2 for trains being limited the prices being quoted by several sources are based on H2 used for cars but the technology used is the same with the only difference being the quantity needed as trains carry heavier loads. The prices found and ultimately used within the tool stated that the H2 fuel compatible with fuel cell technology price currently in the UK was roughly between £10 to £15 per kg. As the costs per kg is in the range of £10 to £15 to price per kg will be assumed to be £12.5. Also, as the prices quoted for H2 gas as in Kg and the tools price will be per litre a conversion is undertaken to show the equivalent price of H2 per litre. A kg of H2 is equal to 14.12 litres so to have a value per litre for the cost of the H2 that can be used within the tool the answer is simply divided showing the cost. The cost of H2 used for the tool although is taken from the price of H2 per kg used for cars it is based on the same technology and is therefore still a valid cost of H2 for in trains.

1 kg of H2 = 14.12 litres

1 Kg of H2 = £12.5

Price of H2 in £ per litre = 14.12/12.5 = £1.13

Another output the tool will be able to produce is the energy consumption of the H2 fuel used and the equivalent diesel fuel. The validation of this output will again be relatively straight forward as the energy consumption of these fuels will be based on the energy density of these fuels which can be found from literature which is the quantity of energy stored in a given space and is usually in Mj/kg or Mj/L. From analysing the literature regrading diesel fuel for automotive purposes energy density there are several different values all within the same range such as 36.9 MJ/L, 34.9 MJ/L, 38.6 MJ/L and 34 MJ/L. Although these values are all relatively close for the tool to calculate the energy consumption that an equivalent diesel train would use one value for the energy density of diesel will be used in the tool so the values found must be average. The below value will be adopted for use in the tool as even though it is averaged it is still valid as it is the averaged value found from the available literature. The same approach for the energy consumption of a H2 train is used as several values for the energy density of H2 are found to be 120 MJ/Kg, 142 MJ/Kg, 120 MJ/Kg, 130 MJ/Kg and 142 MJ/Kg. Again, these values are averaged below to give an energy density of H2 in the tool of is 130.8 MJ/Kg. However, this value is in MJ/Kg whereas the value for energy density is in MJ/L so in order to have both values in the same unit which will ease their comparison the H2 energy will be converted. As previously stated, 1 kg of H2 gas is equal to 14.12 litres so the averaged answer for the energy density of H2 in MJ/Kg is multiplied by 14.12 litres so now both values of energy density for H2 and diesel in the tool are in the same units.

Energy Density of Diesel in the Tool = $\frac{36.9+34.9+38.6+34}{4}$ = 36.1 MJ/L

Energy Density of H2 in the Tool = $\frac{120+142+120+130+142}{5}$ = 130.8 MJ/Kg

Energy Density of H2 = 130.8 x 14.12 = 1847 MJ/Kg

3 Chapter 3: Future Scenarios

3.1 Scenario 1

The future of the rail industry is set to be driven by a number of influencing factors such as growing urbanization, increased passenger and freight demand, greater energy efficiency and reduced reliance on fossil-based fuels. The increased demand and reduced reliance on fossil fuels places the rail industry in an ideal position to shift towards a low carbon economy of the future. The factors that are driving the future of the rail industry also produce new problems such as meeting the increased capacity, increased energy demands whilst simultaneously trying to reduce energy requirements and the costs associated with both. Hansen et al identify further automation of railways as offering opportunity for greater efficiency, control, command and communication, also allows distance between trains to be optimized as well as their energy consumption. This prediction for the future of the rail industry is supported by a wide range of industry experts across several UK rail companies which make up the Technical Strategy Leadership Group (TSLG) who wrote the Rail Technical Strategy 2012. In the Rail Technical Strategy of 2012 authors state that automation will allow for greater capacity as the train's movements become more predictable and more efficient. They also mention that the railway of the future should be more sustainable and that fossil fuels may be potentially replaced by alternative fuels like H2 that have zero emissions at point of use.

The future automation and shift to more sustainable energy efficient technologies creates a future scenario where busy train services can become highly automated with safety zones around trains which are no longer fixed by track side signalling but by the train itself and moves with it. In this future scenario trains commute with traffic control systems avoiding stop and start operations and reducing energy consumption. The new safety zones will allow trains to be closer together and greatly increase the capacity of busy routes. The move towards more sustainable and energy efficient trains that are capable of keeping up with a high passenger capacity allows for the future use of H2 trains on busy highly automated routes to further reduce emissions and create more a more sustainable rail industry. H2 train usage is associated with high costs to manufacture, operate and maintain therefore it may seem counterintuitive to try use them to reduce cost and improve sustainability. However, diesel trains currently use 680 million litres of diesel annually at a cost of over £600m/year in the UK and with the current predictions for rail usage to increase this could potentially increase significantly. A future rail industry that adopts H2 trains will consume a greater volume of fuel due the nature of H2 but the emissions produced by H2 is water and this much more sustainable than the prospects of expanding diesel rolling stock to match the increased rail capacity. The scenario stated also allows the opportunity for a more cost effective use of H2 trains as if used on busy commuter routes that regularly transports high volumes of passengers then the high capital cost incurred in the creation, storage and use of H2 trains may result in quicker return on investments for rail operators and justify their usage.

Giovani et al mention that the characteristics of a route are more important in determining the emission levels. Characteristics such as the number of stops and the distance between them are more important than that of the speed trains operate in establishing emission levels. Faster trains are responsible for lower emissions of CO2 per passenger km. Areas in the UK where there are many stops and operate frequent services which run close to full capacity are mostly routes into London and Giovani et al highlight that to relieve their congestion and meet the additional demand more services are required to meet the capacity and to appease the commuters. To meet these demands trains with greater acceleration and deceleration would be needed on these routes. This would ultimately lead to more existing diesel rolling stock being used and operating in more carbon intensive way on these already busy routes. The UKs DfT figures show that in the autumn of 2017 on a typical weekday there are roughly around a million passengers traveling to London alone with half arriving between the hours of 7:00am and 10:00am. This shows the high capacity in which these routes face particularly in peak hours as half a million people commute to London every weekday over a 3-hour period.

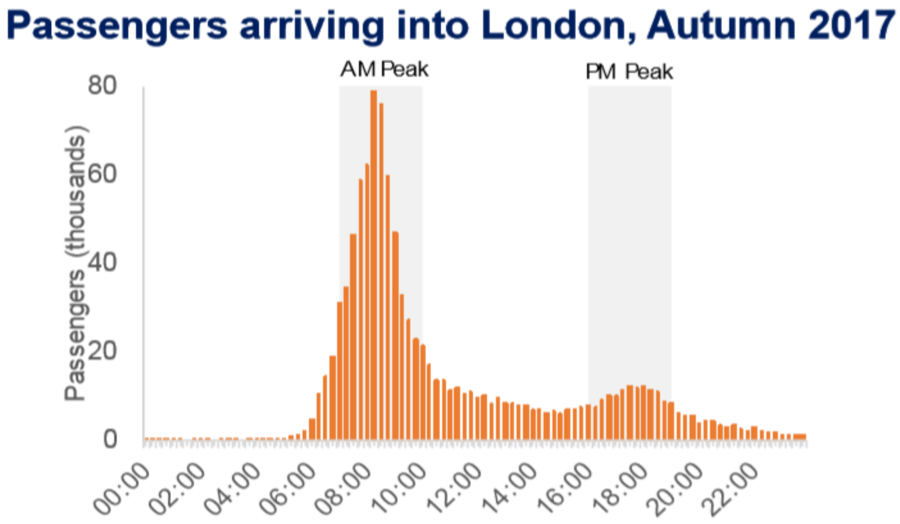


Figure 3-1 Passengers Arriving into London, Autumn 2017

A future prediction would see these routes seeing a growth in passenger usage and which will lead to the requirement for more trains. Thus, making this ideal situation for the use of H2 trains on these routes to meet the growing demand and reduce emissions especially when compared to diesel alternatives. Also, to electrify some of these routes would lead to high costs and high energy demands from the grid. For a given commuter route into London the tool created can be used to show to emissions that could be saved by using a H2 train in the future instead of a diesel train and will also highlight the price comparison of both fuels. The tool will also be able to provide many of the specific requirements a H2 train will have for this given distance. A route that is not electrified will be used in this scenario to compare the H2 fuel costs with the cost of electrification per km as evidence from the literature review showed the cost of electrification of the track to be €840k per km and based on current exchange rates this equates to £770, 364 per km . Although the tool focuses on H2 trains and comparisons between diesel trains additional information gathered from the literature review allows for the cost comparison of the electrification of the route.

FIGURE 3-2 AYLESBURY TO LONDON MARYLEBONE

A passenger commuter train that runs to London and still relies only on diesel multiple units (DMU's) is Chiltern railways which operate the route from Aylesbury to London Marylebone as be seen in Fig 3-2. This route is adopted for this scenario with reasons being that it is only operates DMU's, so the comparison and emissions saved when a H2 trains is used can be highlighted as well as the cost of electrification for this route. The only rolling stock being operated on this line are the class 165 turbo and the class 168 clubman. The characteristics of both these trains and the class 158 passenger train adopted in the tool are relatively similar but the power outputs vary as the class 165 turbo has an engine power output of 261kw and the class 168 clubman has an output of 315kw which the tool is designed to accommodate. This commuter route has 95 trains on average running every weekday travelling a total distance of 34 miles ,54.7km, to its destination with the fastest time taken to complete the journey being 55 minutes. This route will be used as means of showing the effects of introducing a H2 train onto a non-electrified commuter route. This will allow the tool to clearly show any CO2 emission reductions, the comparison of the diesel and H2 fuel price along with the specifications of a H2 train that will be required. The previously found cost per km of electrification also allows for the comparison of costs compared to cost to electrify this entire route. Before this scenario can be tested in the tool for both types of trains the speed must be found for this route. This done simply by using the already provided distance in miles and time which will be converted into hours.

Distance = 34 miles

Time = 55 minutes = 0.916 hours

Velocity = $\frac{Distance}{Time} = \frac{34}{0.916}$ = 37.1 mph

The velocity of the train over this route provides all 3 inputs power, distance and speed required for the tool to carry out its calculation. Both diesel trains used over this route will be analysed separately and then compared to show the differences, as well as high pressure and low-pressure storage tanks will also be tested to show which would be more beneficial for the given train and its power requirements.

3.1.1 Class 165 Turbo

Within this scenario there are two types of trains that will be tested multiple times with several simulations been carried out with the first being the class 165 Turbo diesel which will be analysed on this route. The Aylesbury to London Marylebone service runs an average of 95 services every weekday all being DMU's. The first set of simulations will imagine a scenario where all of these 95 services have been entirely replaced by H2 trains retrofitted around existing diesel rolling stock. The simulation will be carried out for low- and high-pressure storage tanks which will be 35000 kpa or 75000 kpa to establish which is more compatible with the class 165 turbo and takes up the least space. This simulation will show the range of the H2 train, the number of times it will need refuelled to complete this route and the cost of the H2 that will be required to complete this journey 95 times. The tool has not number of journeys input so the distance for journey will therefore be multiped for all 95 journeys to account for ever service being operated on an average weekday. The tool will provide the cost of H2 required but it will also show the cost diesel that would be required so that both can be compared. More outputs such as the volume of H2 storage alongside the energy requirements of the H2 train and the equivalent diesel train energy requirements will also be produced by the tool. The emissions that would have been emitted from a diesel train will also be shown, additional information from the literature review regarding the emissions of CO2 in kg/km of an electric train will also be used to show the emissions of all 3 types of train diesel, electric and H2. However, the data for the emission associated with an electric does not specify whether it is a passenger or freight train and whether or not it has been averaged for various types of electric trains so it can only be used as rough estimate of how an electric train would be compared and hence why it has not been included in the tool itself. A final comparison can be made regarding cost as the length of the track is known and the cost of electrification per km is also known so this cost compared to H2 fuel cost and diesel fuel costs can be analysed. The deliverables from the tool will be:

- Optimized storage pressure
- Range of tank
- Number of times tank needs refuelled
- Cost of H2
- Cost of Diesel
- Emissions of CO2 in kg/km that would have been emitted
- Energy requirements of H2 train
- Energy requirements of diesel train
- Volume of H2 storage

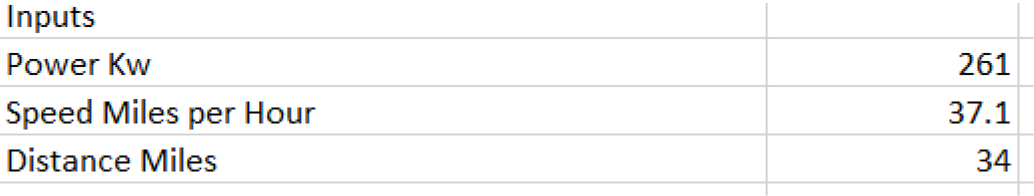
Additional outputs that can be found from research taken place in the literature review and that will not be provided by the tool are:

- Electric train CO2 emissions in kg/km for the same route
- Cost to electrify the track

The class 165 turbo has an engine power of 261 Kw which be taken as the power input and the two other inputs distance 34 miles and speed 37.1 mph has been previously found. The tool only requires these 3 inputs to produce the above deliverables associated with the tool.

