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An Analysis of the Methods used to calculate the Emissions of Rolling Stock in the UK

Timo Esters & Marin Marinov[1]

Abstract

The aim of this study was to analyse and compare the different modes of operation of UK rail based on direct and indirect emissions. The three modes under comparison were; diesel, electric and bi-mode. As well as comparing these three modes of operation, a comparison between Conventional, Freight and High Speed Rail was made. Alternate fuels were considered for diesel and bi-mode locomotives and compared based on their environmental impact. The three chosen methods were used to calculate the emissions of each train and a comparison of these methods was made. In the current UK energy climate, diesel trains emit less emissions than electric trains when factoring in mechanical and air resistances. Bi-mode trains have their place in the UK network but with electrification of the network currently in place, this mode of operation will become redundant in the near future. High Speed Rail, although time efficient, releases high emissions due to energy consumption increasing with the square of speed. Alternative fuels, such as biodiesel, should be a consideration for the future of rail, as emissions fall dramatically with content of biodiesel in fuel blends.

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1. Introduction

In the last decade concern for the environment and greenhouse gas emissions have increased. It is now important for a company to assess the impact their operations have on the environment, and to implement strategies to reduce this impact. The transport sector is particularly concerned with the reduction of emissions, and is constantly striving for more efficient, green technologies in order to reduce its carbon footprint.

The rail industry is changing as more efficient technologies arise and demands increase. Diesel is currently the predominant source of energy used in the UK rail industry as only 40% of the UK rail network is electrified[1]. Currently, large investments are being made into the electrification of certain routes in the UK network[2], as Network Rail aims for a more environmentally friendly system. Plans to introduce bi-mode locomotives (hybrid trains which can operate on an electric supply or diesel engine), to bridge the gap between electrified tracks, are in place and the said locomotives are expected to be fully integrated by 2020[3].

High Speed Rail was first introduced in the UK in 2003 and plans to build a second High Speed Line are currently underway[4]. The necessity for shorter travel times is a major factor when customers select a mode of transport; therefore it is necessary to update the rail network in order to meet the

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demand. Rail freight is also a growing industry in the UK with over 101.7 million tonnes being transported all around the UK in 2011/12. Network rail predicts demand will increase by 140% in the next 30 years[5]; this is not sustainable with current technologies. In order for the UK Rail Network to achieve sustainability alternative fuels and new technologies must be considered.

Biodiesel is the only well-established alternative fuel used in the rail industry; even then it is not commonly used. It has many advantages over diesel, including its low carbon content, but its fuel economy is second to that of diesel; one of the reasons it isn't commonly used in the rail industry[6]. Other fuels such as Liquid Natural Gas (LNG) and Hydrogen are being considered for use in rail[7], and could lead to a more sustainable rail network in the UK.

2. Objectives

The objectives of this paper are to compare methods for calculating direct and indirect emissions of different categories and types of rolling stock for the purposes of the rail services in the UK.

3. Methodology

Background research was carried out in order to gain knowledge on the topic of study, this formed the foundation of the work. Research on emissions and how they are estimated/calculated was undertaken to form the basis of the methods used. A selection of a variety of trains, operating in the UK, was chosen for comparison. Once a full set of trains were found, methods for calculating emissions were reviewed and selected for comparison. All the required data on the selected trains was sourced and the emissions of these trains calculated. Results were collated and analysed and the comparisons stated in section 3. were made.

4. Research

4.1. Modes of Operation

There are two energy sources currently used in the UK rail industry: electricity and diesel fuel. Diesel is still the predominant fuel used to power locomotives in the UK, as only 40% of the network is currently electrified[1]. Other networks in Europe are primarily electrified (Sweden, Netherlands, Germany etc.) with Switzerland being fully electrified[8]. Electric trains do not require an on board engine to produce the power needed, which has the advantage of more passenger seats per length of train, and also reduces the overall weight. This is attractive for train operators as it increases the number of passengers per journey.

There are many variations of the diesel locomotive but they all have one thing in common; they require an engine, transmission and a fuel tank (approximately 6 tonnes in weight when full[9]) to supply their power. Their differences lie in how this power is transmitted to the wheels (mechanical, pneumatic, electrical etc.). These components have to be large in size in order to produce enough power to move the train, increasing the weight considerably and reducing the overall efficiency of the train.

Either Direct Current (DC) or Alternating Current (AC) can supply electric trains. AC is the primary operating mode in the UK with around 65% of track having an AC supply in comparison to 35% of track having a DC supply[10]. AC and DC are supplied to the train in different manors (both via the national grid). AC is supplied through an overhead line that distributes a voltage of 25kV to the network. *Figure 5.1.1.* shows a pantograph attached to the vehicle, which allows contact to be made from the train to the overhead line. A transformer on the train then lowers the voltage to a level that is suitable for traction[11].

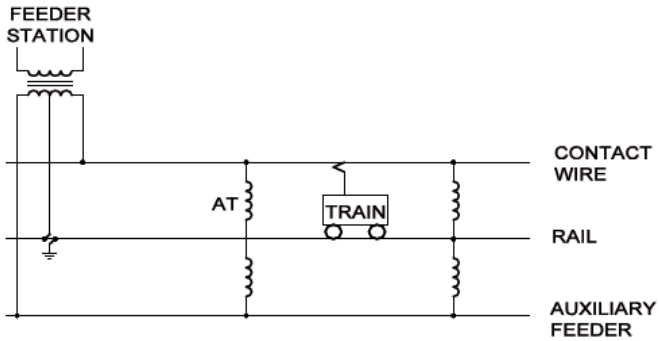

Figure 5.1.1. – Diagram Showing the AC Supply to a Train[11]

DC is supplied via a third rail; 132kV is supplied and is then transformed to 33kV and distributed to the network. Substations then convert the AC supply to 660/750V DC, which is then fed to the train via a third rail. The AC network utilises regenerative braking; whereby the kinetic energy of the locomotive, during deceleration, is converted into electricity and recycled back into the supply saving 10-15% in energy consumption. This technology is also gradually being utilised by the DC network in order to reduce the overall energy consumption of the UK rail network[11].

Bi-mode (dual-mode, electro-diesel) is a hybrid of the two discussed above. The train has the capability of using electrified tracks, where possible, but uses an on board diesel engine to cover tracks that are not electrified[12]. Some bi-mode trains (Alstom Coradia Liner- France) have the capacity to use either third rail DC supply or overhead line AC supply, which allows them to utilise all variations of track[13]. There are three main types of the bi-mode train; primary electric, primary diesel and full dual-mode. A primary electric train is an electric locomotive with an auxiliary diesel engine; its purpose is to bridge small gaps in predominantly electrified routes. The diesel engine only exerts around 600bhp[14], therefore, speed greatly reduces when travelling along non-electrified track. Primary diesel trains are diesel trains with auxiliary electric motors; they are used when non-electric traction is illegal (i.e. in tunnels[15]). Full dual-mode locomotives are able to run at optimal speeds using both an electrical and diesel supply.

4.2. Freight, Conventional and High Speed Rail

Like any mode of transport, rail is used to either transport passengers or goods from one location to another. The demand for passenger rail is on the increase and the usage of rail freight in the UK is said to increase by 30% in the next decade (140% in the next 30 years)[5]. As demands increase the necessity for speed also increases to allow for more frequent services. With the introduction of HS1

in 2003, the potential to transport passengers and freight in a more efficient/rapid manor was established[4].

The UK Rail Network has a long history of providing transport in the UK. The first rail line opened in 1841 using steam engines to power trains. Once this line had been established, the UK rail network expanded at a rapid rate throughout the 1840's with a large number of towns and villages being interconnected[16]. In 1923 all rail companies were grouped together to form 'the Great Four'[17].By the 1960's the rail industry was losing a lot of money; Dr Richard Beeching was employed by the British Government to help solve this problem and to make the UK rail industry profitable. He wrote a report proposing the closure of 2363 stations and 5000 miles of track and the government decided to follow through with his proposition[18].

The introduction of the diesel powered InterCity125 in the 1970's was a turning point for UK rail. The use of plastics instead of metals and introducing a power car at each end, instead of the typical push/pull locomotives of conventional rail, revolutionised the railway experience[19]. The Network was then privatised in 1993[20] and shortly after, in 2002, Network Rail took over responsibility of running the UK rail infrastructure[21]. Not long after this privatisation, the UK's first High Speed line was opened[4].

There are two variations of High Speed Rail (HSR) in the UK; purpose built HSR, and interoperable rail. Purpose built HSR is defined as a network of tracks that allow for trains to run at speeds of 250km/h and above. Interoperable rail is defined as the adaption of current track infrastructure/vehicles to allow trains to run at 200km/h. These two variations arise because the acute bends and curves of conventional railway tracks do not allow for locomotives to reach speeds in excess of 250km/h when travelling along these sections of track[22]. It is not efficient to have the train slow down to an acceptable speed every time a bend approaches. Some interoperable trains have a tilting mechanism in place (such as the Class 390 Pendolino operated by Virgin) in order to decrease the centrifugal force felt by the train and passengers[23]. This allows it to travel at greater speeds round curved track. Two variations of the tilting mechanisms used can be seen in *Figure 5.2.1.*

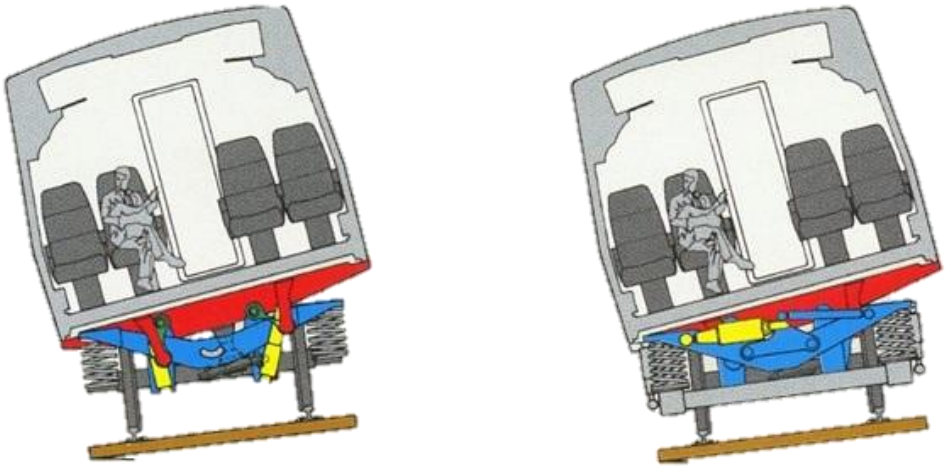

Figure 5.2.1. – A Drawing of the Mechanisms used in Tilting Trains[24]

There is currently only one purpose built HSR system in the UK (HS1) connecting London to the Channel Tunnel. This High Speed line allows passengers to travel from London to Paris in just over 2 hours and from London to Brussels in just under 2 hours[25]. Plans to build a second HSR network in the UK are well underway. HS2 will be implemented in two phases; Phase 1 will connect London to Birmingham, Phase 2 will connect Birmingham to Manchester (via Manchester Airport) and Birmingham to Leeds. Phase 1 will start construction in 2017 and is expected to be open to the public by 2026. Phase 2 is due to be finished by 2033 but consultation is yet to be completed[26]. Journey times will be greatly reduced once both phases are complete. Travel time from London to Manchester being reduced by an hour and London to Leeds just under an hour[27].

As well as passenger service, a large part of the UK rail network is used for freight. As track access costs are at an all-time low, freight in the UK is continually growing as the advantages over road haulage become more and more apparent. One gallon of fuel allows a Heavy Goods Vehicle (HGV) to move a tonne of goods 88 miles on road, whereas, a gallon of fuel can move the same amount 246 miles (on average) by rail[28]. Not only does this cut fuel costs, it also reduces CO_2 emissions as shown in *Figure 5.2.2.* As well as a huge reduction in CO_2 emissions, less than 1/10th of Nitrogen Oxide emissions are produced by rail than that of a HGV. This is due to the actions taken to reduce emissions implemented in recent years including; the renewal of fleet, reduced engine running time and fuel efficiency training for drivers of fleet[29].

