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Electric and hydrogen rail: Potential contribution to net zero in the UK



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ABSTRACT

Electric trains (ET) and hydrogen trains (HT) are considered zero emission at the point of use. True emissions are dependent upon non-tailpipe sources, primarily in energy production. We present UK carbon dioxide (CO₂) operating emission model outputs for conventionally fuelled trains (CFT), ETs and HTs between 2017 and 2050 under four National Grid electricity generation scenarios.

Comparing four service categories (urban, regional, intercity and high speed) to private conventionally fuelled vehicles (CFV) and electric vehicles considering average distance travelled per trip under different passenger capacity levels (125%, 100%, 75%, 50% and 25%).

Results indicate by 2050 at 100% capacity CFTs produce a fifth of the emissions of CFVs per kilometre per person. Under two degree generation scenario, by 2050 ETs produced 14 times and HTs produced five times less emissions than CFTs. Policymakers should encourage shifts away from private vehicles to public transport powered by low carbon electricity.

1. Introduction

The UK has set an ambitious target of net zero emissions by 2050 to reduce greenhouse gas (GHG) emissions under the 2015 Paris Agreement as part of the global effort to tackle climate change (CCC, 2019; Pye et al., 2017). In 2018, transport and energy were the largest emitting sectors producing ~33% and ~27% of total UK GHG emissions respectively (BEIS, 2018a, 2019), with substantial focus needing to be placed on these sectors to meet net zero. The UK transport sector has been dominated by conventionally fuelled vehicles (CFVs) (i.e. petrol and diesel power) which generated ~62% of transport emissions in 2016. Reducing emissions from CFVs has been a key focus for many policymakers (DfT, 2019a). Numerous studies have suggested that encouraging travellers to switch to rail travel from private CFVs can reduce pollution and GHG emission to the air as the environmental impact per kilometre is significantly lower for trains than for road transport (Chapman, 2007; Haseli et al., 2008; Saxe et al., 2016; Zuo et al., 2018). The objective of this paper is to analyse emissions from electric trains (ETs), hydrogen trains (HTs) and conventionally fuelled trains (CFTs) and compare these results with private CFVs and electric vehicles (EVs) for passenger transport, through four different energy generation scenarios from the UK National Grid (National Grid, 2019). Rail service type will also be differentiated by urban, regional, intercity and high speed to take into consideration the distance travelled and to account for shorter train journeys made within cities. These are compared in terms of emissions per passenger kilometre to private vehicles (CFVs or EVs). This will allow quantification of

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the extent to which a move away from private vehicles in favour of urban ETs and HTs can contribute to the UK's national target of net zero.

Rail is often perceived as a 'green' mode of transport as the ~ 2 MtCO_{2e} produced in 2016 was the equivalent of only $\sim 2\%$ of total UK transport emissions (DfT, 2019a). In 2018, the UK Government announced that to reduce rail emissions further, diesel-only trains are to be phased out by 2040. This will result in upgrading almost a third of current trains as well as infrastructure, with $\sim 60\%$ of the rail network not yet electrified (DEFRA, 2019; Royston et al., 2019). Without improvements to the current rail rolling stock, as well as track and platforms, emissions could remain static. Therefore, the need for investment in new trains and electric infrastructure is apparent, not only to offer a real alternative to private CFVs and EVs but to support the broader objectives of integrated transport and achieve a reduction in GHG emissions (Mulley et al., 2017). The phasing process of stock replacement will be a longer-term project compared to that of CFVs as the service life of trains are currently ~ 19.2 years compared to ~ 13.9 years of a CFV, so a technology change from private CFVs to EVs can occur more rapidly (DfT, 2018a, 2019b; SMMT, 2019).