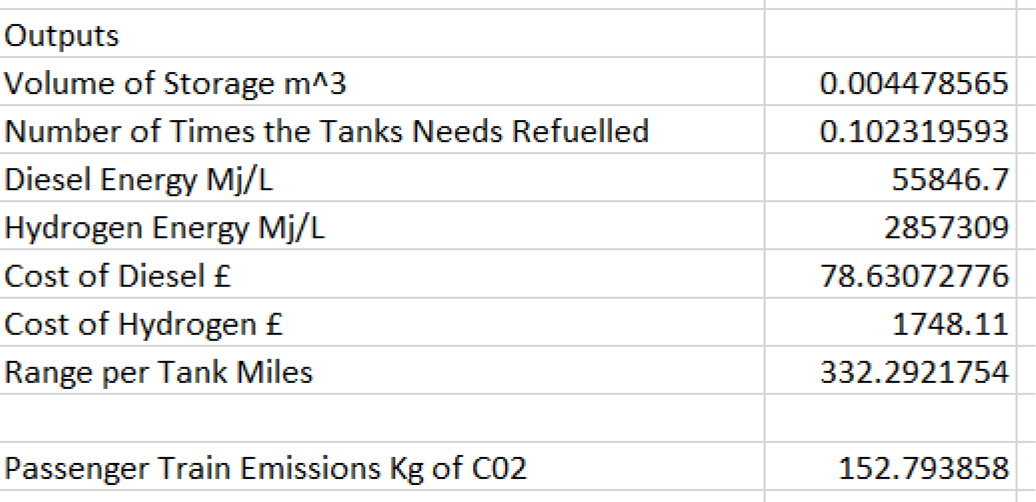
Electric Train CO2 emissions per km = 1.089 x 54.7 = 59.6 Kg of CO2 per km

Cost of route electrification = 54.7 x 370, 364 = £20,258,910.8



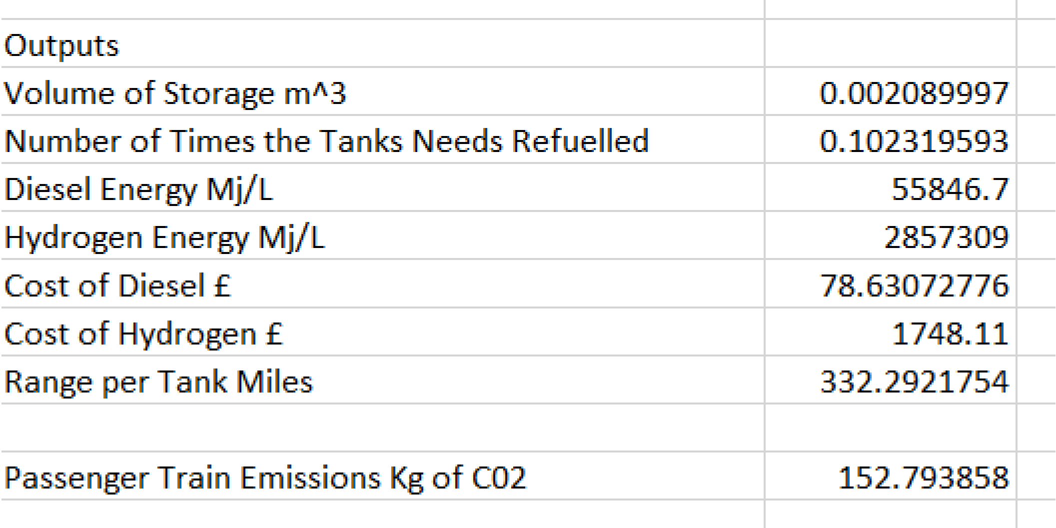
Inputs	
Power Kw	261
Speed Miles per Hour	37.1
Distance Miles	34

Figure 3-3 Class 165 Turbo Tool Inputs



Outputs	
Volume of Storage m^3	0.004478565
Number of Times the Tanks Needs Refuelled	0.102319593
Diesel Energy Mj/L	55846.7
Hydrogen Energy Mj/L	2857309
Cost of Diesel £	78.63072776
Cost of Hydrogen £	1748.11
Range per Tank Miles	332.2921754
Passenger Train Emissions Kg of C02	152.793858

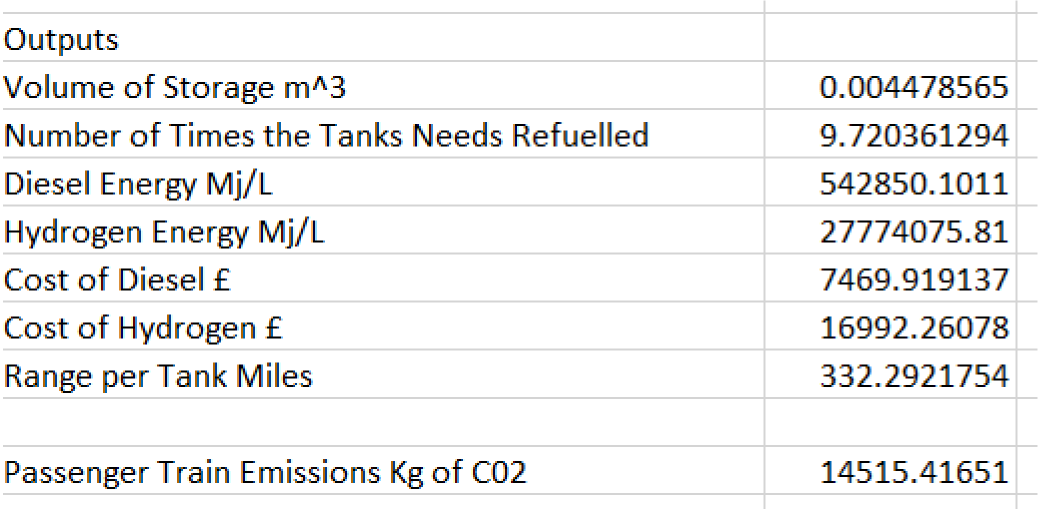
Figure 3-4 Class 165 Turbo Tool Outputs Low Pressure



Outputs	
Volume of Storage m^3	0.002089997
Number of Times the Tanks Needs Refuelled	0.102319593
Diesel Energy Mj/L	55846.7
Hydrogen Energy Mj/L	2857309
Cost of Diesel £	78.63072776
Cost of Hydrogen £	1748.11
Range per Tank Miles	332.2921754
Passenger Train Emissions Kg of C02	152.793858

Figure 3-5 Class 165 Turbo Tool Outputs High Pressure

The pressure difference only effects the volume taken up by the storage tank as expected, the high-pressure storage tank roughly halves the amount of space taken up by the storage meaning that there is potential for more on board storage space of H2 which could massively increase its range. However, higher pressure is associated with higher costs and the compressor and other components will take up significant amount of space for these reasons and as well as the increase cost the lower pressure will be used. The rest of the outputs are not affected by the pressure differences. The above figures only show the emissions and cost of the fuels for 1 journey, but this journey must be repeated 95 times for an average weekday this can be shown in tool as the distance required for the H2 train to travel will be 3230 miles for an average weekdays operation as the route is multiplied by the number journeys required.



Outputs	
Volume of Storage m^3	0.004478565
Number of Times the Tanks Needs Refuelled	9.720361294
Diesel Energy Mj/L	542850.1011
Hydrogen Energy Mj/L	27774075.81
Cost of Diesel £	7469.919137
Cost of Hydrogen £	16992.26078
Range per Tank Miles	332.2921754
Passenger Train Emissions Kg of C02	14515.41651

Figure 3-6 Class 165 Turbo 95 Journeys

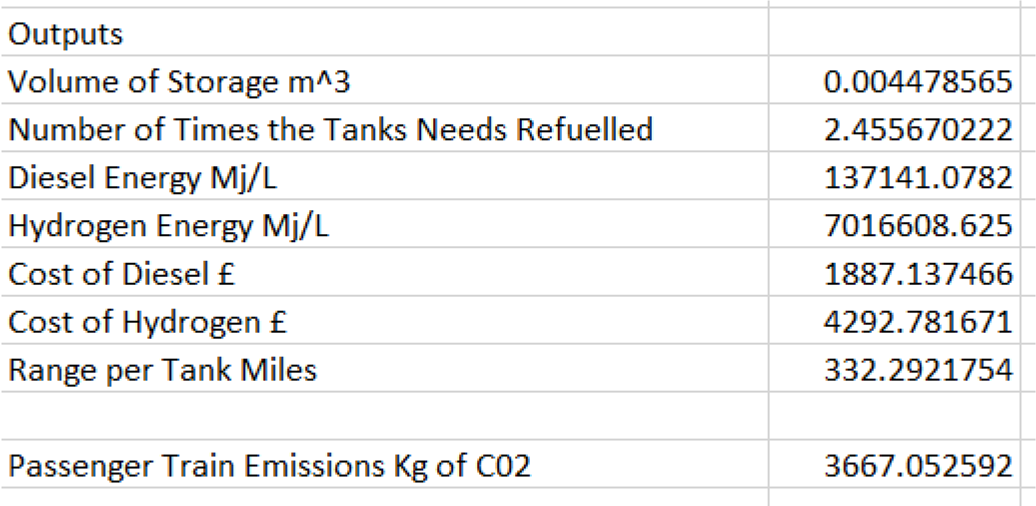
A full tank has a range of 332.3 miles and the route is 34 miles so the train would require refuelling after 9.8 journeys and over a day's operation the H2 train would need to be refuelled more than 9.7 times to meet the demand as can be seen in Fig 3-6 from the tool. When the costs of fuels are compared, H2 is not as cost effective as a fuel source as diesel especially if it is to be used on a daily basis over every journey. When compared to the cost of electrification of the entire track length it may not seem as much but it would take roughly 3.3 years of operating 95 H2 trains every weekday to match the cost of the electrification of the entire track so in the long run to fully switch to H2 as an alternative to diesel, in over 3 years the cost would be equal to the cost of the entire route electrification. It would also not require any route closure effecting the rail operators' profits. In terms CO2 emissions H2 train are a clean fuel at point of use and based only on the weekday operations there is potential to reduce CO2 emissions by over 3774 tonnes in a year. The energy consumption is significantly high but H2 is expected to have higher energy consumption even though H2 it is more energy dense and fuel cell technologies have higher efficiency rate they also have high consumption rates of H2 than ICE consumes diesel and based on the inputs the fuel cells consume almost 3 times more H2 in an hour than a diesel train consumes diesel.

However, when considering H2 as a replacement for diesel there 3 key considerations that must be taken into consideration cost, sustainability and feasibility. From a purely feasibility angle H2 technology when considering storage and all other aspects involved many of these are still developing and existing technology is costly but it is technically feasible and it is able to operate on the same route with the only infrastructure changes being the creation of refuelling station. The second consideration economic feasibility is the one of the major drawbacks currently as H2 fuel is more expensive and to run the Class 165 Turbo on H2 it is 2.3 times more expensive than diesel for an average weekday operation on this route. With the costs associated with H2 trains and potential retrofitting of existing rolling stock it is not currently economical to completely switch all diesel services to H2 as the fuel costs would more than double. Although for this given route it is more economical in the short term to introduce H2 trains over electrification based on the cost of track electrification but the costs of refuelling stations and H2 transportation are not known. If the H2 trains for the Class 165 were to be operated at times of full capacity only, the costs of H2 fuel would still be high but would allow the operator of the route to still make a profit at the current fair prices although considerably less than they would with diesel. The final consideration of sustainability fairs in a much better light as at point of use with water vapour and warm air being the only emissions. When the creation of H2 is considered it may not be as clean as it appears as majority of H2 comes from natural gas reforming but H2 can also be produced via electrolysis and only requires electricity and oxygen for its production.

Overall it is costly but reduces emissions significantly and therefore, it should be seen as more of a balancing act between sustainability with long term CO2 emissions being the goal and being cost of effectiveness for businesses as based on the tool outputs for 95 journeys the cost of every Kg of emissions reduced would be £1.17 and could decrease depending the price of H2. To be able to work in balance with these two factors it is not best for this particular train and route to fully switch to H2 and this maybe the same for other trains and routes. However, for this given route it can be said that it is more economical in the short term and more technically feasible than switching to electrification as this is due to where this route is located. This route passes Chiltern national park and for local environmental reasons it may not be possible to carry out the large-scale infrastructure project to electrify this route. It may be better to operate at time of peak capacity with a balance of H2 trains and diesel trains being used at peak time. It has been previously established that peak time for commuter trains into London is between 7:00 am and 10:00 am with half of passengers travelling at this time. From this it can be assumed that half the trains operate between these hours and this would be the most suitable time for H2 trains to be used. The tool will carry out another simulation based on these conditions so that every second train operating at peak times will be a H2 train and therefore a quarter of the trains operating will be H2 so 24 H2 trains would be operated a day. If the H2 train was to only run 24 times a day the distance input would be reduced to only 816 miles most of the outputs most notable the energy consumed, cost of fuel and the CO2 emissions would be reduced.

Inputs	
Power	261
Speed	37.1
Distance	816

Figure 3-7 Class 165 Turbo 24 Journeys Input



Outputs	
Volume of Storage m^3	0.004478565
Number of Times the Tanks Needs Refuelled	2.455670222
Diesel Energy Mj/L	137141.0782
Hydrogen Energy Mj/L	7016608.625
Cost of Diesel £	1887.137466
Cost of Hydrogen £	4292.781671
Range per Tank Miles	332.2921754
Passenger Train Emissions Kg of C02	3667.052592