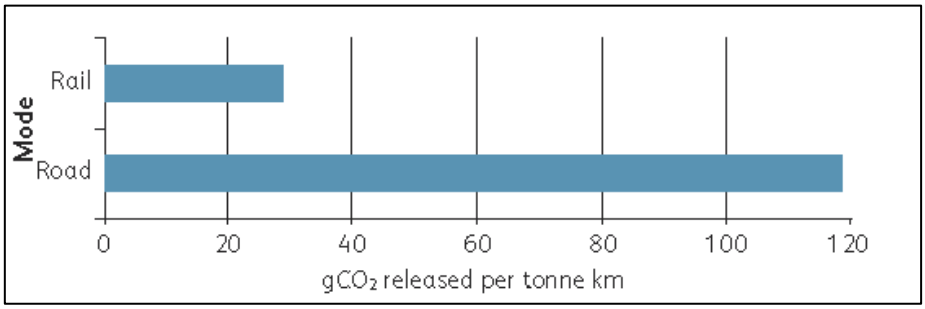

Figure 5.2.2. – A Histogram Comparing the Emissions of Rail and Road Freight[29]

4.3. Power Generation

Both energy sources discussed above (Diesel and Electricity) need to be either generated or processed in order for them to be useful. Diesel is one of many fuels produced by refining crude oil. Crude oil contains numerous hydrocarbons of varying lengths and can be extracted at different temperatures to produce a variety of products[30]. Two of the largest suppliers of diesel fuel for use in the UK rail industry are Exxon-Mobil and Total.

Exxon-Mobil owns the largest oil refinery in the UK (producing 20% of UK capacity) and states that it is twice as efficient as a conventional power station, quoting efficiencies[31] of up to 75%. They also distribute 95% of their clean (processed) products via pipeline[32] to their distribution terminals (pipelines produce negligible emissions compared to other modes of transport) and then to customers via a fleet of trucks. Total's main oil refinery (LOR) is the 3rd largest in the UK[33] (efficiency undisclosed); they distribute their products via road (17%), rail (23%), pipeline (28%) and sea (32%)[34]. The supply of fuel depends on the rail operator; each will have varying indirect emissions dependant on how they transport the oil and how they refine it. This, in turn, will have an effect on the indirect emissions produced by diesel locomotives.

Electricity can be generated in many ways, some more efficient than others. It can be seen from *Figure 5.3.1.* that gas and coal are the main fuels used to generate electricity in the UK[35]. Renewable ways of producing electricity are on a steady rise with an increase of 1.5% seen in the last year (2012-2013). National Grid and SP Energy Networks control the electricity supplied in England, Scottish and Southern control the supply to Scotland[36]. Power from the national grid is supplied to trackside substations, which then supply the overhead line or third rail used to supply trains with the necessary voltage required[11].

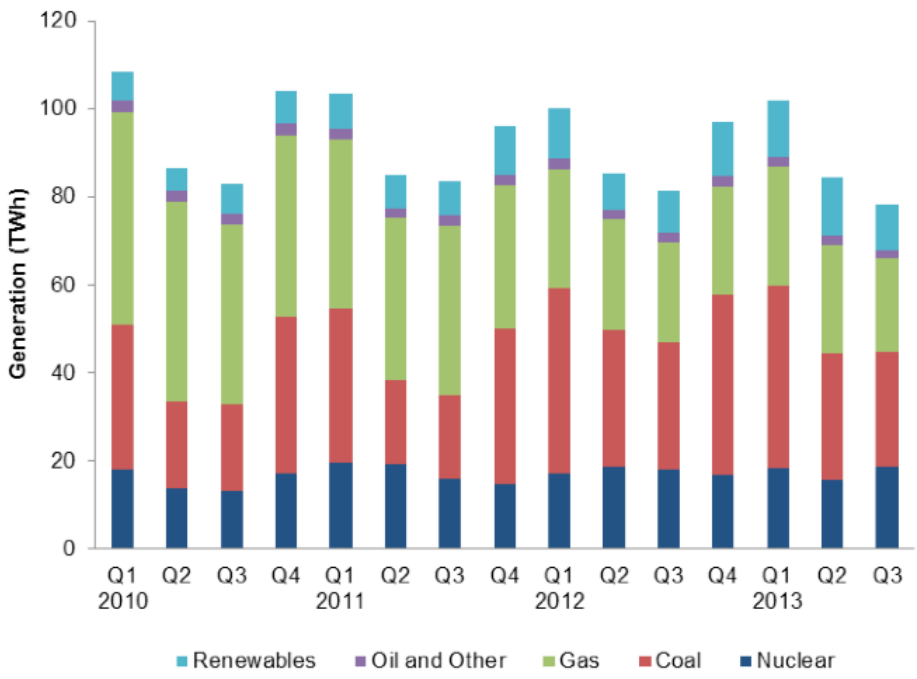

Figure 5.3.1. – A Histogram Showing the Sources of Electricity Generation in the UK[37]

The carbon intensity of electricity generation is an important factor when calculating emissions for trains using electric traction. Carbon intensity is the amount of carbon produced per mega joule of energy generated (kgCO_2e/MJ). CO_2e is the carbon equivalent, which factors in other Greenhouse Gases (GHGs) such as Nitrous Oxide (N_2O) and Methane (CH_4); all are also harmful to the environment[38]. As stated earlier, electricity can be generated using a variety of methods and energy sources, each having a different carbon intensity factor. This makes calculating emissions for electrically powered vehicles much more complex than calculating those with petrol/diesel engines.

4.4. Current and Near Future Developments of the UK Rail Network.

Electrification of certain routes in the UK is currently under development, which will result in 3000km of track being electrified by the end of 2019[39]. Network Rail releases a document every 5 years (Control Period) stating what they plan to implement by the end of the period. Control Period 5 gave a detailed insight into the plans to be underway/complete by the end of 2019. These plans include[40];

- The Electric Spine
- Great Western Electrification
- North Western Electrification
- Trans-Pennine Electrification
- Intercity Express Program (IEP)

As part of the IEP a contract between Hitachi and the UK Government has been signed to provide the rail network with 92 electric and bi-mode trains. These trains will replace the InterCity125 trains on certain routes from December 2017, with reduced emissions and an improvement in reliability. Trains will be in use on the Great Western Main Line as of this date, followed by an introduction to the East Coast Main Line by early 2018. All trains will be in operation on both of these lines by 2020[3].

4.5. Emissions

Emissions from trains not only arise due to the operation of the vehicle, but also from other indirect sources. These direct and indirect sources can be grouped into six categories: direct performance, occupancy Levels, electricity production, rolling stock manufacture, infrastructure and modal shift[41]. The contribution of the manufacture of rolling stock for a proposed HS line in Switzerland is 6.2 tons of CO_2 per car and 3.5 tons of CO_2 for the maintenance per car. The contribution due to new infrastructure of this line is approximately 15000 tons of CO_2/km of track; this figure spans a 60-year period, including maintenance[42]. This illustrates the impact these factors have on emissions, as it is a common misconception that emissions are only caused by the combustion of fuel.

All the factors discussed above, produce a multitude of GHGs other than CO_2. Hydroflourocarbons (HFC) is emitted from air conditioning units, which are found in passenger rail. Sulphur Hexafluoride (SF_6) is used to protect electrical control equipment found in rail systems; 1kg being the equivalent to 22.8 tons of CO_2. During the production of fossil fuels, gases such as Methane (CH_4) and Nitrous Oxide (N_2O) are produced; these are also harmful GHGs, which add to the overall emissions of a train using fossil fuels to provide power[43] (directly or indirectly).

A study was carried out on the emissions of diesel freight trains in the Port of Brisbane in order to calculate the emissions of particular GHGs. The experiment conducted was to find the content of harmful gases within the combusted fuel particles such as; NO_x, SOx, volatile organic compounds (VOC) and particulate matter[44] (PM). This study is mainly focused on CO_2 emissions, other harmful GHG have been converted into CO_2e (CO_2 equivalents).

In order to determine the overall energy consumption and emissions of a vehicle, the whole supply chain needs to be considered. The well to wheel efficiency (efficiency of fuel transport, electricity generation etc.) of trains in the UK is 26%, both for diesel and electric modes of operation[45]. For the purpose of this study, only direct emissions from the operation and indirect emissions from electricity generation have been considered.

4.6. Alternative Fuels

As the push for cleaner energy is becoming more important on a global scale, there has been an increase in the research towards alternative fuels, particularly for transport purposes. Biodiesel is the most established alternative to diesel fuel, as many diesel engines can run on a blend of biodiesel and diesel without undergoing any modifications[46]. It is the only alternative fuel to have successfully met the requirements of the 1990 Clean Air Act amendments[47]. Biodiesel has many advantages over conventional diesel, the most important being its minimal GHG emissions in comparison. B20 (20% biodiesel, 80% diesel) reduces CO_2 emissions[6] by 15%, higher blends are available (B50, B100 etc.) with an even further reduction in CO_2. Biodiesel has been tested in the rail industry in the past but is not commonly used. In 2001 the Tricounty Commuter Rail Authority of Florida operated one of its trains on B100 for 3 months with no issues[48].

Biodiesel can be produced from many organic sources such as; soybeans, rapeseed and peanuts. The oils these crops produce form the basis for biodiesel processing[49]. These organic sources pose a problem if the fuel were to be used on a global scale, for the use in the transportation sector. The quality of the yield may be compromised due to risks that arise from the environment they are grown in. Factors such as weather and pest infection may have a detrimental effect on the yield and could cause a shortage in biodiesel if not compensated for. Algae are another source for the oils used to produce biodiesel and pose a solution to the problem above. It has an oil yield of over 200 times that of any vegetable oil source and can be grown almost anywhere with enough sunlight[49]. This shows great promise for the use of biodiesel as an alternative fuel. For the scope of this project, biodiesel has been considered as a fuel for all diesel and bi-mode trains with different blends being used. This was to establish how advantageous biodiesel is in terms of emissions and whether it is a viable fuel to be used in a sustainable rail industry.

Other alternative fuels have started to surface in recent years, which may have a place in the future of rail. Two energy sources stand out in the rail sector; Liquid Natural Gas (LNG) and Hydrogen. Both are non-intensive carbon fuels and are strong contenders in the sustainable future of transport. LNG would cut CO_2 emissions by 30% and Nitrogen emissions by almost 70%. Hydrogen fuel cells are incredibly environmentally friendly, emitting no GHGs. The indirect emissions from the manufacture of hydrogen are also negligible[7]. However, they were not considered in this report as they require completely new systems to deliver the power required by the trains.

Thorium is another energy source that has taken the public eye in the last few years. Thorium is a fertile radioactive metal that, when combined with a fissile material (e.g. Uranium), can be used to generate nuclear power[50]. The former UN weapons inspector is urging the government to undergo research on this metal as it much safer in reactors, it is also virtually impossible to be used in the creation and development of nuclear weapons. Another attractive attribute of Thorium is its abundance; there is an estimated world resource of 5.385 million tonnes of this element[51]. How environmentally friendly this energy source would be is unclear, but, it may be the next revolution in energy generation. As so little is known about its benefits in this sector, it was not considered in this project but holds great promise for future work.

5. Trains under Comparison

In order for the comparison to be valid it was important to select a train from each operating mode as well as type. Ideally there should be a total of 9 trains for this requirement to be met but as there are no diesel High Speed Trains the total number is 8. *Table 6.1.1.* below shows the trains under comparison and their type and mode of operation.