The impact of electrification of rail infrastructure (including trains and tracks) is perhaps progressed the least in terms of achieving a lower carbon transport network in the UK. Reductions within the energy sector combined with a lowering of emission output overall has meant that rail is accounting for a growing percentage of total emissions, especially as passenger travelling distances are increasing (Salisbury et al., 2015; Saxe et al., 2016). Maintenance of railway tracks play a key role in ensuring both the dependability and safety of rail, as it reduces the potential risks of defects and derailments (Shafiee et al., 2016). Over time, rail tracks can degrade due to cumulative usage, therefore they need to be continually updated and replaced. To accommodate a transition towards ET and HTs in the UK, new tracks will need to be built. In parallel, policy to promote green transport options for both short and long-distance travel will need to be considered through the introduction of travel demand management (TDM) initiatives. TDM initiatives are actions which have the potential to influence an individual's travel behaviour through the introduction of push and pull measures (Gärling et al., 2002; Meyer, 1999). Introduction of TDM initiatives to encourage train use could include park and ride facilities at rail stations, cycle rail schemes which allow passengers to take their bikes on trains with cheaper train tickets. Introducing TDM initiatives provides citizens with efficient and effective access to travel modes that also align with wellbeing, social inclusion and environmental sustainability (Mulley et al., 2017; Stopher and Stanley, 2014).

The role of ETs and HTs towards achieving net zero has been widely discussed as part of a strategy to help decarbonise the train sector within the UK. The level of GHG emissions produced is dependent upon the method of electricity and hydrogen (H₂) generation. This needs to be from renewable or nuclear sources, otherwise environmental benefits are diminished. Electric and hydrogen transport systems can be more easily powered by renewable and low carbon energy sources, making them one of the most efficient energy utilisation systems when compared to private CFVs, buses or aircrafts (Haseli et al., 2008; Marin et al., 2010).

In this paper, train operating emissions are calculated for ETs and HTs using the projected carbon dioxide (CO₂) emissions produced from four UK National Grid electricity mix scenarios between 2017 and 2050 (National Grid, 2018). The first scenario, two degrees, reflects the UK adhering to the global ambition to restrict global temperature rise to below the 2 °C above pre-industrial levels, as set out in the Paris Agreement. This scenario provides large-scale solutions with consumers expected to choose alternative heat and transport options to meet the 2050 targets. This incorporates homes and businesses transitioning to hydrogen and electric technologies for heat and consumers choosing electric and hydrogen alternatives for transport. UK total emissions are expected to meet the 80% emission reduction target, with emissions decreasing from 503 MtCO_{2e} in 2017 to 165 MtCO_{2e} in 2050 (National Grid, 2018). The second scenario, steady progression, makes predictions considering continual levels of progress and innovation at current rates. This scenario is similar to the two degree scenario but adapting at a much slower rate of adoption with consumers slower to adopt to electric and hydrogen transport and with low carbon alternatives for heat limited by costs, lack of information and access to suitable alternatives. In this scenario, emissions are expected to decrease by 58%, not meeting the 80% target, decreasing from 503 MtCO_{2e} in 2017 to 345 MtCO_{2e} in 2050 (National Grid, 2018). Scenario three, community renewables, projects what could happen if consumers and businesses began to install small-scale renewable generation in their homes, offices and neighbourhoods. This scenario foresees local energy schemes to flourish and improving energy efficiency is a priority with emissions expected to meet an 80% emissions reduction, decreasing from 503 MtCO_{2e} in 2017 to 165 MtCO_{2e} by 2050 (National Grid, 2018). The final scenario is the consumer evolution scenario which looks at the shift towards local generation and increased consumer engagement, largely from 2040 onward. In this scenario alternative heat solution uptake occurs where it is practical and affordable, for example, due to the local availability. Consumers choose EVs and energy efficiency measures. Under this scenario, emissions are expected to decrease by 58% and not meet the 80% reduction target with emissions decreasing from 503 MtCO_{2e} in 2017 to 344 MtCO_{2e} by 2050 (National Grid, 2018). Additionally, in the analysis for HTs, emissions produced from steam methane reforming (SMR) with natural gas and SMR with coal gasification with and without carbon capture and storage (CCS) were also examined for 2018.