Figure 3-8 Class 165 Turbo 24 Journeys

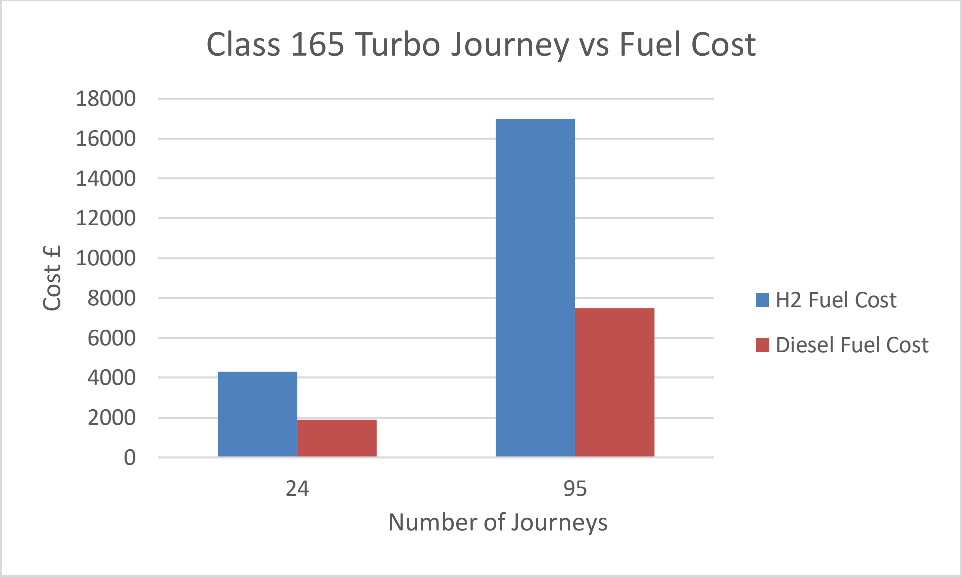


FIGURE 3-9 CLASS 165 TURBO COST OF FUEL COMPARISON

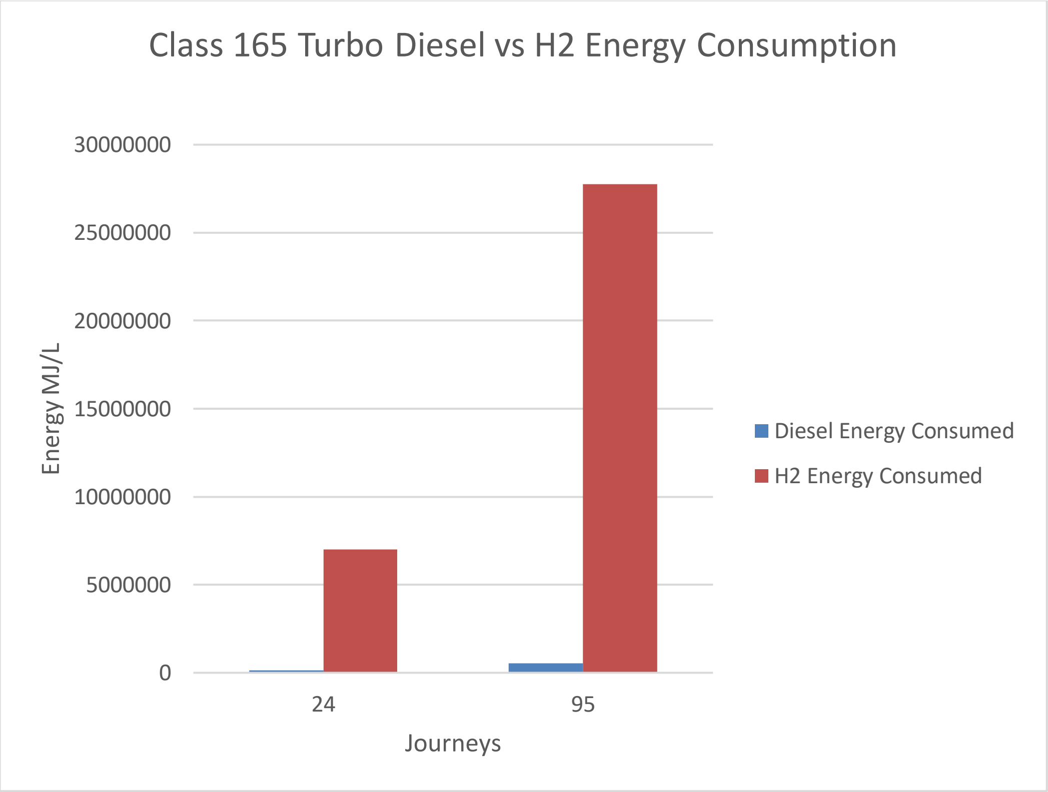


FIGURE 3-10 DIESEL VS H2 TRAIN ENERGY CONSUMPTION

As it can be seen from Fig 4-9 the fuel costs of operating a H2 train based on this route and power requirements that the fuel costs are slightly more than double the diesel costs. When the energy consumption of the are compared in Fig 4-10 it is clear that the energy consumption of the H2 train regardless of number of journeys dwarfs the energy consumption of the equivalent diesel train. The daily fuel costs are significantly reduced by running fewer journeys and based on this it would now take almost 13 years for the H2 to fuel costs to match the cost of electrification of the full track and the cost of every Kg of emissions saved remains constant at £1.17. The H2 train has the added advantage of decreasing the payback period as each journey running at a period of full capacity will be able to generate profit on that given journey whereas for electrification the route would have to be shut at times to electrify the route and in the short term would cost the operator more than the cost of electrification of the track length. Although the environmental benefit is reduced there are still over 953 tonnes of CO2 not being emitted into the atmosphere whilst simultaneously reducing running costs if operated in this manner.

3.1.2 Class 168 Clubman

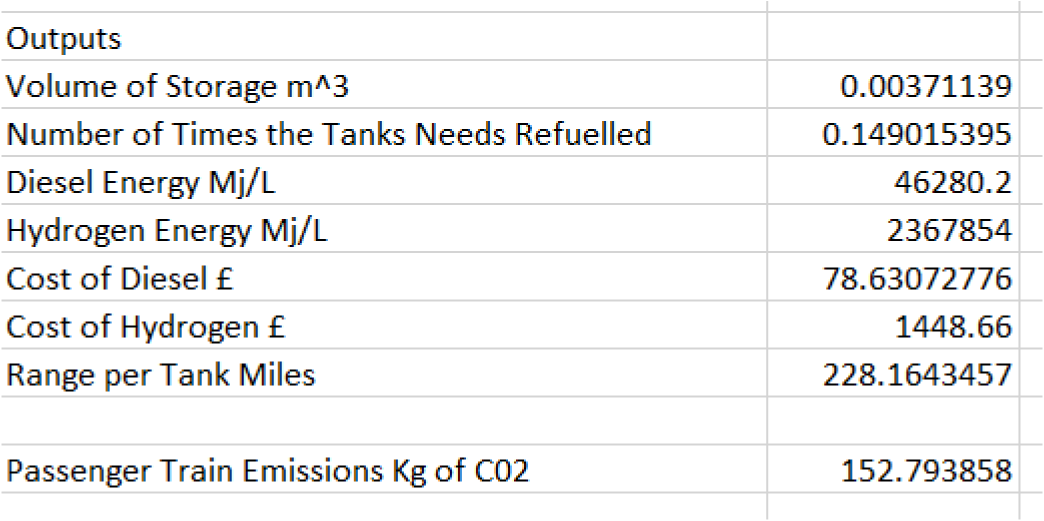
The same method applied for the other diesel train used throughout this route will be applied to class 168 clubman which has a higher power requirement of 315 Kw, but the speed and distance inputs will remain the same. Again, both low pressure and high storage will be tested in the tool to show the difference. The tool will have the same deliverables:

- Optimized storage pressure
- Range of tank
- Number of times tank needs refuelled
- Cost of H2
- Cost of Diesel
- Emissions of CO2 in kg/km that would have been emitted
- Energy requirements of H2 train
- Energy requirements of diesel train
- Volume of H2 storage

All 95 journeys on this route will again be shown to highlight the comparison between the two trains used on this route even though it may not be economically feasible.

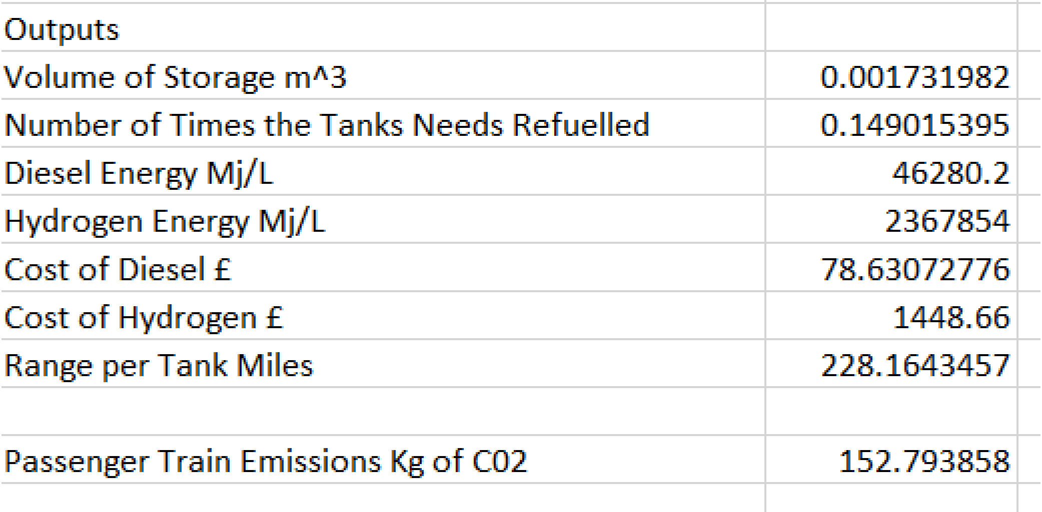
Inputs	
Power	315
Speed	37.1
Distance	34

FIGURE 3-11 CLASS 168 CLUBMAN INPUTS



Outputs	
Volume of Storage m^3	0.00371139
Number of Times the Tanks Needs Refuelled	0.149015395
Diesel Energy Mj/L	46280.2
Hydrogen Energy Mj/L	2367854
Cost of Diesel £	78.63072776
Cost of Hydrogen £	1448.66
Range per Tank Miles	228.1643457
Passenger Train Emissions Kg of C02	152.793858

FIGURE 3-12 CLASS 168 CLUBMAN LOW PRESSURE



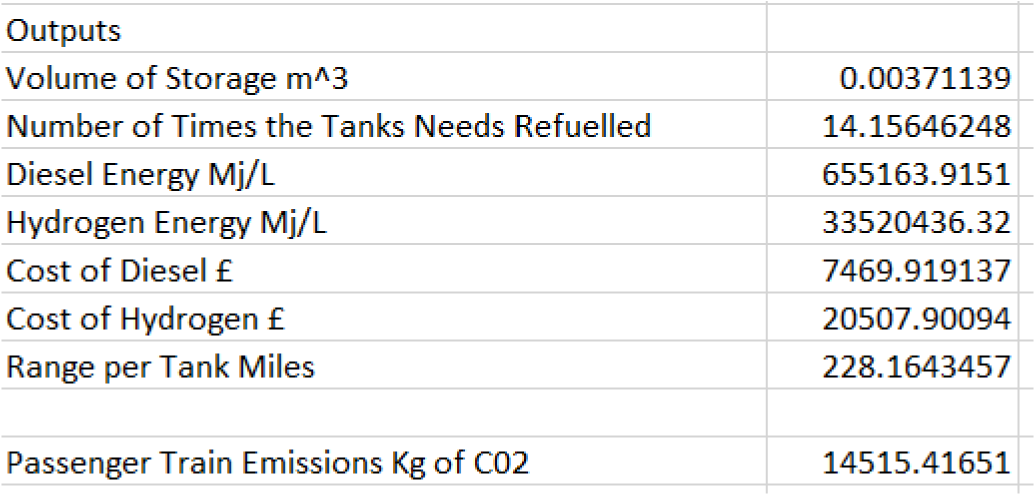
Outputs	
Volume of Storage m^3	0.001731982
Number of Times the Tanks Needs Refuelled	0.149015395
Diesel Energy Mj/L	46280.2
Hydrogen Energy Mj/L	2367854
Cost of Diesel £	78.63072776
Cost of Hydrogen £	1448.66
Range per Tank Miles	228.1643457
Passenger Train Emissions Kg of C02	152.793858

FIGURE 3-13 CLASS 168 CLUBMAN HIGH PRESSURE

The increase pressure again creates more space available for the potential of more storage tanks that could increase the range of the tank or even if the space is great enough introduce another engine and create a hybrid system. The only output changed by the pressure differences is the volume of storage output as expected, but the others remain the same. The increased power requirements of the class 168 clubman have a notable difference in the outputs as the energy consumed is less than, the range is also less as well as the cost of the H2 as volume of storage decreases as the power requirements increase due to the volume taken up by the fuel cells. The emissions over the route remain constant and the differences in outputs will be even greater over the 95 journeys per weekday.

Inputs	
Power	315
Speed	37.1
Distance	3230

Figure 3-14 Class 168 Clubman 95 Journeys Inputs



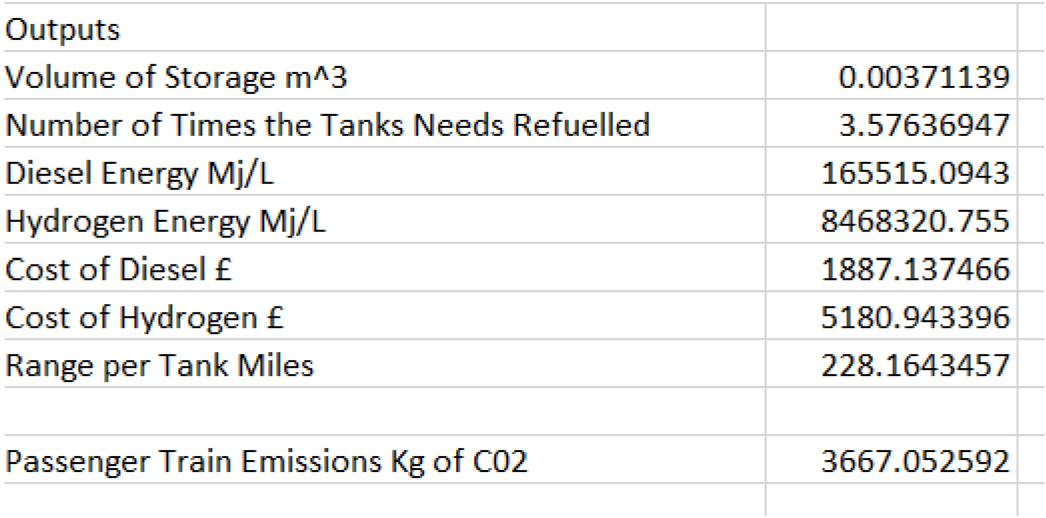
Outputs	
Volume of Storage m^3	0.00371139
Number of Times the Tanks Needs Refuelled	14.15646248
Diesel Energy Mj/L	655163.9151
Hydrogen Energy Mj/L	33520436.32
Cost of Diesel £	7469.919137
Cost of Hydrogen £	20507.90094
Range per Tank Miles	228.1643457
Passenger Train Emissions Kg of C02	14515.41651

Figure 3-15 Class 168 Clubman 95 Journeys

The class 168 clubman used on this route consumes slightly more energy than the other H2 train used on the same route which has lower power requirements. This is due to increased engine and fuel cell sizes used and as a result the train cannot store the same amount of fuel and therefore its range will decrease but due to the increase of the H2 fuel cells the H2 consumption rate increases leading to higher energy consumption. A retrofitted class 168 clubman operating 95 times on this route would require more than 14 refuelling trips and may be difficult to manage during peak hours and effect normal operations if constant refuelling is required. This would also be technically difficult and expensive to create the number of H2 refuelling stations required and the logistical problems faced with transporting the quantities of H2 needed. Although still costly to replace all services on a week day with a H2 train it would take 2.7 years for the cost of H2 fuel required to operate 95 services a weekday to match the cost of electrification of the entire route and is slightly more costly as whole compared to class 165 turbo train. The cost of emissions saved for this H2 operating this quantity of services would be £1.41 per kg of CO2 emissions reduced. As it is currently not economical to run these many services of the H2 train at the current price of H2 as it is more than 2 times more expensive the same approach is applied with half of all services operating between peak hours will be H2 trains.