Table 6.1.1. – Table Showing the Trains under Comparison in this Study

Train	**Rail Class**	**Type**	**Mode of Operation**	**Operational Speed (km/h)**
Hitachi Super Express	800	Conventional	Bi-mode	201
Hitachi Super Express	801	Conventional	Electric	201
InterCity125	43	Conventional	Diesel	201
Eurostar/TGV TMST	373	High Speed	Electric	300
Talgo 250h	S730	High Speed	Bi-mode	250/180*
Class 66	66	Freight	Diesel	120
Class 90	90	Freight	Electric	180
Class 73	73	Freight	Bi-mode	130

*250km/h using electric supply, 180km/h using diesel engine.

The Class 800, 801 and 43 were chosen as both Hitachi Super Express trains will be replacing the InterCity125. The Class 373 was chosen as the electric High Speed Train (HST) as the Class 395 has a maximum operating speed of only 225km/h, which does not qualify for high speed in this study[52]. There are currently no high-speed bi-mode trains in operation in the UK; therefore, it was necessary to use a train that does not operate in the UK. The Spanish Talgo 250h was chosen as the Bi-mode HST for this comparison. The three freight trains were chosen because they are frequently used by freight operators in the UK.

The number of carriages each passenger train uses when in operation was used in this study in order to conduct valid comparison that is applicable to the UK Rail Network. In order to carry out a fair comparison of the performance and emissions for the freight locomotives, the same goods wagon was used for all freight trains. The CQFY wagon was a suitable selection and is used by freightliner in conjunction with their fleet of class 66 locomotives[53]. The goods wagon can hold 2 TEUs (Twenty-foot Equivalent Units) and has a maximum load capacity of 71.2 tonnes[54]. As coal is commonly transported via rail in the UK, it has been used as the freight in this study. In order to determine the number of wagons for each locomotive, the hauling capacity needed to be known. The volume of the TEU and the density of coal were used to find the mass of a fully loaded TEU. This mass was then multiplied by two and the mass of one wagon (16.8t) was added. This mass and the hauling capacity of the vehicles were used to determine the total number of wagons that each locomotive could haul at one time. The maximum of 20 wagons was found and applied to all three locomotives.

6. Methods Employed for Calculating Emissions

6.1. Technical Framework

The energy consumption of a train is influenced by many factors. For the scope of this study only the most influential factors have been considered as technical data on trains is not readily available to the public. The large majority of the energy (≈80%) used by a train is to overcome resistances that the vehicle is subject to when traversing along a track[41]. Once these resistances are found they can be multiplied by distance travelled to find total energy consumption[43]. There are two categories of resistance; inertial/grade resistance and running resistance[55]. Grade resistance has been neglected in this study due to the complexity of calculation when taking into account the curves/bends, inclines and declines of the route. In order for the comparison to be viable, calculations have been performed on a single route for all trains; including grade resistance would have a small effect on the performance of the trains and can be neglected.

Due to the complexity of including grade resistances, an ideal straight track has been used in order to ensure that any energy consumed due to overcoming these resistances is negligible. The trains travel at a constant speed; this eliminates any change in energy consumption due to acceleration and deceleration. Because of this ideal route, driver efficiency was also neglected. This report is a comparison between the performances of trains, taking driver efficiency into account would not be insightful as it would affect each train in a similar manor when travelling along the same route.

Running resistance accounts for mechanical and aerodynamic resistances and is used in this report to calculate the energy consumption and, hence, the emissions of each train. Mechanical resistances arise due to the rolling resistance and frictional forces felt by the wheels[55]. Aerodynamic resistance is a combination of frictional drag and pressure drag; both are heavily influenced by the shape and length of the train[56]. Running resistances of a train can be modelled using the standard Davis Equation[57]:

$$R = A + Bv + Cv^2$$

where R = *resistance (N)*
v = *speed (m/s)*
A, B & C = *coefficients*

A, B and C are coefficients determined from experimental data specific to the train. A is a constant that describes the bearing resistance and is proportional to the mass of the train. B accounts for the rolling resistance of the train and C the air resistance. As C is multiplied by the square of the speed, air resistance is accountable for a larger portion of the resistance, particularly as speed increases[43].

Although these resistances account for a large majority of the energy consumption, there are other factors that add to the total consumption of the train. Comfort functions, applicable to all passenger rail, contribute to energy consumption, these include; heating, air ventilation systems and lighting etc. These comfort functions are accountable for approximately 20% of the trains total energy consumption but are not taken into consideration as it is not possible to calculate given the available data. It would also be detrimental to the comparison as freight trains have negligible energy

consumption due to these functions. Regenerative braking can also reduce a train's energy consumption. As an ideal track and constant speed has been used, no braking takes place; therefore, has not been included in the calculations.

Discussed above are the factors that contribute to the direct emissions of a train. Emissions do not only arise from the direct operation of the vehicle; the building of infrastructure, the manufacture of the train, the losses from well to wheel etc[41]. all add to the total emissions of the train. Including these would require access to sensitive data and cooperation from several professionals in the rail industry. This would not be feasible for the scope of this project, hence, the emissions due to the operation of the vehicles were focused on.

Three methods for calculating the resistance have been found. The depth of these methods vary, each uses a different approach to calculating resistance. These methods will form the basis of the calculations. Once the resistance is found, further calculation is required to assess the impact of other factors, such as; load, percentage of electrified track (bi-mode trains) and alternative fuels (diesel powered trains) etc.

6.2. UIC method

The International Union of Railways (UIC) is an organisation that compromises of a number of members across the global rail industry. UIC includes a diverse range of members from railway companies to infrastructure managers. Members include; Network Rail, DB Schenker Rail and Amtrak. Established in 1922, the UIC are a renowned network of rail professionals[58].

The methodology used for this paper was taken from: High Speed, Energy Consumption and Emissions by Alberto Garcia[56]. Some of the formulas were neglected as they include factors that are not in the scope of this project.

Mechanical resistances arise due to the contact between the wheels of the train and the track. These resistances depend on the mass of the train. All formulas in this method give the energy consumption rather than the resistance of the train, as the distance travelled is already factored into the equations. Energy consumption due to mechanical resistance is given by:

$$E_m = (a + a_c).m.l$$

where a = *coefficient depending on rolling stock (N/t)*
a_c = *coefficient depending on route (N/t)*
m = *mass of train (tonnes)*
l = *length of route (metres)*

Coefficient a_c depends on the number of curves on a track and their length and radius. A straight track is used, therefore, this coefficient can be ignored. The equation now becomes:

$$E_m = a.m.l$$

Coefficient '*a*' is characterized by the rolling stock and is independent of the track. For conventional locomotives this value lies between 12N/t and 20N/t, for high-speed trains this value lies between 5N/t and 9N/t. To ensure a fair study, the same value was applied to each category of train (conventional, high speed etc.). An average was taken for both high speed and conventional, giving all high speed trains an '*a*' value of 7N/t and freight trains a value of 16N/t. Due to interoperable rail (class 800/1 and 43) travelling at higher speeds than conventional rail, it is assumed that the '*a*' value for these trains will lie between the values for conventional and high speed vehicles. The upper and lower limits were taken and an average of 12.5N/t was found for interoperable rail.

Aerodynamic resistance is broken down into two parts; drag due to pressure forces and drag caused by friction. Energy required to overcome pressure drag is given by:

$$E_p = c_p . S_f . \int T_f \, . v^2 . dl$$

Where c_p *= pressure drag coefficient (N/(km/h)*^{2}*.m*^{2}*)*
S_f *= cross-sectional frontal area of train (m*^{2}*)*
T_f *= tunnel factor*
v = speed (km/h)
l = length of route (metres)

As there are no tunnels on the chosen route the equation becomes:

$$E_p = c_p . S_f . v^2 . l$$

c_p is a coefficient determined using experimental data specific to individual trains. As this data was unavailable for this study, assumptions had to be made. The paper gives a value for conventional trains and high speed trains, which are 0.022N/[(km/h)^{2}m^2] and 0.0096N/[(km/h)^{2}m^2] respectively. Both values assume a cross-sectional area of approximately 12m^2, this area is within the range of 10-12m^2 for all trains under comparison, therefore, it is acceptable to use these coefficients. The freight trains fall under the conventional category and HSTs under the high speed category. Due to the interoperable trains travelling at higher speeds and having a more aerodynamic shape than the freight trains, an assumption was made that this coefficient would be in the range of the two, stated above, for this type of train. Thus, the average of the two was found giving the interoperable rail vehicles a value of 0.0158N/[(km/h)^{2}m^2].

The second part of aerodynamic drag arises due to the friction between the fluid (air) and the surface area of the train. As previously, tunnel factor has been neglected, therefore, energy needed to overcome frictional drag is given by:

$$E_f = c_f . S_m . v^2 . l$$

Where c_f *= frictional drag coefficient (N/(km/h)*^{2}*.m*^{2}*)*
S_m *= wet surface area (m*^{2}*)*
v = speed (km/h)
l = length of route (m)

S_m is the wet surface area where the train will feel shear stresses due to the forward motion of the train. S_m is given by:

$$S_m = \big((2H) + W\big).L_t$$

Where H = *height of the train (m)*
W = *width of the train (m)*
L_t = *length of the train (m)*

Coefficient c_f depends on the surface roughness and continuity of the surface. Again, as data for specific trains is not available, assumptions had to be made. The values for conventional and high speed rail are 0.0003N/[(km/h)^2.m^2] and 0.00021N/[(km/h)^2.m^2] respectively. For consistency, the average was found for interoperable rail, giving them a value of 0.000255 N/[(km/h)^2.m^2]. It is worth pointing out that the c_f tends to fall as the train's length increases to over 200m. A majority of the trains under comparison are longer than 200m, but, as there is no quantitative method or formula given in the UIC paper, it had to be neglected and the values discussed above were used for all trains, regardless of their length.

Another component that contributes to energy consumption is the resistance due to the air intake of the vehicle. This air intake is predominantly used for the purpose of air ventilation for passengers. A formula is given in the paper but a value for the constant k_{ea} was not given, therefore, this aspect of energy consumption was not included.

6.3. RSSB method

The Rail Safety and Standards Board (RSSB) have a similar structure to the UIC, they are a none profit organisation funded by major stakeholders in the railway industry. They have over 50 members including; Bombardier Transportation UK Ltd, Freightliner UK and Alstom transport. They also gain funding from the Department for Transport[59] (DfT).

The methodology used for this study was taken from their paper: Quantification of Benefit of Train Mass Production[57]. It uses a modified version of the Davis Formula, discussed previously in this section. The modified Davis Formula is shown as:

$$R = k.M + (B_1 + B_2).v + C.v^2$$

where k = *constant of proportionality*
M = *mass of the train (kg)*
B_1 = *constant*
B_2 = *constant*
v = *speed (m/s)*
C = *constant*

B_2 is the mass of cooling air and the mass of ventilation air. As data is difficult to find on the air intake of specific trains and was neglected in the UIC method; it was also disregarded when using this method. The Davis Equation thus becomes:

$$R = k.M + B_1.v + C.v^2$$

The typical value for k was given as 12; this value was used for all trains under comparison. B_1 is another constant, which relates to the rolling resistance of the train and is linearly proportional to the mass of the train, it is given by:

$$B_1 = 0.064M$$

C is a constant used to describe the aerodynamics of the train, given by:

$$C = \frac{\rho}{2}.C_d.A_x$$

where ρ *= density of air (kg/m³)*
C_d *= drag coefficient*
A_x *= cross-sectional frontal area of train (m²)*

The density of air used was 1.247kg/m^3 which is the density of air[60] at a temperature of 10°C (UK average in 2013)[61].The drag coefficient C_d comprises of many other coefficients which are affected by different properties of the train. C_d is given by:

$$C_d = C_{dht} + C_{dl} + C_{db} + C_{di} + C_{de}$$

where C_{dht} *= head and tail drag coefficient*
C_{dl} *= frictional drag coefficient*
C_{db} *= bogie drag coefficient*
C_{di} *= extra drag coefficient*
C_{de} *= pantograph drag coefficient*

C_{dht} is determined by the pressure forces at the head and tail of the train. It has a typical value ranging between 0.19 and 0.6. A similar methodology was used, as in the UIC method, in order to apply the same constraints for a viable set of results for comparison. Freight trains were given a value of 0.6 and high speed trains a value of 0.19. The average of these two was found to be 0.395, therefore, was applied to the interoperable high-speed trains. C_{dl} is linearly proportional to the length of the train and is given by:

$$C_{dl} = L.L_f$$

where L *= length of train (m)*
L_f *= length factor*

A typical length factor lies between 0.004 and 0.005, as this does not alter across train types, the average was taken and a value of 0.0045 was used for all trains. Coefficient C_{db} is included to account for the drag forces caused by the bogies of the train. C_{db} is given by:

$$C_{db} = 2N_v . B_f$$

where N_v *= number of vehicles*
B_f *= bogie factor*

The bogie factor ranges between 0.03 and 0.02 depending on the train. For this purpose, an average of 0.025 was applied to all trains. C_{di} is an extra drag coefficient dependent on the number of vehicles and is given by:

$$C_{di} = 0.025(N_v - 1)$$

C_{de} is a drag coefficient used to account for the pressure forces felt by the pantographs on an electric train. Diesel trains do not require pantographs, therefore, this term was neglected for all diesel locomotives. For all electric trains, the method gives a typical value of 0.06 to be used.