For the purposes of this study, rail services have been divided into four categories: urban, regional, intercity and high speed. Urban rail incorporates light and underground rail services. Regional rail incorporates slow to medium speed regional services. Intercity rail includes faster inter-regional services while high speed rail in our study comprises Eurostar services from London St Pancras International (the Channel Tunnel Rail Link or High Speed 1 (HS1)), although there are plans for more extensive high speed services by 2040 from London, Birmingham, Manchester and Leeds with the High Speed 2 (HS2). Using these rail service categories and the National Grid electricity scenarios, we examine which will produce the lowest emission levels to help achieve UK net zero policy.

1.1. Railway network in the UK

The UK is deemed 'the birthplace of railways', as it is home to one of the oldest rail networks in the world. Currently, Network Rail

(NR) owns and operates the national railway infrastructure as a public body of the UK Government covering a total of ~31,000 km of track (including passenger and non-passenger routes), ~30,000 bridges and viaducts as well as thousands of tunnels, signals, and level crossings across the UK (ORR, 2017; Wang et al., 2020; Williams Rail Review, 2019). Most train services however, are provided by private operators (Bowman, 2015). This rail network is of vital economic importance carrying ~4.4 million passengers daily on ~22,000 passenger trains and ~11% of the UK's freight (Power et al., 2016). However, in recent years, modernisation of trains and infrastructure in the UK has fallen behind many European countries with only ~37.9% of passenger railway track in the UK electrified, the equivalent of ~6,012 km of ~15,847 km in 2018/19.

England has seen a substantial increase in rail usage in recent years with London having the highest level with almost two-thirds of trips in England in 2017/18 either starting or ending in London. London's public transport system is an interesting case study as while personal vehicle ownership is high, the high level of public transport network utilisation means emissions per capita are substantially lower proportionally than the rest of the country (DfT, 2019c). Rail usage across the UK has increased significantly within the last 20 years, ranging from 102% (Wales) to 247% (West Midlands). These increases are an indication of consumers switching travel habits while being influenced by socio-economic factors. Ensuring that adequate, environmentally clean services are available for consumers to feel confident in their new travel choice is imperative to achieve the success of initiatives like those in London.

Enhanced consumer experience is an important objective and is crucial for achieving high use and profitability in highly competitive environments when multiple travel options are available (Hernon and Nitecki, 2001; Lemon and Verhoef, 2016; Mogaji and Erkan, 2019). Therefore, it is essential that rail services set themselves apart from the competition of personal vehicles or flying, by providing a quality service that enhances a users experience. However, service quality is considered to be multidimensional and can vary from consumer to consumer with everyone having a different perception of what quality service should entail (Brady and Cronin, 2001; Korda and Snoj, 2010; Mogaji and Erkan, 2019). The UK's rail services are considered underdeveloped, except in London, with passengers often complaining about fare levels, overcrowding, scheduling issues and considering rail travel less convenient than personal vehicles. The exception is London where the network is better developed and hence more convenient (Nash et al., 2019; Setyawan and Diah Damayanti, 2018). Where there are insufficient rail carriages during peak travel times, overcrowding can be an issue and can adversely affect both passengers and train operators. For example, during peak travel time, on average ~17% of individuals were standing on trains in all major cities in 2019 (DfT, 2019b). London had the highest number of standing passengers in 2018/19 at ~230,000, with the second highest in Birmingham with ~17,300 passengers (DfT, 2019b). This lack of space for passengers can cause reduced physical comfort during travel, reduced productivity and increased stress (Preston et al., 2017). Although overcrowding is currently an issue in London, the level of demand is such that even increases in fares are unlikely to see a reduction in demand for rail travel. Currently, UK wide, rail passengers are more likely to be in the highest income quartile. This is mostly due to commuters travelling in London and the South East which has the highest income band and accounts for a considerable proportion of rail travel (Brand and Preston, 2010). In addition, technological improvements such as improved fare collection and management, such as the Transport for London (TfL) Oyster card with its capped daily cost, allows consumers to benefit from integrated travel between public transport modes (Logan et al., 2020).