Inputs	
Power	315
Speed	37.1
Distance	816

FIGURE 3-16 CLASS 168 CLUBMAN 24 JOURNEYS INPUTS



Outputs	
Volume of Storage m^3	0.00371139
Number of Times the Tanks Needs Refuelled	3.57636947
Diesel Energy Mj/L	165515.0943
Hydrogen Energy Mj/L	8468320.755
Cost of Diesel £	1887.137466
Cost of Hydrogen £	5180.943396
Range per Tank Miles	228.1643457
Passenger Train Emissions Kg of C02	3667.052592

FIGURE 3-17 CLASS 168 CLUBMAN 24 JOURNEYS

From a sustainability perspective there is no difference in CO2 emission outputs when both tools are compared from the tool but this would differ only slightly in reality. If the emissions that could be saved are the same for both trains operating 24 services during peak capacity on an average weekday then the only difference be the cost of fuel associated with each retrofitted H2 train. The cost of H2 fuel used on a weekday operation for the class 168 Clubman would take over 10 years to match the cost of track electrification and if operated this way it would makes H2 passenger trains more economical compared to electrification.

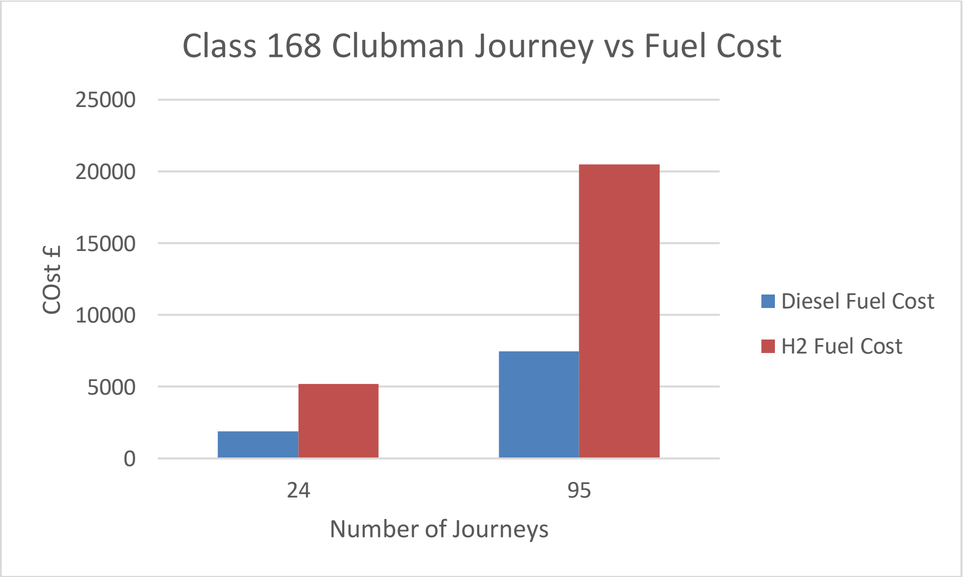


FIGURE 3-18 CLASS 168 COST OF FUEL COMPARISON

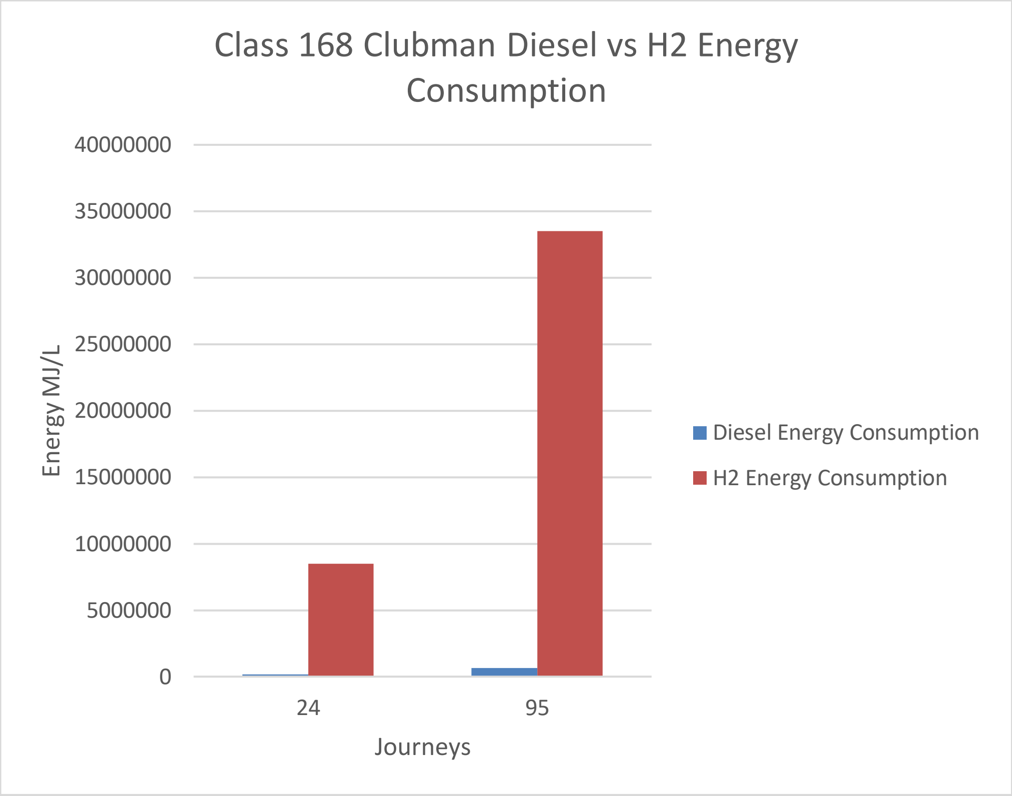


FIGURE 3-19 DIESEL VS H2 TRAIN ENERGY CONSUMPTION

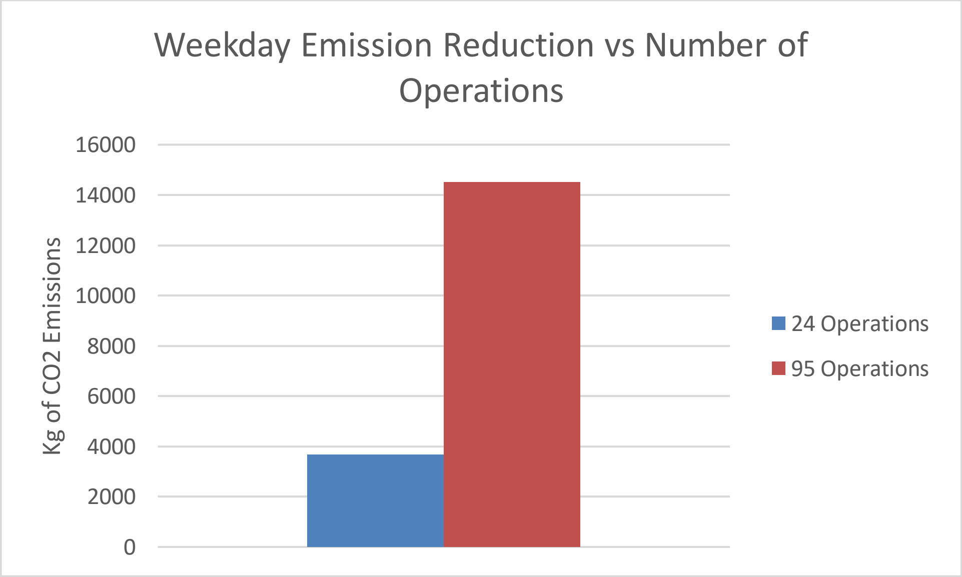


FIGURE 3-20 EMISSIONS REDUCED PER OPERATION

As the result from the tool indicates that both retrofitted H2 trains that would operate on this line would save the same amount of CO2 emitted into the atmosphere mean the only differentiating factors that can be established in this scenario are cost of fuel, energy consumption, range and cost of every Kg of CO2 emissions saved. The results produced show that the retrofitted class 165 turbo with the lower fuel cell power requirements fared much better on this route using H2 as it range was considerably greater as it complete an extra 104 miles before needing refuelling meaning it could complete the journey an additional 3 times. This ultimately leads to lower energy and fuel consumption reducing the fuel cost for the lower powered H2 train. The lower powered train also had a lower price for every Kg of CO2 emission saved at £1.17 compared to the higher power rated train which would cost £1.41 for Kg of CO2 emissions reduced. In terms of balancing the most cost effective and environmentally friendly H2 passenger train the lower rated train the class 165 turbo proved to be best. Overall the scenario was able to determine the amount of CO2 emissions that could be reduced by retrofitting existing diesel rolling stock with H2 fuel cells and operating them on non-electrified routes and how to optimize their usage whilst balancing their high fuel cost to make them more cost effective. The outcome of scenario is that lower power passenger trains are ideally more suitable for H2 usage for commuter trains and result in lower operating costs and greater range, when its operating cost is compared to electrification of the same route it is more economical and in the long run has the potential to reduce a greater amount of CO2 emissions than an electrified route based on the evidence found. However, the cost of retrofitting existing diesel rolling stock, improving rail infrastructure creating H2 refuelling stations or the creation of new H2 fuel rolling stock have not been considered and would increase the overall costs associated with its usage and the source of the H2 fuel may also have an adverse effect on the environmental benefit.

3.2 Scenario 2

The rail freight industry’s future is an area which is consistently being analysed and investigated by industry professionals to try and determine the future problems it may face and existing challenges it faces at present and how these can be met in a way which bares the future developments of rathe rail industry in mind. The Freight Network Study 2017 by Network Rail studies the future of freight rail developments across the UK. The aim of this study is to look into the long-term development of the UK rail freight industry over the next 30 years and is called the Long-Term Planning Process (LTPP). The quantity of goods being transported via freight trains has increased significantly over the last 20 years and the current annual value is in the region of £30bn. The industry is estimated to grow as it is seen as being both economically and environmentally friendly despite the heavy reliance on DMU’s. The study states that the future growing demands of this industry should be met in a sustainable way, as the main demands the industry faces are meeting growing capacity and the existing capability of the network and its existing DMU’s. The current rail freight sector has seen an increase in the flow of freight traffic towards the already existing busy routes applying more stress on these routes. Both freight and passenger capacity has seen extra demand on the entire UK rail network. As recently as 2013/14 there has been a slight reduction in rail freight usage going against the upward trend over the past 20 years. This sudden decline has been caused by the rapid decrease in demand for coal as means electricity generation and therefore lot less coal freight traffic. The freight industry generates more than £1.6bn per annuum of economic benefits to the UK and between 2019 and 2024 the government is set to continually fund rail freight enhancements. An area that was identified as an opportunity to improve the rail freight capacity is to make use of additional capacity on the existing passenger rail network. This could potential positive impacts of transportation of goods in urban areas where logistics have previously been a problem. Some of the challenges the industry faces are the high costs and long life of the assets they currently have at their disposal as locomotives tend to have an operating life of 25 to 30 years. The future of the rail freight industry also faces the issue of political uncertainty when it comes to long term investment into the development of future technologies, greater stability and certainty is needed for any future strategic policy. A.Woodburn states that one of the main areas where technological development may help improve the rail freight industry is in the decarbonisation. A.Woodburn mentions technologies such as electrification and H2 fuel cells can be used for the reduction of CO2 emissions. This again is heavily dependent on government policy and funding.

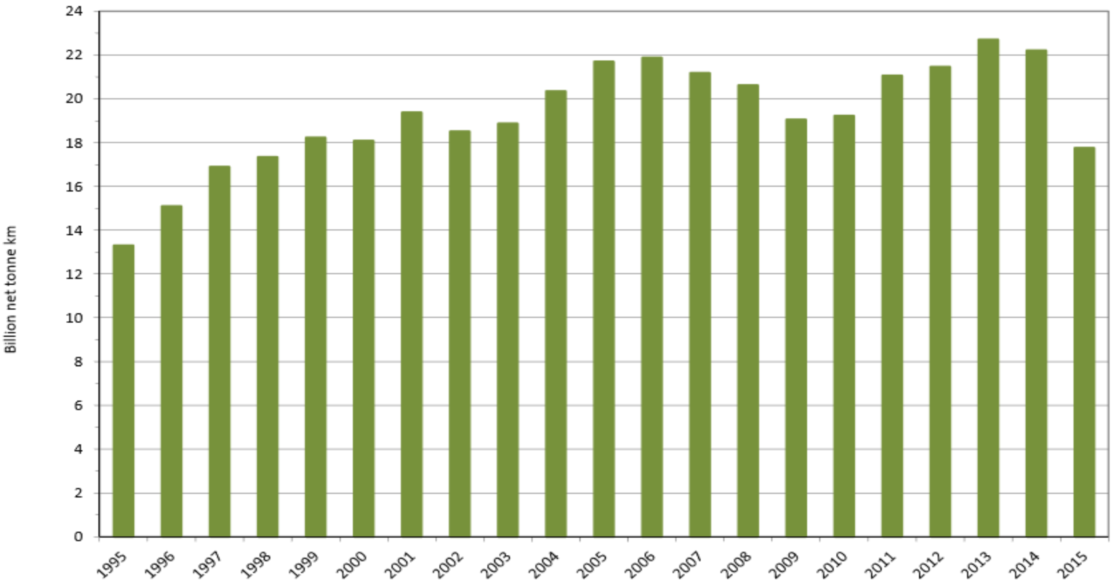


FIGURE 3-21 NET TONNE KM'S PER YEAR

To establish a future scenario based around the future of the rail freight industry certain assumptions must be made such as consistent government policy, funding and commitment to decarbonisation. The increase in freight use is partly to reduce congestion and air pollution. In the previous scenario passenger routes that relied on diesel trains as their only source of transport were analysed and compared to H2 trains on the same route but in this scenario H2 freight trains will be assessed to determine first there feasibility and secondly, to be compared to existing diesel and electric freight trains and also the costs associated with operating H2 freight trains. The tool has the capabilities to calculate these outputs, but certain predictions can be made. Freight trains will require more fuel as they carry heavy loads and they travel further so require longer range, based on these two aspects of freight rail the H2 freight trains will have a higher fuel consumption and therefore cost will be significantly higher than that of the H2 passenger trains analysed in the first scenario. Although H2 freight would inevitably be more costly they offer a greater opportunity for CO2 emission reductions and will ultimately offer a more expensive and sustainable method of freight transport. A future scenario investigates the adoption of H2 freights as a replacement for existing diesel and electric rolling stock and within this scenario the tool will show results for H2 freights over two different routes. One route being a longer cross-country route and the other being shorter urban route and the tools results will be based around a retrofitted class 66 freight train. This is due to the assumption that long distance H2 freight may be extremely costly due to fuel and power demands but the tool has the ability to show a freight route over any distance so it can be compared. The two freight routes that will be tested in this scenario will be both from London Gateway and the cross-country destination will be the Coatbridge terminal 354 miles away and the other route will be to the Birmingham terminal a distance of 121 miles away. Although both distances seem relatively considerably far it is still valid to refer to one route as cross-country and the other as urban route as London Gateway to Coatbridge terminal route is almost half the length of the UK and the London Gateway to Birmingham terminal travels between two of the UK's largest cities.