6.4. DTU method

The methodology used was taken from the paper: Driving Resistance from Railroad Trains[62]. The project was funded by the European Commission and was published in 2005. The paper uses a fundamental approach to calculating resistance, which is split into two parts. The two resistive forces are shown in *Figure 7.4.1.* below.

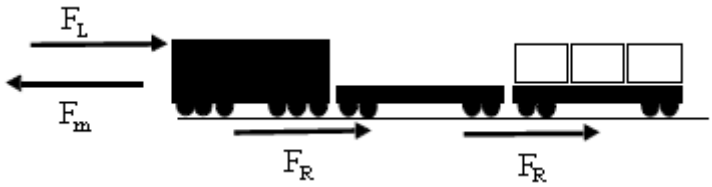

Figure 7.4.1. – Free Body Diagram of a Train in Motion[62]

Summing the forces in the free body diagram above gives:

$$F_m = F_R + F_L$$

where F_m *= total resistance of the train (N)*
F_R *= rolling resistance (N)*
F_L *= air resistance (N)*

Rolling resistance is given by:

$$F_R = f_R . m . g$$

where f_R *= rolling resistance coefficient*
m = mass of train (kg)
g = gravitational acceleration (m/s²)

the rolling resistance coefficient, f_R, is given by:

$$f_R = C_0 + C_1 . \left(\frac{v}{v_0}\right) + C_2 . \left(\frac{v}{v_0}\right)^2$$

where C_0, C_1 *&* C_2 *= coefficients*
v = speed (km/h)
v_0 *= speed constant = 100km/h*

C_1 & C_2 are found using the table in the paper, there are two values for each; C_1 & C_2 for passenger trains are 0.25×10^{-3} and 0.5×10^{-3} respectively. The value of C_1 for freight trains is 0.5×10^{-3} and the value of C_2 is 0.6×10^{-3}. C_0 is given by:

$$C_0 = \frac{f_{sl} . m_l + f_{sv} . m_v}{m}$$

where f_{sl} *= rolling resistance coefficient for locomotive*
f_{sv} *= rolling resistance coefficient for carriages*
m_l *= total mass of locomotives (kg)*
m_v *= total mass of carriages (kg)*
m = total mass of train (kg)

f_{sl} is found from a table provided by the paper, there are two coefficients and they depend on the number of axles the locomotive has. A six axle locomotive has an f_{sl} value in the range of 2.5×10^{-3} – 3.5×10^{-3}; the average of 3×10^{-3} was used. The other value, for four axle locomotives, lies between 3.5×10^{-3} and 4.5×10^{-3} and an average of 4×10^{-3} was used. f_{sv} is a function of axle load and is given by:

$$f_{sv} = C_{cv} + \left(\frac{F_A . n_{ax}}{m . g}\right)$$

where C_{cv} *= coefficient*
F_a *= axle pressure constant = 100N*
n_{ax} *= total number of axles of carriages*

C_{cv} is a coefficient that depends on the type of vehicle, it is also found in the report. C_{cv} for freight trains is given as 0.6×10^{-3}, the value for passenger trains is slightly lower, given as 0.4×10^{-3}. Air resistance (F_l) has a similar form as in previous methods and is given by;

$$F_L = \frac{\rho}{2} . C_L . A_x . v^2$$

where ρ = *density of air* = *1.247kg/m³ (used in previous methods)*
C_L = *drag coefficient*
A_x = *cross-sectional frontal area of train (m²)*

C_l is calculated by summing the contributions of the carriages and locomotives. It is given by:

$$C_L = \sum C_{car} + C_{loco}$$

where C_{car} = *drag coefficient of a carriage*
C_{loco} = *drag coefficient of the front loco*

C_{car} and C_{loco} are both given in tables. C_{loco} is defined by the number of axles, shape of the locomotive and whether it is an electric or diesel powered train, the values used can be found in *Table 7.4.1.*

Table 7.4.1. – Table Displaying Coefficients used Depending on Trains Design

Electric Locomotives	**C_{loco}**
Four axles, normal shape	0.8
Four axles, aerodynamic shape	0.45
Six axles, normal shape	1.1
Six axles, aerodynamic shape	0.55
Diesel Locomotives	
Four axle	0.6
Six axle	1.1

The same method of averages was used to find C_{loco} for electric interoperable locomotives giving a value of 0.625. C_{car} values are also given in a table; the coefficients for passenger vehicles and for goods vehicles are 0.15 and 0.218 respectively. Most passenger trains have a locomotive at either end of the train; the locomotive at the back end of the train is treated as a carriage when calculating the overall drag coefficient. This is done because the carriage in front displaces the air, whereas, the locomotive at the rear does not, and will only feel a small amount of drag similar to that of a carriage.

6.5. Additional Calculations

Once energy consumption was found, efficiency needed to be factored into the calculations in order to determine the true energy consumption of the trains. The consumption found using the three methods was divided by the train's efficiency to give the actual energy consumption. As data on the efficiency of the locomotives was unavailable, an assumption had to be made. After some research it was found that a diesel engine has a typical efficiency of approximately 40%[63], the overall efficiency of electricity generation in the UK was found to be 36% in 2011[64]. These efficiencies were then applied to each mode of operation to find the actual amount of energy consumed.

At this stage, for electric trains, the energy consumption was converted from joules into watt-hours. The Department for Environment, Food and Rural Affairs (DEFRA) publish a document stating the carbon factors and is updated annually. The figure for the carbon intensity of electricity generation in the UK in 2013 was 0.44548kgCO_2e/kWh[65]. This value includes emissions from other GHGs, which are found and converted into CO_2 equivalents based on their detrimental effect on the environment. The energy (in kWh) is divided by this carbon factor to give the total emissions. The method for finding diesel emissions requires more information, but is still relatively straightforward. The calorific content of diesel fuel (MJ/l) was found using the same document published by DEFRA. The value was found to be 35.9MJ/l[65]. Energy consumption (in MJ) was then divided by the calorific content to find the total amount of fuel combusted in litres. The emission factor for diesel fuel was used (also taken from DEFRA[65]) and had a value of 2.6008kgCO_2e/l, this value was multiplied by the amount of fuel consumed to give the total emissions.

Emissions for passenger rail is conventionally given in kgCO_2e/passenger-km, emissions of freight trains are usually expressed as kgCO_2e/ton-km. In order to find emissions in this form, the load factor of the train needs to be known. For the scope of this study all possible loads have been taken into account, from 1% to 100%. The load of the vehicle has an effect on the overall mass, particularly in freight. This has been accounted for in calculations. The approximate average weight of a passenger was taken to be 80kg.

The method used to calculate the emissions of diesel trains was used for biodiesel. As biodiesel usually comes in diesel blends with different percentage of biodiesel content, it was necessary to combine the emissions from both diesel and biodiesel. For this study B5, B20, B50 and B100 were used to gain an understanding of the significance of biodiesel content with respect to emissions produced. As the calorific content of biodiesel (33.3MJ/l)[65] is slightly lower than that of diesel, the amount of fuel consumed increases with the percentage of biodiesel; this had to be included in the calculation.

For all bi-mode trains it was necessary to find out the effect the amount of electrified track had on their total emissions. Emissions for bi-mode trains were calculated for both modes of operation, electric and diesel. The emissions from the electric mode of operation are then multiplied by the percentage of electrified track and added to the emissions from diesel multiplied by the diesel operated portion of track.

7. Data Collection

Data was found using various Internet sources and databases. As stated earlier, some of the data was not available to the public and assumptions had to be made (i.e. drag coefficients and vehicle efficiency). The data can be seen in *Table 8.1.1.* displaying all the necessary data to calculate the resistance of all trains.

Table 8.1.1. – Table Showing Data Required to Calculate Resistance of Each

	Class 800	**Class 801**	**Class 43**	**Class 373**	**Class S730**	**Class 66**	**Class 90**	**Class 73**
No. of vehicles	10	10	10	16	11	21	22	22
No. of carriages/wagons	8	8	8	14	9	20	20	20
No. of locomotives	2	2	2	2	2	1	2	2
Mass of locomotive (t)	71.35	68.7	69.5	68.5	55.85	126	84.5	77
Mass of carriage/wagon (t)	35.6	34.35	35	38	27.9	16.8	16.8	16.8
No. of axles (carriage)	4	4	4	3	2	4	4	4
No. axles (locomotive)	4	4	4	4	6	6	4	4
Total mass of train (t)	428.1	412.2	414.6	682.2	363	462	505	490
Total length of train (m)	255	259.9	218	318.92	183	320.6	336.68	333.12
Height of train (m)	3.85	3.85	3.9	3.74	4	3.91	3.96	3.79
Width of train (m)	2.7	2.7	2.74	2.81	2.96	2.65	2.74	2.64
Operational speed (km/h)	201	201	201	300	180/250	120	180	130
No. of seats	610	649	406	298	289	n/a	n/a	n/a

Sources:

Class 800/1; Agility Trains – Super Express Key Facts (pdf), Eversholt Rail Group – Class 395 EMU (pdf), railway-technology.com – Hitachi Super Express Trains, UK (article).

Class 43; archive.today/www.railpage.org.au – XPT specifications (datasheet), British Rails InterCity 125 and 225 (1992) – Roger Barnett (paper), Porterbrook (2012) – Mk3 Locomotive Hauled Coaches (pdf), angeltrains.co.uk – Class 43 – BREL, First Great Western (datasheet)

Class 373; therailwaycentre.com – Traction & Stock Recognition – class 373 (datasheet), southernelectric.org.uk – Class 373 Eurostar (image), Eurostar.com - Eurostar to run inaugural train on high speed 1 (article)

Class S730; talgo.com – Talgo 250-250h Datasheet (pdf)

Class 60; therailwaycentre.com – Traction & Stock Recognition – Class 66 (datasheet), cfcla.com.au – CQFY Wagon Datasheet, emdiesels.com – Class 66 Product Information (pdf)

Class 90; therailwaycentre.com – Traction & Stock Recognition – Class 90 (datasheet), cfcla.com.au – CQFY Wagon Datasheet, class90electriclocogroup.co.uk – Technical Information Fact Sheet

Class 73; therailwaycentre.com – Traction & Stock Recognition – Class 73 (datasheet), cfcla.com.au – CQFY Wagon Datasheet

8. Implementation of Results

There is a large range of factors that affect the energy consumption of a train; the results are separated and discussed in terms of each input. These factors have varying impacts on the results and are discussed in detail below.

8.1. Speed

Speed has a large impact on energy consumption. As the air resistance increases exponentially with speed it is expected that the HSTs have the largest energy consumption in comparison to the other types, particularly freight.