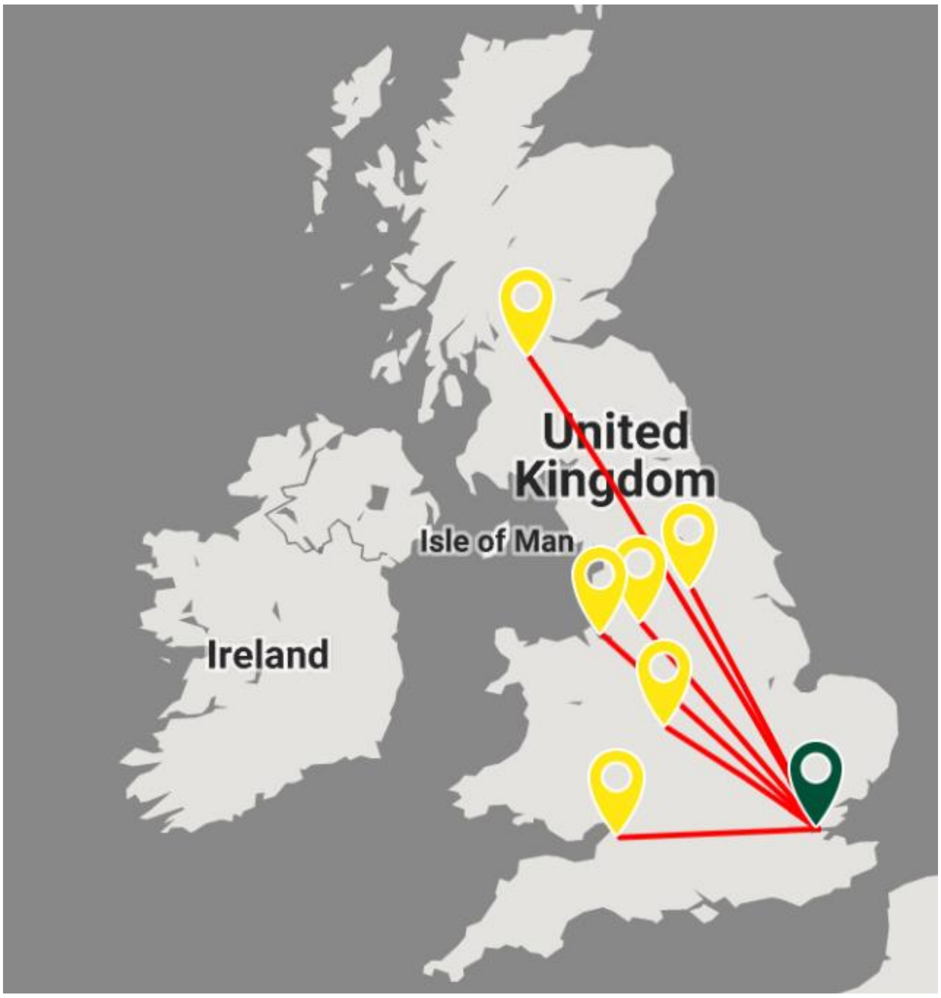


FIGURE 3-22 UK FREIGHT TERMINAL MAP

In this scenario a fundamental difference between the last scenario is that the cost of electrification will not be compared to the cost of the required H2 fuel. This is due to both routes to the destinations in this scenario are electrified and all the routes electrified in the UK can be seen in purple and green and all routes where electrifications projects are planned are highlighted in blue as of August 2018 which can be seen in Fig 3-22. Although this scenario cannot compare the cost of track electrification of the track length it can be compare the diesel and H2 emissions to electric train emissions 1.089 Kg of CO2 per Km. The source does not specify if this a passenger or freight train so any comparison with the emissions of electric train is only estimation.

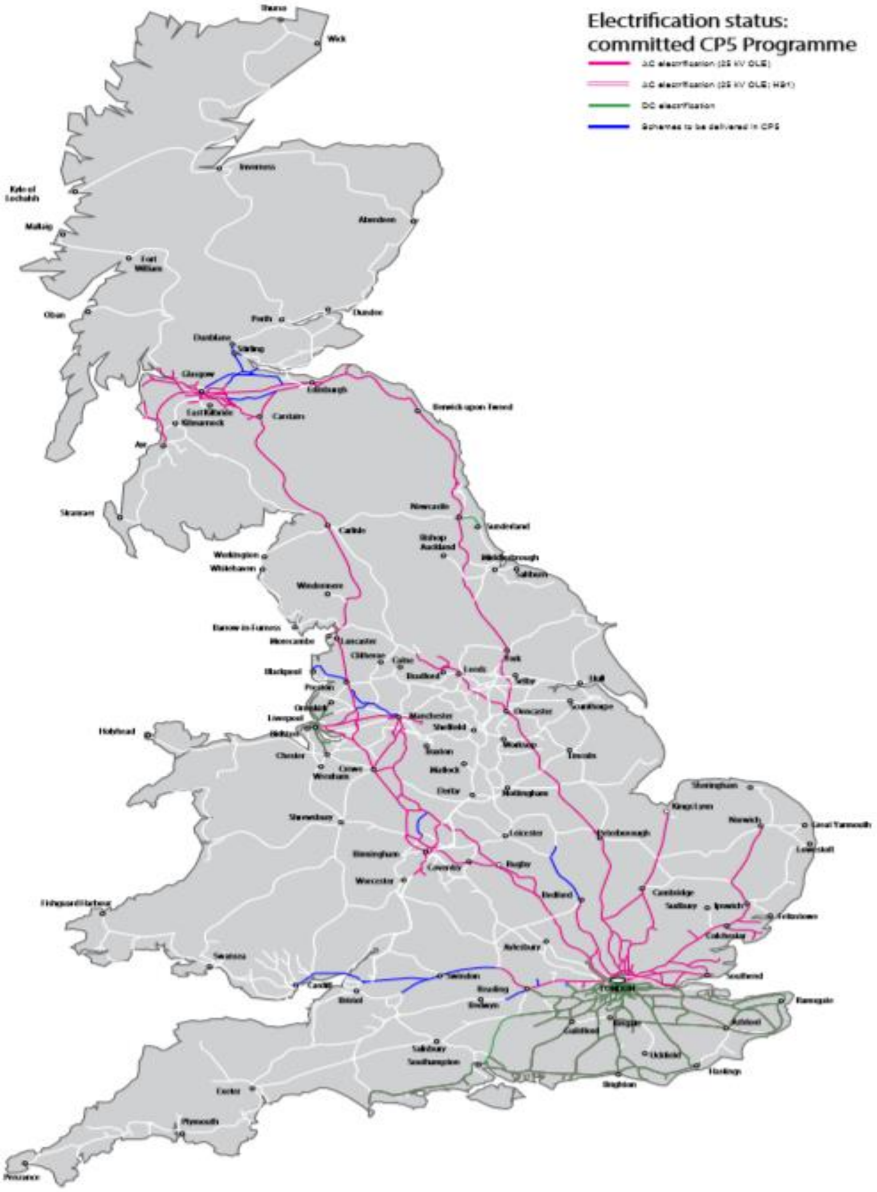


FIGURE 3-23 ELECTRIFICATION MAP OF THE UK RAILWAYS

3.2.1 London Gateway to Coatbridge Terminal

To get the desired outputs from the tool the 3 inputs the required are needed, the distance and power are already known as the power requirements are based around a class 66. The class 66 operates regularly on this line so the tool is well matched to give an accurate prediction of a retrofitted H2 class 66 that would operate on this route. As the speed of the H2 train would be operating on this route is not known it can be found in a similar way the speed was found in scenario 1. The time is required for this and it will again be taken from the rail schedule from London Gateway which operates daily services from London Gateway to Coatbridge terminal, this schedule also shows previous journeys and the time taken to complete them. To establish the average time for this journey 5 previous journey times are taken, 9 hours 20 mins, 10 hours 47 mins, 9 hours 27 mins, 9 hours 39 mins and 9 hours 32 mins, then averaged giving overall average time of 9 hours 45 mins. The electrical train emissions will also be calculated for this route so all 3 types of trains and their emissions can be compared.

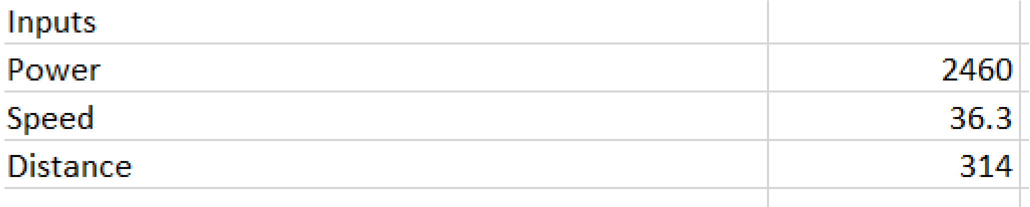
Distance = 314 miles

Time = 9 hours 45 mins = 9.75 hours

Speed = $\frac{Distance}{Time} = \frac{354}{9.75}$ = 36.3 miles per hour

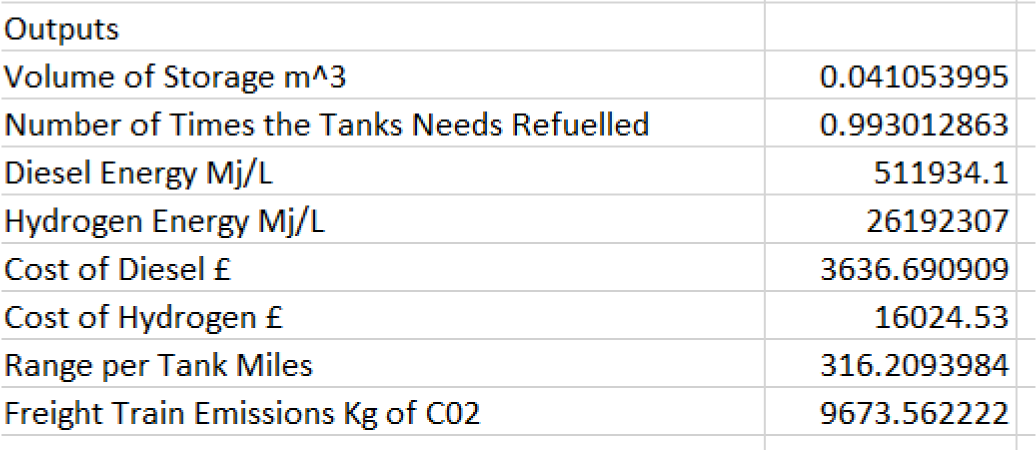
Electrical Train Emissions Kg of CO2 per Km = 569.6 x 1.089 = 620.3 Kg of CO2

When all 3 inputs speed, 36.3 miles per hour, distance, 354 miles, and power, 2460 Kw, the tool will be able to produce the same deliverables as the previous scenario but these will all be behave differently due to the distance, power requirements and the number of fuel cells that are required. This scenario like the previous one will again show both effects of low-pressure storage, 35000 Kpa and high pressure 75000 Kpa and how much space may be saved in terms of storage.



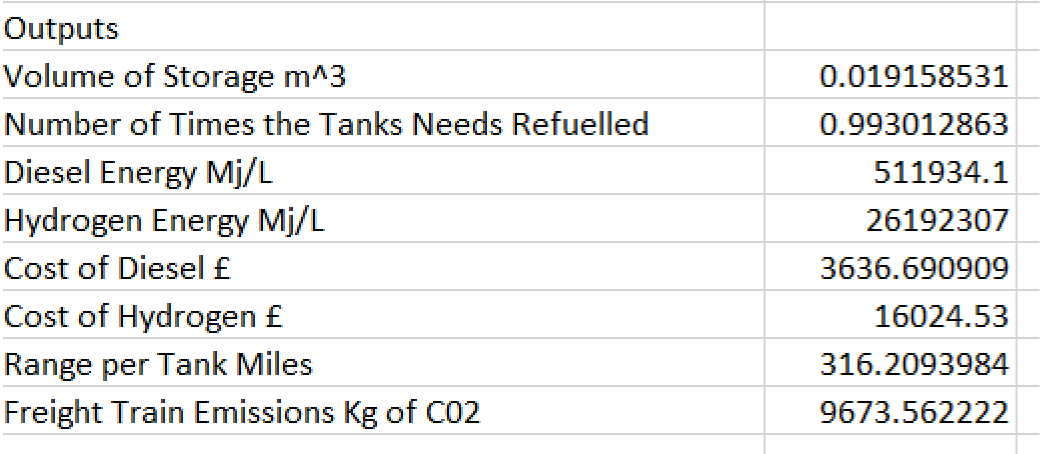
Inputs	
Power	2460
Speed	36.3
Distance	314

FIGURE 3-24 FREIGHT INPUTS



Outputs	
Volume of Storage m^3	0.041053995
Number of Times the Tanks Needs Refuelled	0.993012863
Diesel Energy Mj/L	511934.1
Hydrogen Energy Mj/L	26192307
Cost of Diesel £	3636.690909
Cost of Hydrogen £	16024.53
Range per Tank Miles	316.2093984
Freight Train Emissions Kg of C02	9673.562222

FIGURE 3-25 LOW PRESSURE FREIGHT RAIL



Outputs	
Volume of Storage m^3	0.019158531
Number of Times the Tanks Needs Refuelled	0.993012863
Diesel Energy Mj/L	511934.1
Hydrogen Energy Mj/L	26192307
Cost of Diesel £	3636.690909
Cost of Hydrogen £	16024.53
Range per Tank Miles	316.2093984
Freight Train Emissions Kg of C02	9673.562222

FIGURE 3-26 HIGH PRESSURE FREIGHT RAIL

The results are similar to that of the pressure differences for storage tanks from the H2 passenger train as the space taken up at the high pressure is less than half that at the lower pressure but the fuel required and the number of fuel cells are much higher than a passenger train as the fuel required is almost 10 times greater. More fuel cells and greater fuel requirements leads to greater costs and high-pressure storage which is an additional expense that would massively increase the cost even though it has the potential to double the range it will not be adopted for analysing this route. The results from the tool for the given route that will be used can be seen in Fig 3-25 showing an average daily operation. If these results are analysed with the same two factors sustainability and cost effectiveness as a passenger H2 train it can be seen that to operate the same daily service over this freight route that just under 10 tonnes of CO2 emissions can be reduced daily and roughly just over 3500 tonnes of CO2 annually but at the cost of over 4 times the price of diesel fuel for the same daily journey. The H2 train will have zero emissions and fairs well when compared to electrical trains and diesel trains in terms of emissions but even though the emission data for an electrical train is more of broad estimate it offers large improvements over diesel freight train emissions for cross country freight travel. The H2 freight service would also have to refuel along the way, the tool does not take into consideration the time taken to refuel the train which could have an adverse effect on this service as the journey time would have to increase to account for refuelling and the feasibility of the creating a H2 fuelling station on the route and changing the already existing infrastructure is not considered and the cost implications this would have on any freight operator. The storage and transportation of any H2 to the refuelling creates more logistical problems when using H2 freight trains. The cost of kg of emissions reduced based on the fuel price of H2 would be £1.65 is slightly more expensive than compared to H2 passenger train due to loads which freight trains carry and their subsequent greater power requirements leading to more H2 fuel cells and higher H2 consumption rates. Even though freight train range is relatively good greater use of electrification may be more economically and technically feasible for long distance freight travel when compared to the fuel costs as it can be seen on Fig 3-25 that the electrification infrastructure to majority of the UKs major cities is already there.