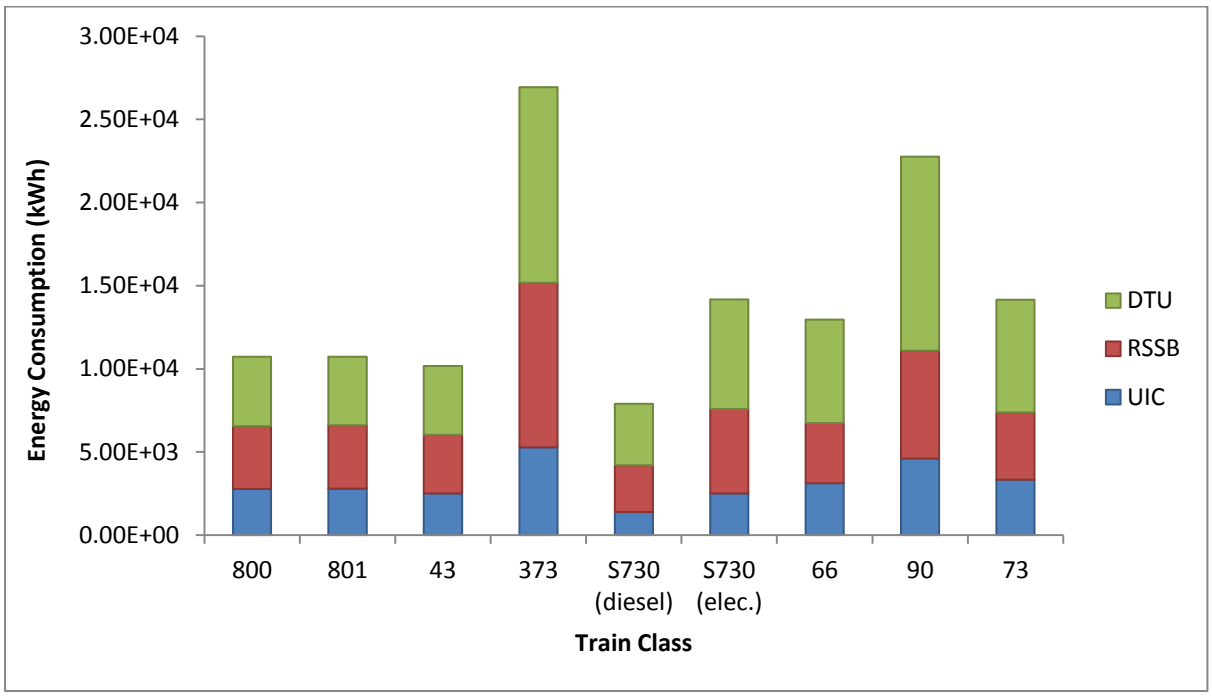

Figure 9.1.1. - Energy Consumption of Fully Loaded Trains Running at Operating Speed

Figure 9.1.1. shows the large variation in energy consumption between methods. Although the magnitude of the results varies greatly from method to method, it can be seen that when comparing each train, the methods display a similar trend. The class 90 displays an unexpectedly large energy consumption in comparison to the other freight trains. This is due to the operational speed of the class 90 being 50km/h higher than that of the class 73 and 60km/h higher than the class 66. Both the class 90 and the 373 HST display the largest energy consumption in all three methods, the length of these trains may contribute to this but cannot be solely dependent on length, as the class 73 and 66 have the same number of wagons.

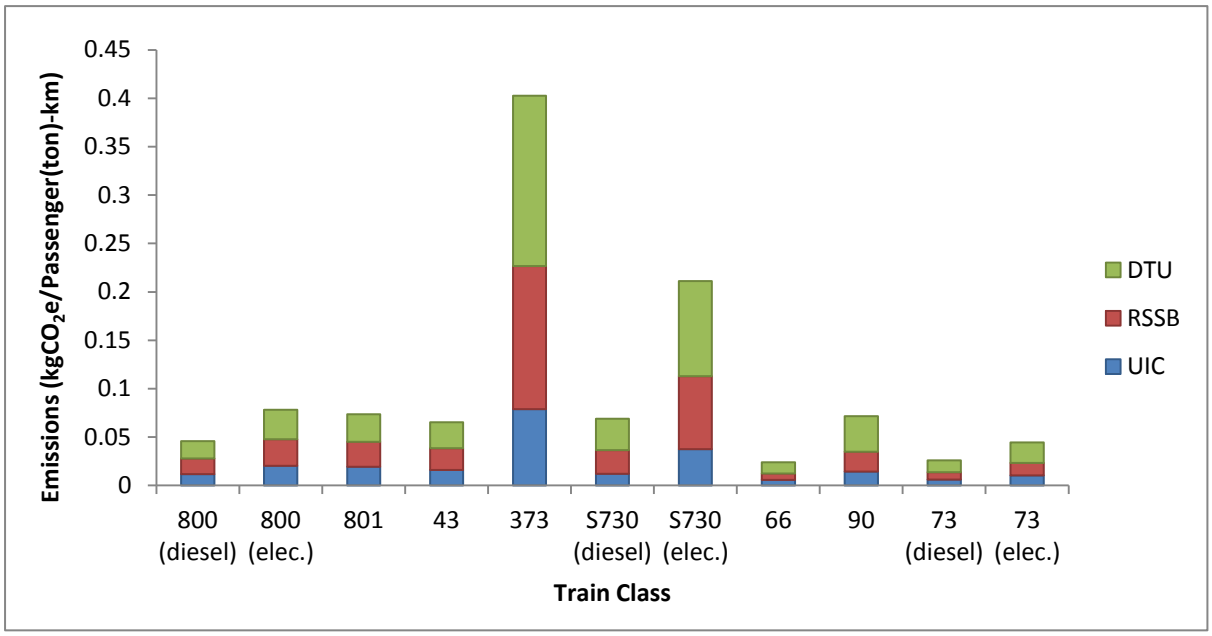

Figure 9.1.2. - Emissions of Fully Loaded Trains Running at Operational Speed

Figure 9.1.2. shows the emissions of each of the trains, bi-mode trains have been separated mode of operation for comparison. It can be seen that the difference between High Speed and the other types of railway is large. The difference in energy consumption is less between trains than the emissions they produce per passenger kilometre; this is due to the seating capacity of the passenger trains. The length of the class 373 is 318m and has a seating capacity of 298, comparing this to the class 801, which has a length of 260m and a seating capacity of 649, it can be stated (as emissions are given per passenger kilometre) that the seating capacity of the train plays a large role in the overall emissions. A reason high speed trains have less seating capacity may be due to the journey length and the purpose of the vehicles. The 373 travels from the UK into Europe, therefore, the comfort of the passengers is more important than an Intercity line which will be mainly occupied by business people commuting shorter distances. The difference in emissions and energy consumption for the freight trains under comparison barely fluctuate, this is because the freight trains were subjected to the same load capacity.

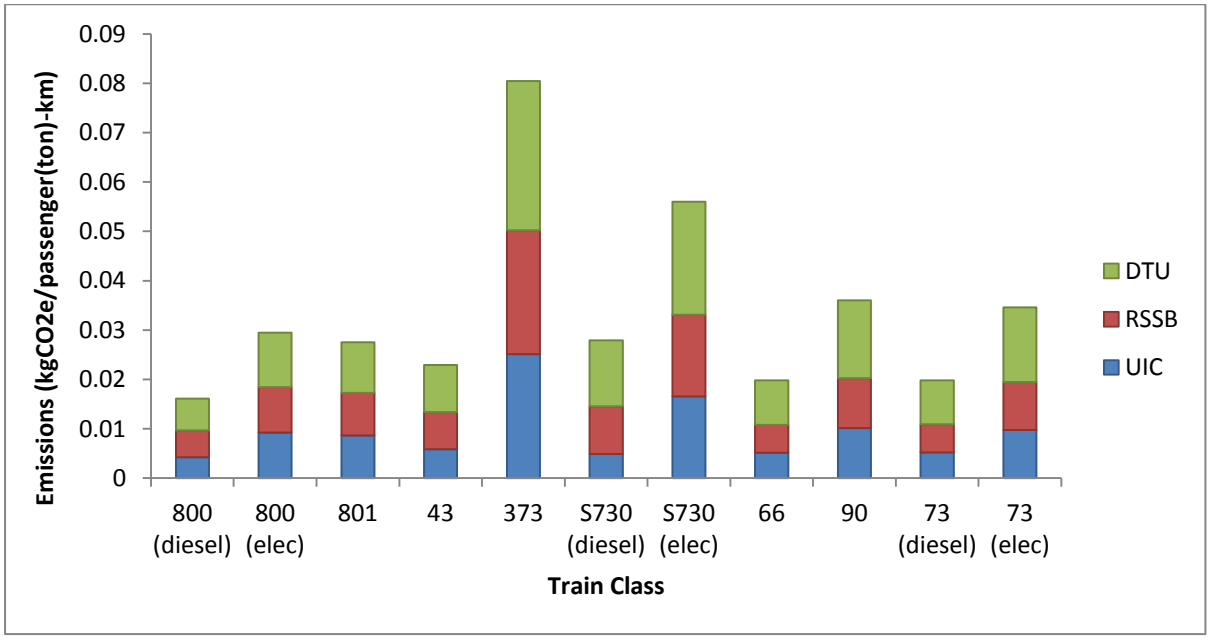

Figure 9.1.3. - Emissions of Fully Loaded Trains Running at 100km/h

Figure 9.1.3. shows emissions of trains at a constant speed of 100km/h. Comparing this to *Figure 9.1.2.* above, it is evident that the speed the trains are travelling at has a large impact on energy consumption and, hence, emissions. The emissions produced by the class 373 at 100km/h are reduced by a factor of 20 when speed has been reduced by a factor of 3. The S730 gives off almost twice the amount of emissions when running on electricity than diesel. This shows that the carbon intensity of UK electricity generation is not low enough for electric vehicles to be sustainable.

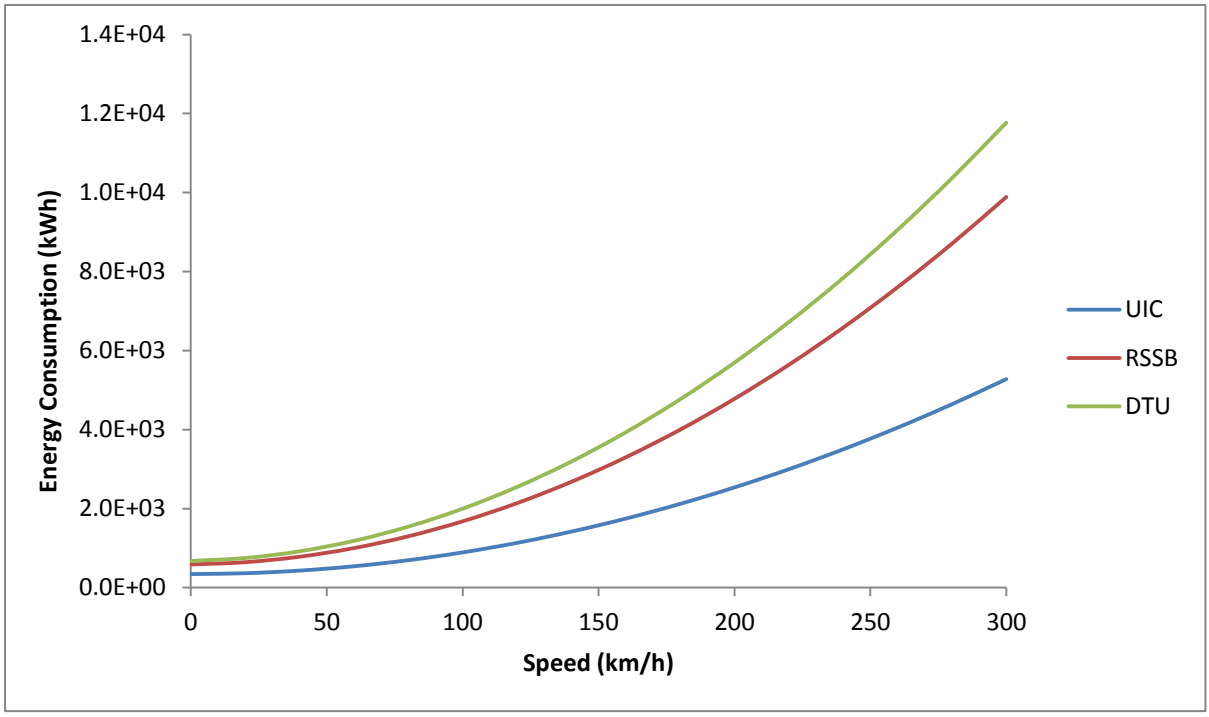

Figure 9.1.4. - Energy Consumption of the Class 373 at Varying Speeds

The class 373 was used to show the effect speed has on energy consumption. As was expected, the energy consumption increases exponentially with speed, shown in *Figure 9.1.4*. The results from the UIC method do not increase as quickly as the other two methods. This shows that the effect of air resistance is not as dominant when using this method when comparing it to both other methods, which increase at a similar rate. This may be due to the drag coefficients that were used during calculation. For the UIC method, drag coefficients were not as detailed and tailored to specific train types as the other two methods; they were simply designated by type (Conventional, High Speed, and Interoperable).

Using the DTU method it can be seen, from *Figure 9.1.4.*, that reducing the speed of the Class 373 from 300km/h to 250km/h reduces energy consumption by almost 4000kWh. This reduces the emissions from 0.1759kgCO_2e/passenger-km to 0.1342kgCO_2e/passenger-km. This translates to a 23.7% reduction in emissions when speed is reduced by 16.7%.

8.2. Carbon Intensity

Previous results show that, currently, electric trains release more GHGs than diesel trains in terms of emissions due to the fundamental operation of the vehicle. This is due to the carbon intensity of UK electricity being relatively poor in 2013. Future predicted carbon intensities, taken from national grids publication – UK Future Energy Scenarios, were used to predict when electric trains would become more sustainable and how long it could take for these trains to be carbon neutral.

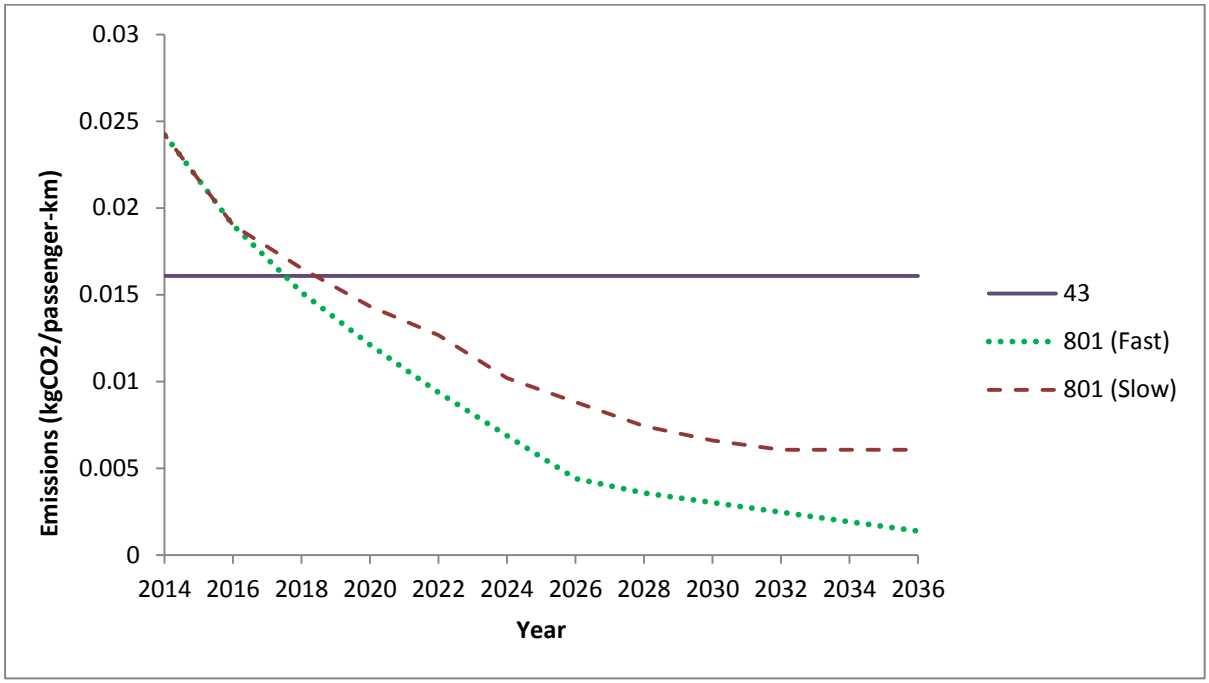

Figure 9.2.1. - The Effect of Carbon Intensity on Electric Trains

The paper gives a possibility of two scenarios; Gone green (Fast) and Slow Progression (Slow). In order to highlight the effect of carbon intensity, the class 801 has been used as the electric train in comparison to the class 43 diesel train. It can be seen, from *Figure 9.2.1.,* that the emissions of the 801 will be equal to that of the class 43 during 2017 in the 'fast scenario' and 2018 in the 'slow scenario'.

For the 'Gone Green' scenario, the emissions of the class 801 would be approximately 0.00125kgCO_2e/passenger-km by 2036 which results in a reduction of around 2000% from current figures. If slow progression were to occur the reduction would be around 420%. Although the emissions for trains are currently higher (2014), the potential for them to have almost negligible emissions in the near future is achievable.

8.3. Load Factor

The number of passengers/goods transported has no effect on the overall emissions of the train. It is typical to find out the environmental impact of transport per passenger or, for goods vehicles, per ton. This is because GHG emissions are assessed on a per person basis in order to quantify the impact these gases have on the environment. Emissions are reported per passenger/ton kilometre, the load the train carries, has a profound effect on these emissions. Therefore, it is important for train operators in the UK to maximise the load of each service in order to reduce their impact on the environment.

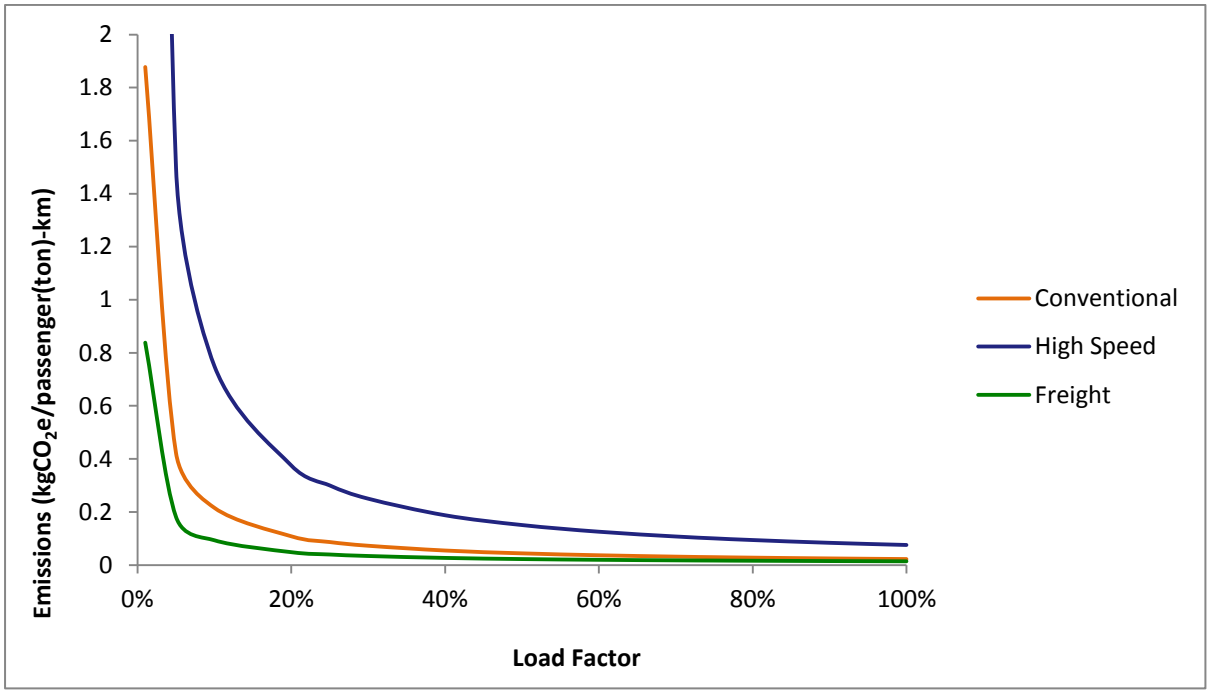

Figure 9.3.1. - Effect of Load Factor on Emissions for each Train Type

It can be seen, from *Figure 9.3.1.* that emissions decrease exponentially as load increases. The average of the three methods was used to find this information. The average of the three train types was then taken in order to see how they differ from each other. The emissions of conventional and freight trains decrease at a rapid rate in comparison to that of HSTs. The emission from 50% loaded to 100% is almost negligible, whereas, there is still a noticeable difference in the emissions of HST from 50% to 100% load. This difference is noticeable in HST as the energy consumption is much greater, therefore having a larger impact on the rate of change.

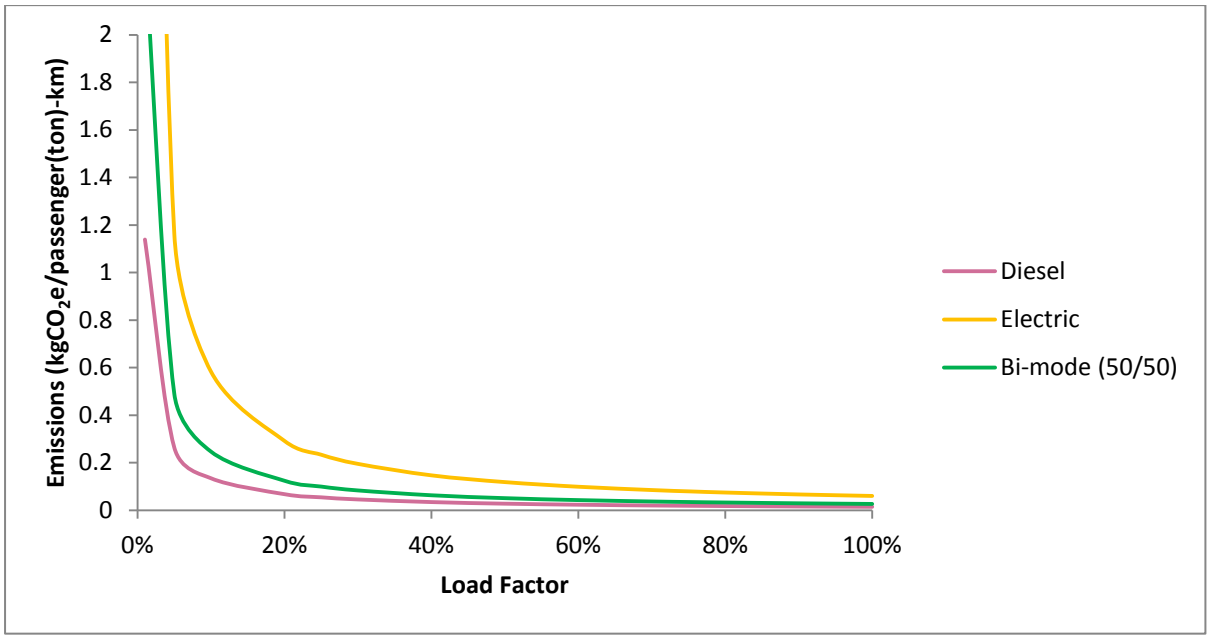

Figure 9.3.2. - Effect of Load Factor on Emissions for Each Mode of Operation

Again, looking at *Figure 9.3.2.,* the same thing can be said about electric trains. As there were no diesel high-speed trains for comparison, the emissions due to diesel trains seem to have a much lower impact than electric trains. This difference would not be as great had a HS diesel train been factored into the averages. The emissions for bi-mode trains in this plot were calculated using a route of 50% electrified track. It can be seen in figure that the bi-mode trains display figures closer to the diesel trains than that of HS. This is also influenced by the lack of diesel HST as discussed previously.