3.2.2 London Gateway to Birmingham Terminal

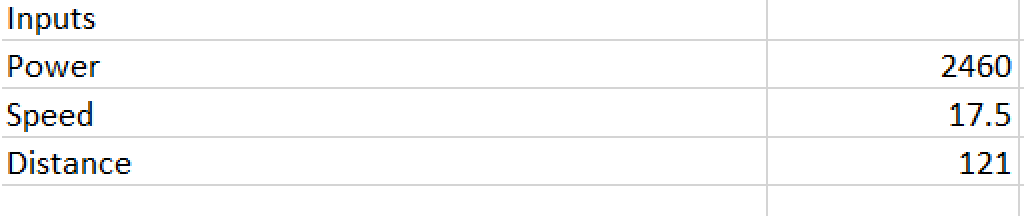
The same methodology for the cross-country freight route will be applied to the shorter urban rail between London Gateway and Birmingham terminal. The power input is again is the same 2460 Kw as the class 66 used in the tool operates on this route, the distance input is 121 miles and the time again is found from taking 5 journey times from the London Gateway schedule which operates daily services to the Birmingham terminal. The 5 times that will be used to establish the average journey time are 6 hours 25 mins, 6 hours 21 mins, 9 hours 18 mins, 6 hours 26 mins and 6 hours 11 mins giving an average journey time of 6 hours 56 mins. From this the final input the speed will calculated as well as the emissions of the equivalent electric train over the same route.

Distance = 121 miles

Time = 6 hours 56 mins = 6.93 hours

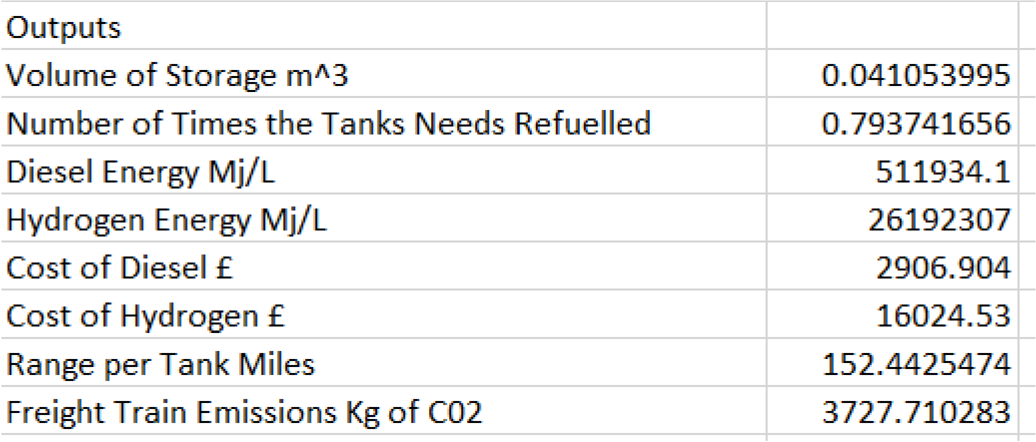
Speed = $\frac{Distance}{Time} = \frac{121}{6.93}$ = 17.5 miles per hour

Electrical Train Emissions Kg of CO2 per Km = 194.7 x 1.089 = 212 Kg of CO2



Inputs	
Power	2460
Speed	17.5
Distance	121

FIGURE 3-27 SHORT DISTANCE FREIGHT RAIL



Outputs	
Volume of Storage m^3	0.041053995
Number of Times the Tanks Needs Refuelled	0.793741656
Diesel Energy Mj/L	511934.1
Hydrogen Energy Mj/L	26192307
Cost of Diesel £	2906.904
Cost of Hydrogen £	16024.53
Range per Tank Miles	152.4425474
Freight Train Emissions Kg of C02	3727.710283

FIGURE 3-28 SHORT DISTANCE FREIGHT OUTPUTS

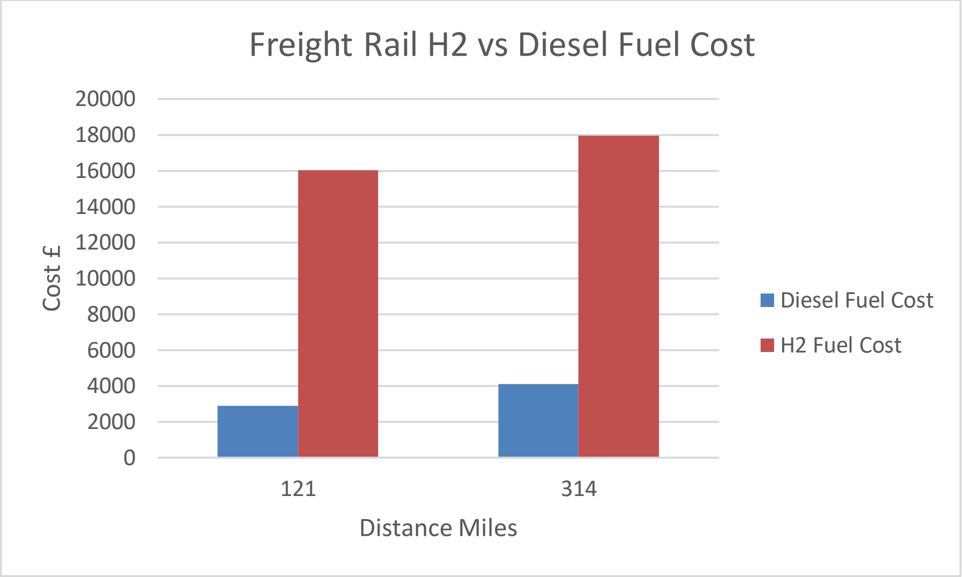


FIGURE 3-29 FREIGHT RAIL FUEL COST COMPARISON

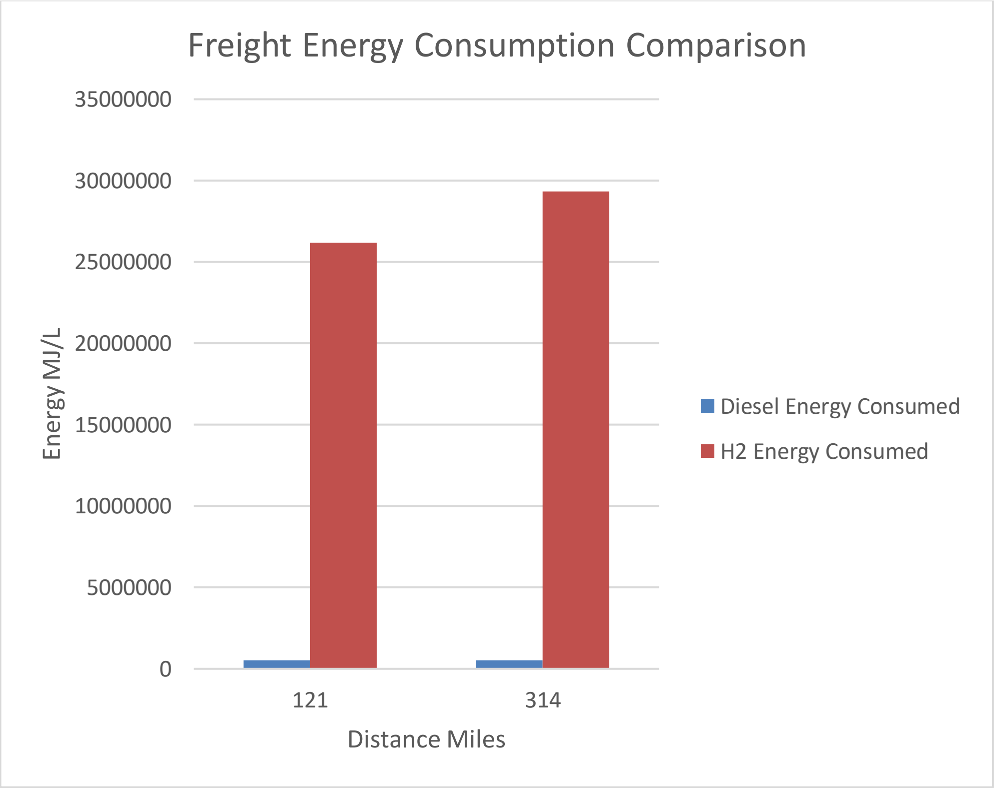


FIGURE 3-30 FREIGHT RAIL ENERGY CONSUMPTION COMPARISON

The short distance outputs differ significantly as short distance freight route travelled by a H2 train does not require refuelling but the outputs produced by the tool also show that the range of the H2 is less than half and their isn’t much of cost difference between the long term and short term freight journeys. Even though it does need refuelled over this journey, if a return journey is required then the train would not have the fuel available to complete this and a refuelling station would be required. The problem of refuelling means that it may be more feasible to store the H2 used at even high pressures and add more fuel tanks to save refuelling and increase the range, but these methods are both expensive. The costs of H2 fuelled required for freight rail travel will be much higher than passenger H2 travel which would create a greater demand on H2 and could potentially increase its carbon footprint as H2 will be required to be produced from numerous methods such as reforming natural gas which produces CO2 and the transportation of the large quantities H2 will again increase its carbon footprint. The cost comparison between diesel and H2 for this journey is considerable as the of H2 needed at its current price is more than 5 times more expense. It will also require significantly more amounts of energy and in terms emissions that could be saved there is large potential available as nearly 4 tonnes of CO2 per journey of emissions will be reduced and over 1360 tonnes annually could be saved. Again it comes down balancing both decarbonisation with cost as currently it would cost £4.3 per Kg of CO2 emissions reduced and when compared same metric for long distance H2 freight travel which is £1.65 per Kg of CO2 emissions reduced which would show purely on this metric alone that cross-country freight would appear to be advantageous for balancing costs with decarbonisation for H2 freight usage. However, this does not consider the added difficulty and expense of creating H2 refuelling stations.

3.3 Scenario 3

The final scenario will look into the use of operating H2 passenger trains on the UK's high-speed rail infrastructure and its prospects on the future of the high-speed rail in the UK. There a currently 3 high speed ranges operating on the UKs rail network and these are speeds up to 110 mph, 125 mph and between 140-180 mph. As there are different ranges for high speed rail on the existing rail network that can operate at over 110 mph the high-speed rail network across the UK is extensive. However, currently only HS1 operates at the highest speeds and is shortest of all high-speed routes and is entirely electrified running from London to the channel tunnel. HS1 is a double track electrified route with a maximum speed of 186 mph. The HS1 route is part of the Trans-European high-speed rail network (TENS), it also improves domestic passenger trains as some can run on this route between London and Kent and has the added facility to allow freight traffic operations. HS1 was the first new British railway line in 100 years and was introduced into service in 2003, the rolling stock that runs on this line are electric trains such as the class 373 which is large high speed passenger train that is 400 m long and has the capacity to carry up to 750 passengers. As this is an electrified route this scenario will focus on replacing DMUs designed for operation at high speeds up to 125 mph running on routes across the UK and it will also focus on the use of H2 trains being adopted on the new HS2 line which is not yet completed and would operate at speeds of around 186 mph and currently there are very few trains in the world capable of achieving these speeds. The future of high-speed rail in the UK is potentially the HS2 line which is planned to run between London and Birmingham and plans to serve the Midlands and the North West regions. High speed rail lines are perceived as a method of shortening journey times between major cities and seen as an effective way of increasing the capacity on the rail network.

FIGURE 3-31 EXISTING AND PROPOSED HIGH-SPEED RAIL NETWORK

Rail have always been seen as good for the environment compared to other methods of transport due to its low carbon footprint with regards to HS2 debates and respect to global objectives to reduce overall carbon footprints. Cornet et al analyse the longer-term environmental impacts of HS2 as the decisions around HS2 is seen as a short-term solution to immediate problems such as economic growth and improved rail connectivity but does not consider the long-term levels of carbon emissions. HS2 is now £55 billion high speed rail project that is supposed to connect London to Birmingham with further expansion to connect Manchester, Leeds and Sheffield. HS2 has been questioned by many and the Eddington 2006 Stern report states that “assumption that more and faster are always better”. HS2 also opens up a debate about environmental impact that could be caused as rail is usually seen as a low carbon method of transportation but the energy requirements will increase with speed and so will the CO2 emission factors due to the high carbon impact on the local environments as the construction of additional rail infrastructure comes with high carbon costs although the extent of this would be difficult to measure. HS2 has not been fully analysed from a reduction in carbon footprint perspective but the governments sustainability policy states that HS2 should try and deliver low carbon long distance journeys. The carbon effects of HS2 are dependent on the speed that the UK electricity generation will shift towards decarbonisation as it could potentially be an entirely electrified route like HS1 meaning the electric trains would produce no direct emissions but it would place major energy demands on the UK grid and most likely majority of this surplus energy needed would not be produced by the renewables. Partly because renewable energy supply is intermittent making it difficult to predict as result for consistent energy needs for these routes it is most likely going to be provided via energy generated from fossil fuels or nuclear. If the use of H2 trains were to be adopted for HS2 then the carbon footprint will no longer be dependent upon the electricity generation mix of the UK electricity grid and will not create additional demands on the grid as it will be independent from it.

Based on this the two scenarios that will be tested are a scenario where existing rolling stock will be tested on a current high-speed route and the second scenario will be the testing of H2 train on the not yet completed HS2 which operates at much higher speeds.

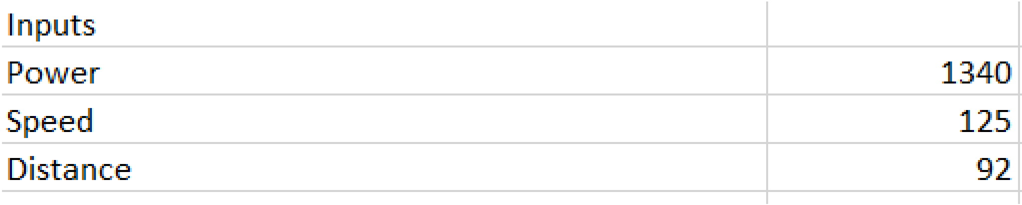
3.3.1 High Speed Rail Network

The DMUs that currently operate on the UKs existing high-speed routes which can reach speeds of up to 125 mph are the class 43 with an engine power output of 1320 kW and class 180 which has an engine output of 560 Kw. As both these trains are DMUs that run on the high-speed lines they will both be tested by the tool to show what the equivalent high-speed H2 train with a high and low engine power output would produce in outputs from the tool. This part of the scenario will have several sub sections as both trains will be tested over the same route between Newcastle and Edinburgh Waverly. This route operates at speeds of around 125 mph and 87 journeys a day with a journey time of 1 hour and 25 mins and based on this journey time if one H2 train was to be introduced to this route there could only be a maximum of 16.9 services from this train in a day. So, both trains will initially test one journey and then test 16 journeys to see what the tool produces for H2 trains operating at these speeds over these many journeys in day. Any predictions regarding this scenario are difficult to predict as the previous scenarios have not tested H2 trains at these speeds but one prediction could be made regarding the power outputs of trains based on scenario. The lower power output passenger train in scenario 1 proved to be more suited to adaption for the use of H2 this scenario will show whether or not this is still the case and how suited the use of H2 will be to the future of high-speed rail in the UK on existing lines.

FIGURE 3-32 EDINBURGH WAVERLY TO NEWCASTLE

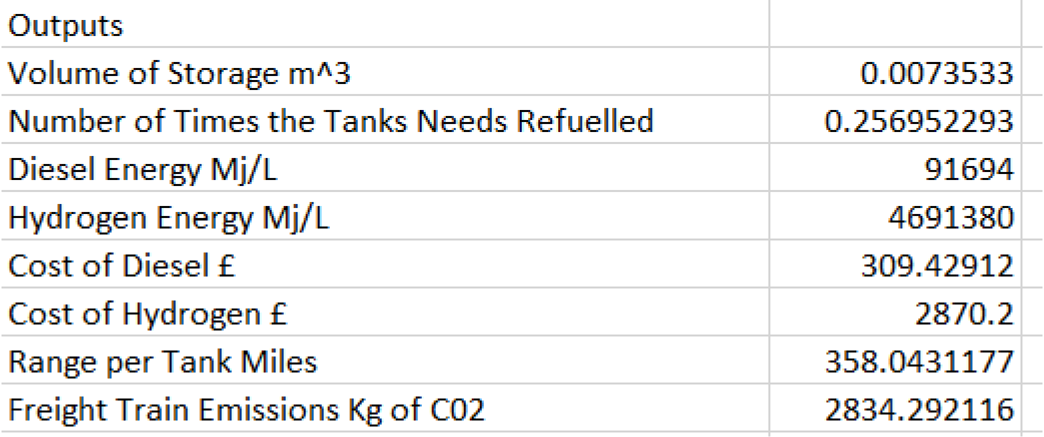
3.3.1.1 High Speed Rail Network Class 43

The inputs of for the tool are all known in this part of the scenario and no other calculations are required, the initial inputs are speed 125 mph, distance 92 miles and power 1320 Kw. This first results produced by the tool are for only one journey to initially see how the H2 train would operate at these speeds. The second part of this subsection within this scenario will focus on how the H2 train would manage and what the outputs the tool would produce for this journey over 16.9 trips as this is the maximum amount of services that one train can operate on this route daily but 16 trips will be used as to allow time for stops and refuelling. Hobson and Smith use similar emission factors for several freight trains and the intercity 125 which is a similar high-speed train to the class 43 which is being tested in this scenario. So, for this reason the emissions produced from the tool that will be used for the analyse of high-speed passenger trains will be the same as the emissions produced for the freight trains.



Inputs	
Power	1340
Speed	125
Distance	92

FIGURE 3-33 CLASS 43 INPUTS



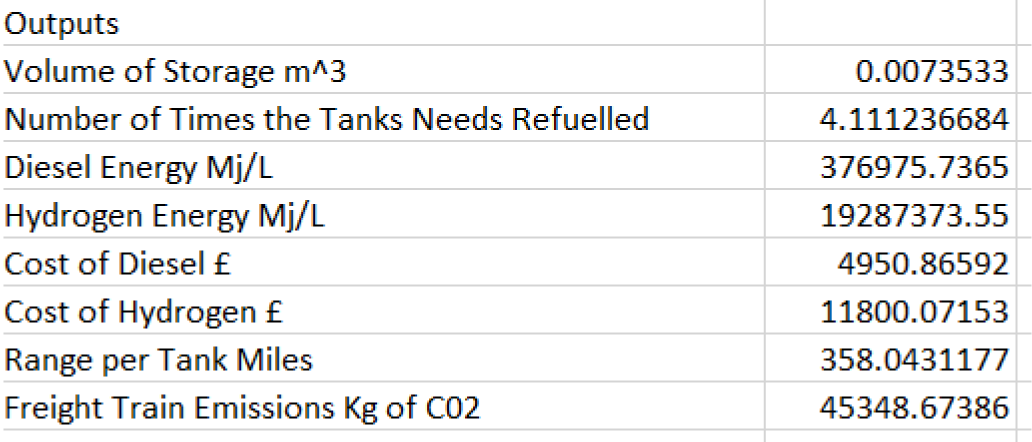
Outputs	
Volume of Storage m^3	0.0073533
Number of Times the Tanks Needs Refuelled	0.256952293
Diesel Energy Mj/L	91694
Hydrogen Energy Mj/L	4691380
Cost of Diesel £	309.42912
Cost of Hydrogen £	2870.2
Range per Tank Miles	358.0431177
Freight Train Emissions Kg of C02	2834.292116

FIGURE 3-34 CLASS 43 OUTPUTS

Based on the outputs produced from the tool for the class 43 high-speed train the range is relatively good as the H2 trains operating on this route would be able to carry out 3.9 journeys over this distance before needing refuelled. Meaning over the 16 daily journeys one train could be predicted to make 4.1 refuelling's but this will be confirmed in the analyse over 16 journeys. The energy consumption compared between both fuels again is significant as the H2 trains requires a lot more energy and also consumes fuel at a much higher rate than a high-speed diesel train. For operating a H2 train at speeds of 125 mph the cost difference has grown massively as it is roughly 9.3 times more expensive than the diesel fuel costs. To put these costs in perspective compared to the two other types of passenger trains previously tested in the first scenario where the lower power H2 passenger train fuel cost were 2.3 times more expensive and the slightly higher power passenger train was 2.7 times more expensive. So it is significantly more costly for fuel but this may not be the best comparison as the high speed train is larger meaning it carries a heavier load and also requires more power from the fuels cell so a better comparison might be the freight trains compared in scenario 2. For the two types of freight train there is a large difference in the cost of fuels compared as the short distance freight train journey tested showed that the cost of H2 fuel compared to diesel was 5.5 times greater and for the long distance freight journeys the cost difference showed that it was slightly cheaper at 4.4 times more expensive for H2 fuel. All of the previously tested scenarios so far compared to the high-speed passenger train has showed that the high-speed class 43 has the greatest fuel costs of the H2 trains tested in the tool so far. The results will be analysed from a CO2 emissions reduction perspective once it has been tested overall 16 journeys that operate on this route daily for one train to see if there is deviation in these results once the distance increases. The only input that will change is the distance which will increase from 92 miles to 1472 miles.

Inputs	
Power	1340
Speed	125
Distance	1472

FIGURE 3-35 CLASS 43 INPUTS 16 JOURNEYS



Outputs	
Volume of Storage m^3	0.0073533
Number of Times the Tanks Needs Refuelled	4.111236684
Diesel Energy Mj/L	376975.7365
Hydrogen Energy Mj/L	19287373.55
Cost of Diesel £	4950.86592
Cost of Hydrogen £	11800.07153
Range per Tank Miles	358.0431177
Freight Train Emissions Kg of C02	45348.67386

FIGURE 3-36 CLASS 43 16 JOURNEYS OUTPUT

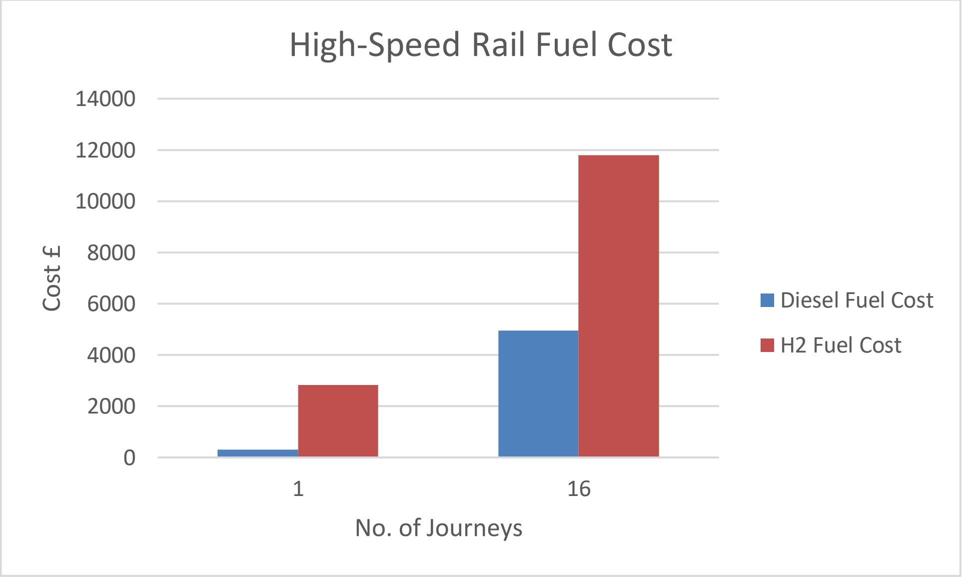


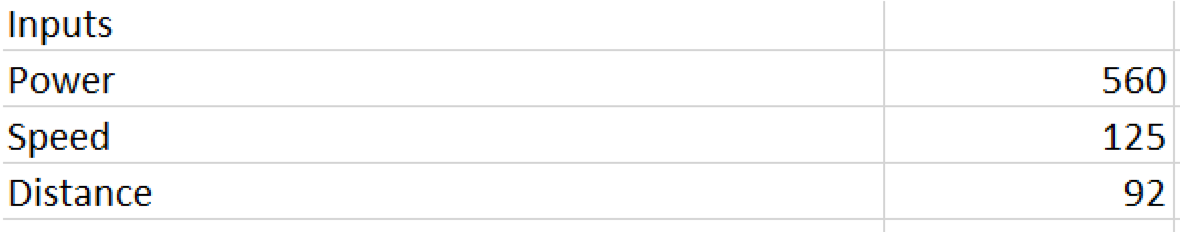
FIGURE 3-37 CLASS 43 HIGH-SPEED FUEL COSTS

The prediction of the number of refuelling stops the H2 train is accurate and there has been a cost decrease over the distance in comparison to the two fuels as it is now only 2.4 times more expensive for H2 fuel. From this it can be said to operate a higher power high-speed passenger train on existing high-speed lines it is more economical to run over long distances. Although the tool does not take into account the number of stops, type of track and gradients on this route. In terms of costs of every kg of CO2 not being emitted it would work out to £0.26 but as there is no solid data for the emissions factor of a high-speed passenger train assumptions have been made equating it to the same as emissions produced from a diesel freight train.

Although this value for the class 43 may not be as accurate or reliable as for the other scenarios the switch to H2 still offers a positive environmental benefit and is also more cost effective than freight rail and like H2 regional passenger trains.