8.4. Percentage of Electrified Track

The percentage of electrified track has an effect on bi-mode train's emissions and is solely dependent on the carbon intensity of the electricity generation. If electricity generation in the UK becomes carbon neutral, then it would be beneficial to use the electrical supply where possible. As it stands, in the current energy climate, operators would be more inclined for their fleet to traverse along non electrified routes in order to reduce their emissions.

The class 800 has been selected in order to see the difference in each method. It can be seen from *Figure 9.4.1.* that the rate at which emissions increase is very similar for both the RSSB and DTU methods, whereas, the UIC method seems to increase at a slower rate.

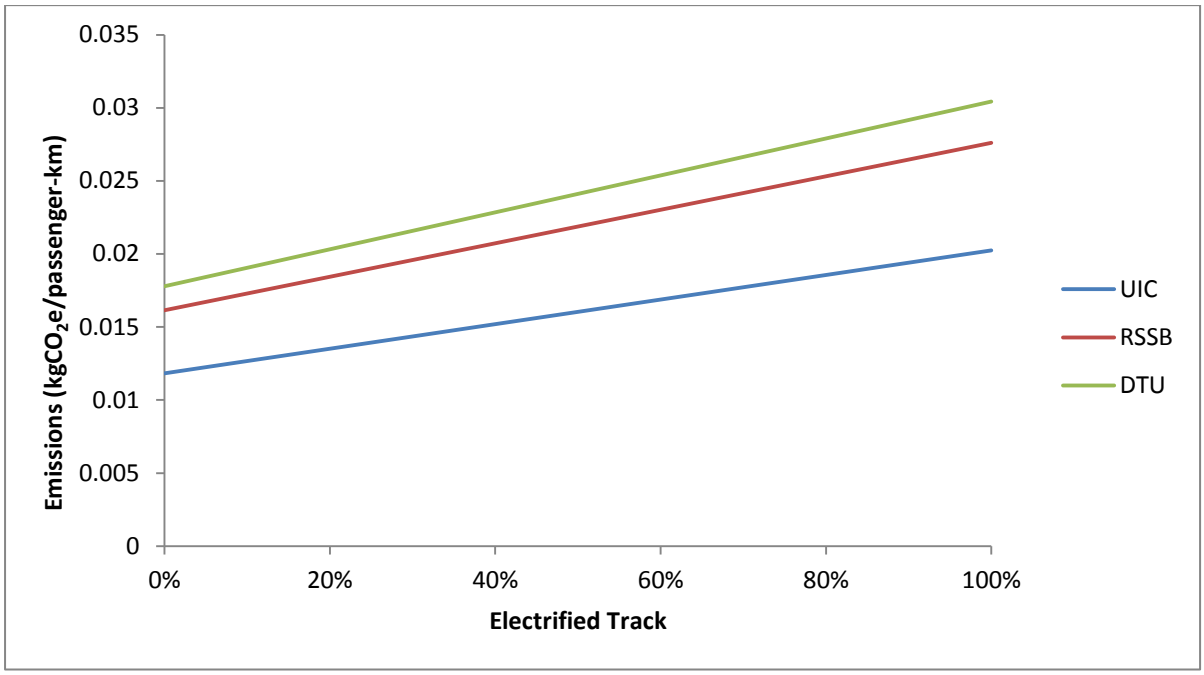

Figure 9.4.1. - Emissions of the Class 800 on different Percentage of Electrified Track

This is explained by the initial value of the energy consumption. Different conversion factors are used to find emissions from diesel and electric modes of operation, therefore, the plot lines take the form $y=(m_1+m_2).x$ rather than the typical form $y=mx+c$. This means that the gradient increases a very small amount with the percentage of electrified track, hence why the rate of change increases with the initial value of energy consumption. The emissions increase by almost a factor of 2 from fully diesel operation to fully electric, again, this shows that the current methods used for energy generation in the UK are not sustainable.

8.5. Alternative Fuels

Biodiesel was the only alternative fuel used in this study as other alternatives still require further research and development in order to be used as a reliable fuel source. The percentage of biodiesel in a biodiesel blend is approximately linearly proportional to the emissions produced. Running a train on B100 would produce negligible emissions and should be a serious consideration in the future of rail.

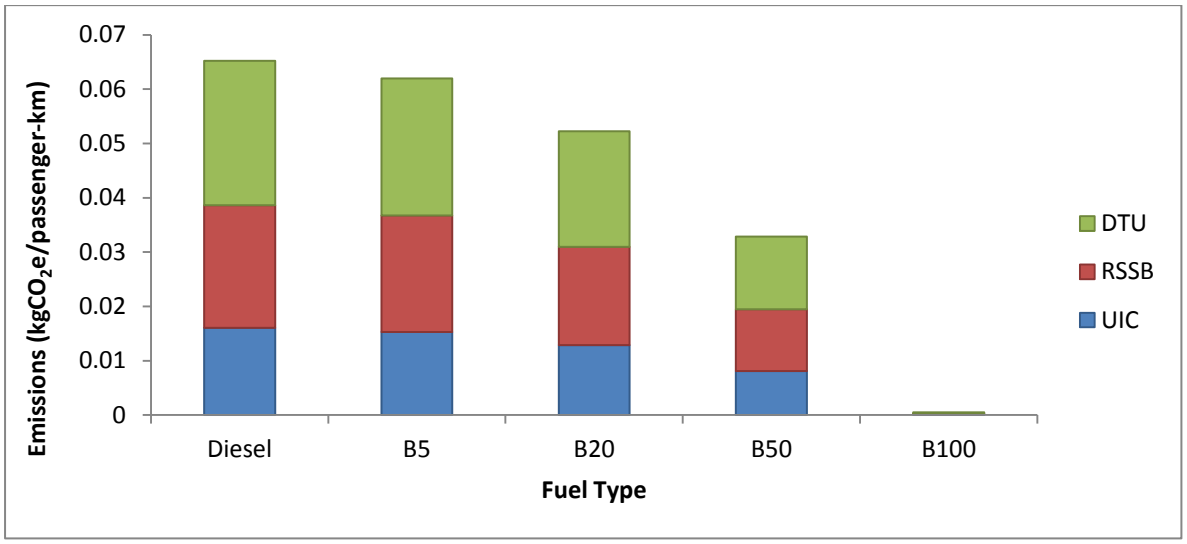

Figure 9.5.1. - Emissions of the Class 43 using Varying Blends of Biodiesel

Figure 9.5.1. shows that biodiesel is successful in reducing the emissions of diesel and bi-mode trains. It can be confirmed that B20 reduces the emissions of diesel trains by approximately 15-20%, B50 reduces the emissions by almost 50% and the emissions of 100% biodiesel are almost negligible. It may be possible to run diesel trains on these fuels with little or no modifications to the technology, although the long term effects of running a train on B100 are not known.

8.6. Sensitivity Study of Methods Used

As the three methods used produce values of varying magnitude, it was necessary to be able to quantify which method is most accurate. During the data collection process, the fuel consumption for the class 43 was found to be 0.84l/100-seat-km when travelling at 125mp/h (201km/h)[66]. As some contributions to energy consumption were not included in this study, it was necessary to do some further calculation on the results given. The percentage of energy consumption due to mechanical and air resistance for an intercity train (without regenerative braking) is approximately 80%[41]. Taking this into account, the fuel consumption for the class 43 using the UIC, RSSB and DTU methods are 0.77275l/100-seat-km, 1.084l/100-seat-km and 1.2763l/100-seat-km respectively. The UIC method seems to give the most accurate result using this data. In order to confirm that it is the most accurate, a comparison to the consumption of another train was made.

The average energy consumption of the class 801 is 0.028kWh/seat-km[41]. The consumption found using the UIC, RSSB and DTU methods was 0.043kWh/seat-km, 0.05852kWh/seat-km and 0.06368kWh/seat-km respectively. Again, the UIC method gives the closest result, although it is almost twice the magnitude of the actual consumption. The consumptions calculated were found when the train was travelling at a constant top speed of 200km/h, whereas, the average consumption will have been calculated using a range of speeds. It is unlikely that the train will be travelling at its top speed constantly during operation, therefore, as air resistance increases with the square of speed, it is fair to assume that the energy consumption would be much less when an average is taken over a range of speeds.

9. Conclusion

It has been found that, in the current energy climate of the UK, the emissions of electrically powered trains are higher than that of diesel locomotives. This is due to the current carbon intensity of electricity generation being high in the UK. If the correct steps are taken towards carbon neutrality, the emissions from electricity generation should fall dramatically by 2040, making electric powered vehicles much more sustainable and environmentally friendly than diesel trains. Bi-mode trains offer interoperability between tracks which is an advantage on the UK rail network. In terms of emissions, they are currently more desirable than electrifying the track; although, the embedded emissions resulting from this electrification would need to be factored in, in order to quantify the true advantages of bi-mode trains. As plans to electrify the UK rail network are currently in place and carbon intensity reduction is being focused on, the advantages of bi-mode trains will be short lived.

High speed trains consume a lot more power than conventional rail. If the carbon intensity reduces to a sustainable figure, the emissions of HSR will be negligible. In order to evaluate this point properly, the emissions that arise from the manufacture and infrastructure of HSR would need to be considered; to give a thorough analysis of the life cycle emissions. HS2 will not be in operation until around 2030. If the progression towards carbon neutrality follows predictions, then HS2 should be relatively sustainable by the time it is open to the public.

Emissions due to rail freight are lower than that of passenger rail. This is a result of the density of the goods being carried compared to the density of passengers. Passengers also require comfort functions and facilities such as toilets etc. this also adds to the energy consumption. Diesel traction is frequently used in rail freight because of the access this grants within the UK rail network. If the carbon intensity of electricity generation is to follow the predictions and the UK rail network becomes fully electrified, then it will be worthwhile investing in electric traction for rail freight.

Out of the three methods used, it has been confirmed that the UIC method gives the most accurate results, although it cannot be said that it is an accurate method for calculating energy consumption due to the factors that have been neglected in this study. In order to fully assess the accuracy of any of the methods used, a full well-to-wheel approach to calculating emissions must be taken. This includes; taking into account the efficiency of the oil refineries used to produce the diesel petroleum, how the fuel is transported to the locomotive and the emissions produced during oil refinement and electricity generation.

In order for each train to be assessed on their energy performance and emissions, more accurate and specific data on each train is required. In particular, the assumptions made for the drag coefficients may not be appropriate. As the resistance due to drag, has the most significant effect on energy consumption, the drag coefficients need to be specific to that train. The efficiency of each vehicle will vary greatly from the value used in this study once transmission losses and engine efficiency are taken into account. This would require a much more detailed analysis of the drive systems used in each locomotive. To eliminate these assumptions, a more in depth data collection would have been necessary, contacting various manufacturers and professionals in the rail industry to be granted access to specific train data. To carry out a more thorough comparison, a larger sample of trains could have been collected; this would give a much clearer insight into the differences between each type and mode of operation resulting in a more extensive set of results.

10. Future Work

The trains used in this study were assessed and compared based on the emissions they produce during operation. The future direction of this study would be to branch out and look at other influences on the emissions of trains coupled with a consideration of other alternative fuels, for a more complete assessment of their performance. Further work would include:

- A full life cycle analysis of emissions to be carried out, including emissions arising from: the implementation and building of infrastructure, manufacture and maintenance of trains, disposal of expired vehicles or equipment etc.
- A more in-depth study on the advantages and disadvantages of alternative fuels, with the consideration of other new technologies and energy sources such as LNG and Hydrail.
- Calculations carried out on the effect the mass and density of goods carried by rail freight has on the emissions these locomotives produce.
- An inclusion of all factors that contribute to emissions such as: grade resistances, which arise from the nature of the route (bends, inclines and declines etc.), regenerative braking and the energy consumption due to passenger comfort functions.
- A study on the effect the route has on the overall energy consumption and emissions of a train; this would include a comparison carried out on a selection of varying routes to be able to quantify the effect coasting, travelling along curved tracks etc. has on energy consumption.

References

[1] Network Rail. (2009). Electrification. *Network RUS*. p4.
[2] Network Rail. (2013). Strategic Business Plan for England & Wales. *Control Period 5*. (3), p46-47.
[3] Ltd, W. (2014). *Intercity Express (IEP) | Hitachi Rail Europe*. Available at: http://www.hitachirail-eu.com/super-express-iep_57.html [Accessed 2 Feb. 2014].
[4] Highspeed1.com, (2014). *High Speed 1 – Rail*. Available at: http://www.highspeed1.com/Rail [Accessed 3 Mar. 2014].
[5] Network Rail. (2010). The Value and Importance of Rail freight. (Executive Summary), p6.
[6] Fueleconomy.gov, (2014). *Biodiesel*. Available at: http://fueleconomy.gov/feg/biodiesel.shtml [Accessed 25 Feb. 2014].
[7] Railway-technology.com, (2014). *Hydrail and LNG: the future of railway propulsion? - Railway Technology*. [online] Available at: http://www.railway-technology.com/features/featurehydrail-lng-future-railway-propulsion-fuel/ [Accessed 26 Feb. 2014].
[8] News.bbc.co.uk, (2014). *BBC NEWS | UK | £1bn plan to electrify rail line*. Available at: http://news.bbc.co.uk/1/hi/uk/8164070.stm [Accessed 30 Jan. 2014].
[9] News.bbc.co.uk, (2014). *BBC NEWS | UK | The great train debate: Electric or Diesel?*. Available at: http://news.bbc.co.uk/1/hi/uk/8163331.stm [Accessed 29 Jan. 2014].
[10] Railway-technical.com, (2014). *UK Railway Statistics*. Available at: http://railway-technical.com/statistics.shtml [Accessed 30 Jan. 2014].
[11] Network Rail. (2009). Electrification. *Network RUS.* (3), p18-21.
[12] Jay Andreas. (n.d.). Energy, Environmental and Economic Benefits. p3.

[13] GmbH, D. (2014). *SNCF orders electro-diesel inter-city trainsets*. RWG. Available at: http://www.railwaygazette.com/news/single-view/view/sncf-orders-electro-diesel-inter-city-trainsets.html [Accessed 2 Feb. 2014].
[14] Freeman, Allen G. (1962). *British Railways: Today and Tomorrow*: Ian Allan. p88-89.
[15] Amtrak. (2011). Requirements Document. *PRIIA Dual Mode (DC) Passenger Locomotive*. (1), p4.
[16] Networkrail.co.uk, (2014). *Great Western Railway*. Available at: http://www.networkrail.co.uk/VirtualArchive/great-western/ [Accessed 12 Mar. 2014].
[17] Networkrail.co.uk, (2014). *North British Railway*. Available at: http://www.networkrail.co.uk/VirtualArchive/north-british/ [Accessed 12 Mar. 2014].
[18] BBC News, (2014). *Did Beeching get it wrong 50 years ago?*. Available at: http://www.bbc.co.uk/news/uk-21938349 [Accessed 12 Mar. 2014].
[19] Simpson, D. (2013). *How we made the InterCity 125*. the Guardian. Available at: http://www.theguardian.com/culture/2013/sep/09/how-we-made-intercity-125 [Accessed 12 Mar. 2014].
[20] Gov.uk, (2013). *20 years since rail privatisation - Speeches - GOV.UK*. Available at: https://www.gov.uk/government/speeches/20-years-since-rail-privatisation [Accessed 12 Mar. 2014].
[21] Networkrail.co.uk, (2014). *Our history - Network Rail*. Available at: http://www.networkrail.co.uk/aspx/729.aspx [Accessed 12 Mar. 2014].
[22] Uic.org, (2014). *General definitions of highspeed - UIC - International Union of Railways*. Available at: http://www.uic.org/spip.php?article971 [Accessed 3 Mar. 2014].
[23] Persson, Rickard (2007). *Tilting Trains*. Linköping, Sweden: VTI. p9.
[24] Railway Technology. (n.d.). *Alaris Tilting Trains, Spain.* Available: http://www.railway-technology.com/projects/alaris/. [Accessed 12th March 2014].
[25] Highspeed1.com, (2014). *High Speed 1 – International Rail Services*. Available at: http://www.highspeed1.com/rail/international-rail-services/ [Accessed 3 Mar. 2014].
[26] Hs2.org.uk, (2014). *Key dates | HS2*. Available at: http://www.hs2.org.uk/about-hs2/key-dates [Accessed 12 Mar. 2014].
[27] Hs2.org.uk, (2014). *Better journeys between cities | HS2*. Available at: http://hs2.org.uk/about-hs2/facts-figures/connectivity-journey-times [Accessed 12 Mar. 2014].
[28] Network Rail. (2010). The Value and Importance of Rail freight. (2), p19.
[29] Network Rail. (2010). The Value and Importance of Rail freight. (4), p23-24.
[30] Bp.com, (2014). *How refining works | About BP | BP Global*. Available at: http://www.bp.com/en/global/corporate/about-bp/what-we-do/making-fuels-and-products/how-refining-works.html [Accessed 6 Feb. 2014].
[31] Exxonmobil.co.uk, (2014). *Fawley refinery*. Available at: http://www.exxonmobil.co.uk/UK-English/about_what_refining_fawley.aspx [Accessed 10 Feb. 2014].
[32] Exxonmobil.co.uk, (2014). *ExxonMobil in the UK - Refinery to customer*. Available at: http://www.exxonmobil.co.uk/UK-English/about_what_refining_customer.aspx [Accessed 10 Feb. 2014].
[33] Uk.total.com, (2014). *Total in the UK - Activities: Lindsey Oil Refinery*. Available at: http://www.uk.total.com/activities/lindsey.asp [Accessed 10 Feb. 2014].
[34] TOTAL UK Limited. (n.d.). Lindsey Oil Refinery Fast Facts. p1.
[35] Department of Energy and Climate Change. (2013). Electricity. *Energy Trends*. 1 (5), p38.
[36] Www2.nationalgrid.com, (2014). *About electricity | National Grid*. Available at: http://www2.nationalgrid.com/uk/our-company/electricity/ [Accessed 11 Feb. 2014].
[37] Department of Energy and Climate Change. (2013). Electricity. *Energy Trends*. 1 (5), p39.
[38] EPA. (2008). Direct Emissions from Mobile Combustion Sources. (1), p2.
[39] Network Rail. (2013). Strategic Business Plan for England & Wales. *Control Period 5*. (1), p11.
[40] Network Rail. (2013). Strategic Business Plan for England & Wales. *Control Period 5*. (3), p46.
[41] Network Rail. (n.d.). Comparing environmental impact of conventional and high speed rail. (2), p3-12.

[42] Åkerman, J. (2011). The role of high-speed rail in mitigating climate change. *Transportation Research Part D: Transport and Environment*. 16 (5).
[43] SYSTRA. (2011). Factors affecting carbon impacts of HSR. *CARBON IMPACTS OF HS2*. 3.1 (1), p4-11.
[44] Johnson, G.R. (2013). Remote measurement of diesel locomotive emission factors and particle size distributions. *Atmospheric Environment*. 81 (1).
[45] Hoffrichter, Andreas. (2012). Transportation Research Part D: Transport and Environment. *Well-to-wheel analysis for electric, diesel and hydrogen traction for railways*. 17 (6).
[46] Afdc.energy.gov, (2014). *Alternative Fuels Data Center: Diesel Vehicles Using Biodiesel*. Available at: http://www.afdc.energy.gov/vehicles/diesel.html [Accessed 25 Feb. 2014].
[47] Biodiesel.org, (2014). *Biodiesel Basics - Biodiesel.org*. Available at: http://biodiesel.org/what-is-biodiesel [Accessed 25 Feb. 2014].
[48] Pahl, Greg (2010). *Biodiesel: Growing a New Energy Economy*: Chelsea Green.
[49] Demirbas, Ayhan. (2007). Importance of biodiesel as transportation fuel. *Energy Policy*. 35 (2)
[50] World-nuclear.org, (2014). *Thorium*. Available at: http://www.world-nuclear.org/info/current-and-future-generation/thorium/ [Accessed 17 Apr. 2014].
[51] BBC News, (2014). *Thorium backed as a 'future fuel'*. Available at: http://www.bbc.co.uk/news/science-environment-24638816 [Accessed 17 Apr. 2014].
[52] Anon, (2014). Available at: 1. http://www.hitachirail-eu.com/class-395-high-speed_43.html [Accessed 3 March. 2014].
[53] Freightliner.co.uk, (2012). *Freightliner Group Ltd - State of the art Intermodal and Bulk Haulage wagon fleet*. Available at: http://www.freightliner.co.uk/en/fleet/wagons/#ar-4 [Accessed 5 Apr. 2014].
[54] CQFY (n.d.). *Wagon Data Sheet.* Available at: http://www.cfcla.com.au/datasheet/CQFY_Wagon_Data_Sheet.pdf [Accessed 5 Apr. 2014]
[55] International Union of Railways. (2003). Evaluation of Energy Efficiency Technologies for Rolling Stock and Train Operation of Railways. (4), p18.
[56] Garcia, Alberto. (2010). High Speed, Energy Consumption and Emissions. 1 (4), p23.
[57] RSSB. (2007). Quantification of Benefit of Train Mass Production.
[58] Uic.org, (2014). *UIC Corporate brochure - UIC - International Union of Railways*. Available at: http://www.uic.org/spip.php?article2541 [Accessed 24 Apr. 2014].
[59] RSSB. (n.d.). A Guide to RSSB.
[60] Engineeringtoolbox.com, (2014). *Air - Density and Specific Weight*. Available at: http://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html [Accessed 10 Apr. 2014].
[61] Gov.uk. (2014). Average Temperatures and Deviations from the Long Term Mean. *Energy Trends*. (7),
[62] Lindgreen, Erik & Sorenson, Spencer C.. (2005). Driving Resistance from Railroad Trains. (2), p2-7, 30-33.
[63] Paxmanhistory.org.uk, (2014). *Paxman History Pages - Paxman and Diesel Rail Traction*. Available at: http://www.paxmanhistory.org.uk/paxrailt.htm [Accessed 3 Apr. 2014].
[64] Pure Energy Professionals. (n.d.). Electricity Generation Efficiency. (1), p1.
[65] DEFRA, (2014). *DEFRA Carbon Factors*. Available at: http://www.ukconversionfactorscarbonsmart.co.uk/ [Accessed 8 Apr. 2014].
[66] MacKay, David. (2008). *Sustainable Energy - Without the Hot Air*. 3rd ed. UK: UIT. p135.

An Analysis of the Methods used to calculate the Emissions of Rolling Stock in the UK

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Highlights

- In the current energy climate of the UK, the emissions of electrically powered trains are higher than that of diesel locomotives. This is due to the current carbon intensity of electricity generation being high in the UK;
- Out of the methods used, the UIC method gives the most accurate results, although it cannot be said that it is an accurate method for calculating energy consumption due to the factors that have been neglected in this study;
- As the resistance due to drag, has the most significant effect on energy consumption.

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