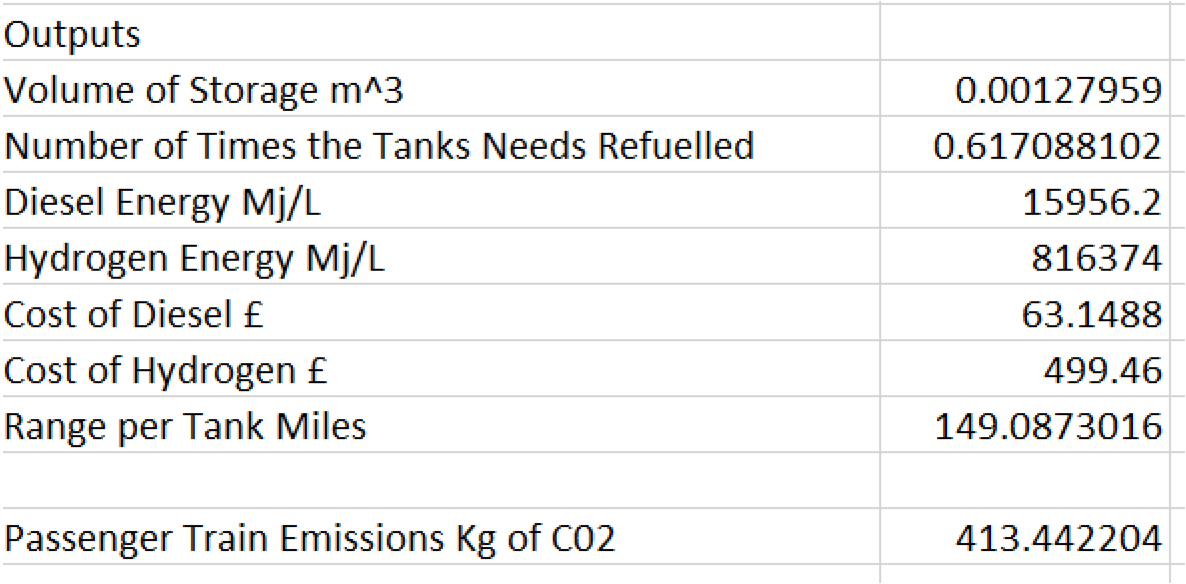
3.3.1.2 High Speed Rail Network Class 180

An identical approach for the class 180 on the same route with the only output changing being the power output will be used. The initial distance tested on the tool would be 92 miles as before and the speed would again be 125 mph with power input being 560 Kw. Unlike the previous high-speed passenger train the emission factor of a freight train will not be assumed but instead the emission factor of a passenger train in the tool.



Inputs	
Power	560
Speed	125
Distance	92

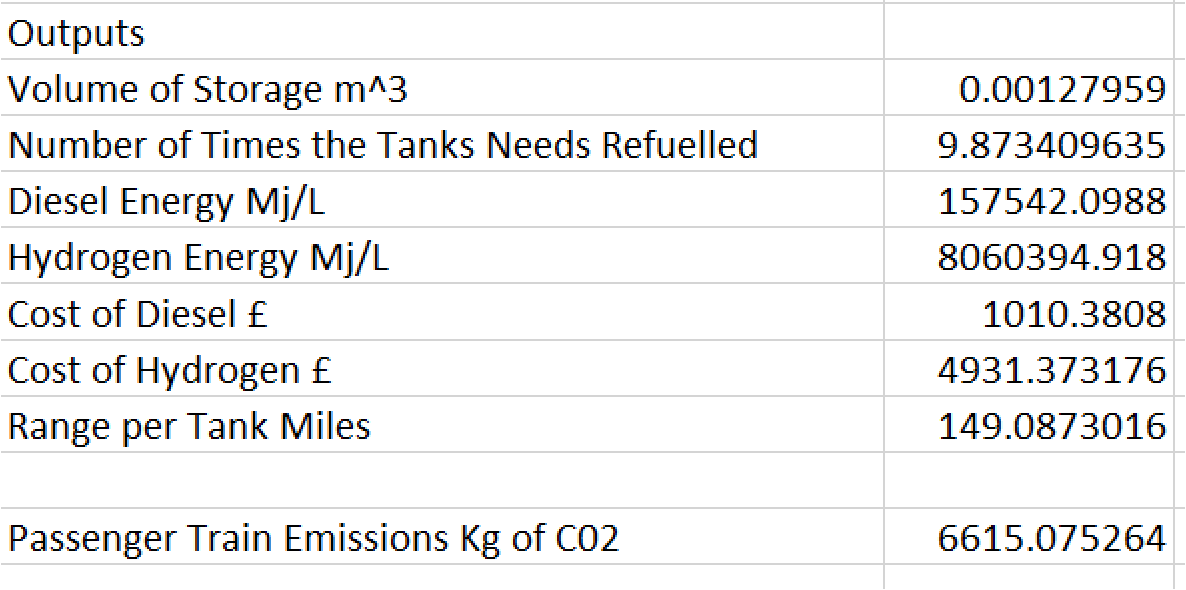
Figure 3-38 Class 180 Inputs



Outputs	
Volume of Storage m^3	0.00127959
Number of Times the Tanks Needs Refuelled	0.617088102
Diesel Energy Mj/L	15956.2
Hydrogen Energy Mj/L	816374
Cost of Diesel £	63.1488
Cost of Hydrogen £	499.46
Range per Tank Miles	149.0873016
Passenger Train Emissions Kg of C02	413.442204

Figure 3-39 Class 180 Outputs for 1 Journey

The lower power high-speed passenger trains range is much less as can be seen in Fig 3-38 as it would only complete 1.6 journeys before needing refuelled. This will result in lower fuel costs as can be seen but ultimately this is due to limited range and amount of fuel it is able to store. The engine space for this type of passenger train within the tool once taken up by the volume of fuel cells required to match the engine power demand leaves very little space for the storage of H2. Even though the load, H2 consumption rate and energy consumption of this H2 train is less than the other high-speed train tested its range is its main limiting factor as it would require additional space for H2 storage as the engine space once filled with the necessary fuels does not leave enough volume that could be used for H2 storage as the other train tested has more than double the range.



Outputs	
Volume of Storage m^3	0.00127959
Number of Times the Tanks Needs Refuelled	9.873409635
Diesel Energy Mj/L	157542.0988
Hydrogen Energy Mj/L	8060394.918
Cost of Diesel £	1010.3808
Cost of Hydrogen £	4931.373176
Range per Tank Miles	149.0873016
Passenger Train Emissions Kg of C02	6615.075264

FIGURE 3-40 CLASS 180 OUTPUTS 16 JOURNEYS

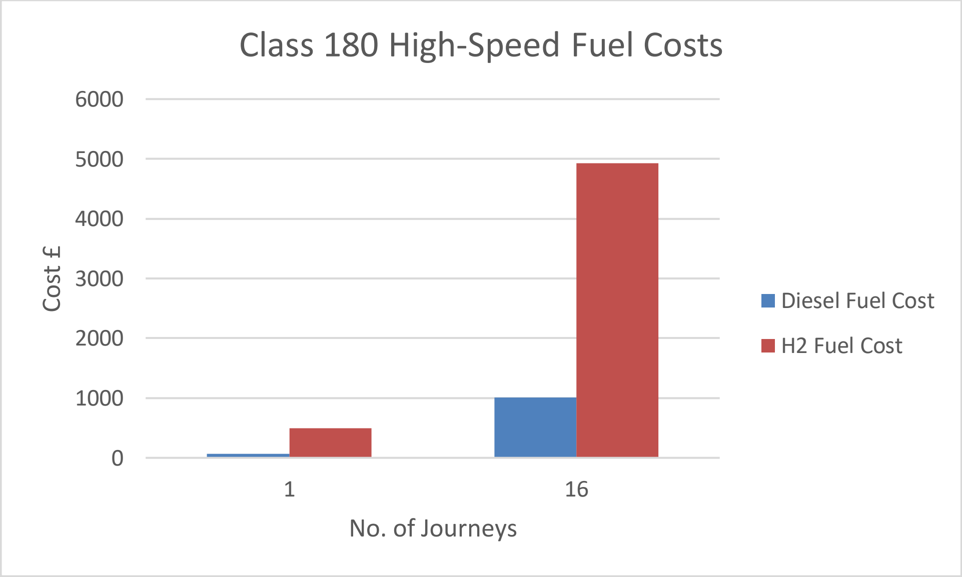
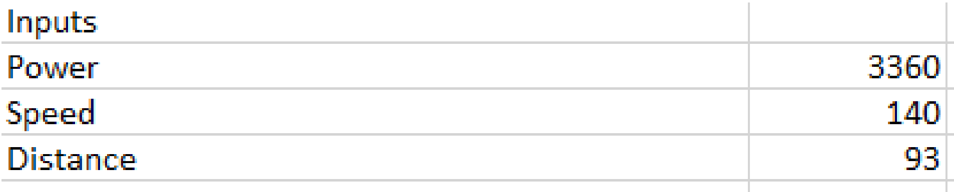


FIGURE 3-41 CLASS 180 HIGH-SPEED FUEL COSTS

When analysed over 16 journeys it becomes clearer that a high-speed passenger train operating on this line would not be suitable due to its limited range and that it would require nearly 10 refuelling stops. Although in terms of cost of H2 per Kg of CO2 being reduced shows that it would only cost £0.75 and has the potential to save 2400 tonnes of CO2 being emitted. The class 180 high-speed train offers a more affordable way to reduce the cost the emissions but due its limited range and infrastructure required for number of times it needs refuelled this to become technically feasible.

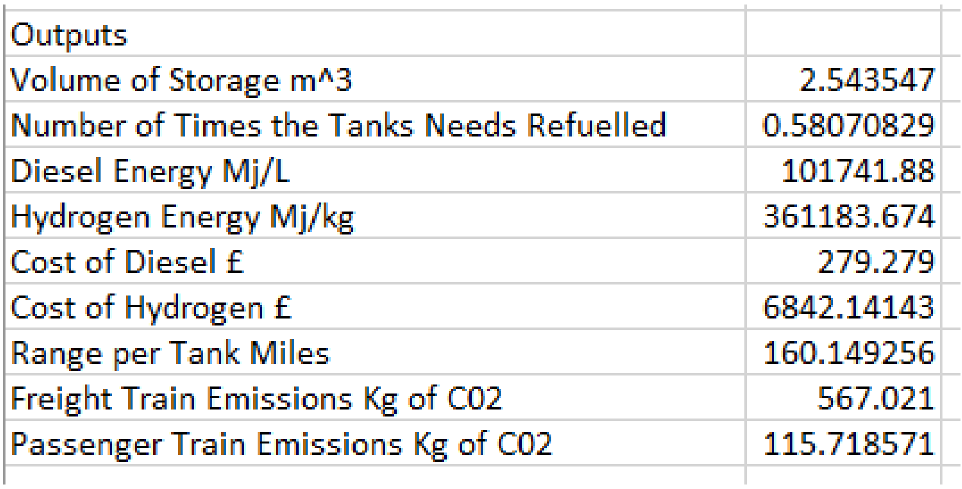
3.3.2 High Speed 2

HS2 is split into two phases with phase 1 being between London and the West Midlands and phase 2 connecting the North of England. Phase 1 is currently undergoing construction and is set to be completed by 2026 and is to be electrified like HS1. Based on this an assumption is made that the rolling stock that would operate on HS2 would be the same as would operate on HS1. Even though phase 1 of HS2 is set to be electrified this scenario will test H2 trains operating at speeds of up to 140 mph like on HS1. This part of the scenario will test H2 trains on phase 1 of HS2 with the engine power requirements being taken from the existing HS1 rolling stock. A passenger commuter train that operates on this line is the class 395 a high-speed train an operates at a speed of 140 mph and is capable of greater speeds. The 3 inputs that will be used in the tool are the power 3360 Kw, distance 93 miles and speed 140 mph. No diesel trains would operate on this route so the emission savings based around diesel and freight trains will not be applicable for this scenario. Instead the emissions factor previously quoted for electrical trains will be used for purposes of comparison and to give an estimate of the CO2 emission saving that could be made and is 1.089.



Inputs	
Power	3360
Speed	140
Distance	93

FIGURE 3-42 CLASS 395 HIGH-SPEED TRAIN



Outputs	
Volume of Storage m^3	2.543547
Number of Times the Tanks Needs Refuelled	0.58070829
Diesel Energy Mj/L	101741.88
Hydrogen Energy Mj/kg	361183.674
Cost of Diesel £	279.279
Cost of Hydrogen £	6842.14143
Range per Tank Miles	160.149256
Freight Train Emissions Kg of C02	567.021
Passenger Train Emissions Kg of C02	115.718571

FIGURE 3-43 CLASS 395 HIGH-SPEED TRAIN

The final H2 train to be tested in the tool the high-speed Class 395 travels roughly the same distance over 1 journey as the Class 180 in the previous section. When compared the range of the Class 395 is slightly greater but despite this the costs are much greater and the ability to determine emissions is decreased. The most notable difference between them is the consumption of H2 and the price increase. The range produced in the tool is not as promising either as it would need to be refuelled on a return journey as it would only manage 1.7 journeys per tank.

4 Chapter 4: Conclusion and Future Work

From each scenario several conclusions were able to be made about passenger, freight and high-speed passenger trains adopting H2 as their primary fuel source based on the outputs produced from the tool. The first scenario where low power and high-power passenger trains were tested over the same route, the result showed that the lower power passenger train is more suited to use of H2 as the tool results produced a greater range and therefore less refuelling. It also showed that the cost of every kg saved of CO2 saved is less than that of the higher-power passenger train. Therefore, the lower power passenger train is more cost effective at reducing emissions than the higher power passenger trains. The second scenario where the use of H2 trains in the freight rail sector was tested and the tool showed that long distance freight travel was more advantageous for the adoption of H2 compared to shorter distance freight journeys. Over long distance freight journeys there is greater reductions in CO2 emissions and shorter distance freight journeys with H2 as the fuel are as cost effective as a means of reducing CO2 emissions for freight transport. However, although the long-distance freight proved better matched with H2 as it fuel source than the shorter distance freight journeys, most the lines are already electrified and may prove to be better to fully switch to an electrified rail network. Despite this it is still worth investing H2 as future technology for freight transport as it offers potential for greater decarbonisation and it also takes away some of the reliance placed on the energy grid.

The final scenario where H2 high-speed rail was analysed and tested in the tool much of the emissions data is not as readily available but evidence from the literature states that constant acceleration and deceleration has a greater impact on the emissions produced and not its overall speed. The existing high-speed passenger trains based on the emission data available showed that they were the most economical on terms of cost of reducing CO2 emission compared to both passenger and freight trains. The HS2 route tested in the tool showed that not only was there a large energy requirement difference between fuels but the cost of the two fuels compared was also large. The future of H2 trains is still dependent upon several factors such as the cost reduction of H2 to make it more competitive with diesel, improvement in storage at high pressures and the life of fuel cells. Although there are still aspects to improve before the widescale use of H2 as a fuel source for trains the current trend to move away from fossil-based fuel and specifically diesel is key to future adoption of H2 trains. More information regarding high-speed trains that operate on the future HS2 routes is needed to be able to make more accurate predictions from the tool. Future work that would further improve the tool and its range of outputs would be to gather more information on high-speed train and their emissions and also to take a wider focus on the rail industry outside the UK, explore other rail networks that may be more compatible for the use of H2 trains and to include greater information regarding electric trains within the tool.

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