Urban rail travel plays a key role in many of the UK's major cities by providing public transport services within metropolitan areas (González-Gil et al., 2015). Urban rail is regarded as an ideal solution to reduce the restrictions of urban mobility due to the superior capacity, safety, reliability and environmental performance of the service when compared to the private car. Although there can be capacity constraints that leave little scope for increasing future urban rail use, push and pull TDM initiatives can be implemented to actively encourage rail use. However, in terms of environmental emissions, urban rail may lose its competitive edge if it does not reduce its energy usage while maintaining or enhancing its service quality and capacity (González-Gil et al., 2014). Most modern ETs use regenerative braking to recover some of the kinetic energy lost during their frequent stops, including most underground metro networks and London's Dockland Light Railway. Broader utilisation of this technology will help reduce overall train energy usage.

To achieve the UK's goal to phase out diesel-only trains by 2040 further track upgrading for electrification is required, however railway electrification is not considered cost effective for some routes, particularly in low traffic density regions (Hoffrichter et al., 2016). The introduction of electro-diesel bi-mode trains or HTs, with electricity generated from nuclear or renewable methods has been considered an alternative solution (DfT, 2019b; Royston et al., 2019). HTs are considered hybrids as they use a fuel cell to generate electricity, with power generation sufficient both to maintain speed and top up a battery which is discharged during acceleration and charged by regenerative braking (Peng et al., 2019). Rail using H₂ fuel cell technology remains uncommon on a global scale, however advancements have been made in other countries which the UK can learn from. For example, in Lower Saxony in Germany, Alstom announced the introduction of the hybrid Coradia iLint in September 2016 which currently operates on a 50 km route and has lower operating costs than diesel alternatives and a range of ~1,000 km (Brunet and Ponsard, 2017; Fragiaco and Piraino, 2019; Murray-smith, 2020). This range will allow rail travel for longer distances and to more rural areas where it is currently difficult or uneconomic to electrify due to route length or lack of space within urban areas (Staffell et al., 2019). In a UK context, HTs could be particularly successful in areas like the Scottish West Highlands where there are areas of prolonged hills, allowing battery power to augment from fuel cells on ascent and then during periods of descent the battery could be charged from the fuel cell (Murray-smith, 2020). Therefore, as technology advances, and drawing from what has been learned in other countries, it is likely that countries like the UK will need to have a combination of electric and hydrogen rail.

1.2. Electricity generation in the UK

To understand the implications of greater electrification of public transport, projecting future energy demand and its associated

GHG emissions is an important topic for research, business and policy making. Without the introduction of a more ambitious climate policy, focusing on mitigation targets for 2050, the UK could struggle with inadequate ambition and make poor investment choices towards 2100 (Pye et al., 2017). The Committee on Climate Change (CCC), a UK Governmental advisory body, called for a set of 'clear, stable and well-designed policies' to be introduced to reduce emissions across the economy, with the CCC believing current policy is insufficient to meet net zero (CCC, 2019). Ensuring policy changes target electricity decarbonisation while incorporating the greater electrification of transport networks will help reduce emissions towards net zero for two of the UK's highest emitting sectors, transport and electricity generation. To do this, the CCC has set several five-yearly carbon budgets which currently run to 2032 to ensure the UK Government remains on target to reduce GHG emissions. The UK is currently in the third carbon budget (2018–2022) which aims for a ~37% reduction in emissions (~2,544 MtCO₂e) compared to 1990 levels.

For the purposes of this research, we have focused on four National Grid scenarios to analyse the carbon intensity of electricity generation. The National Grid projections reduce carbon and other GHG emissions by 96% by 2050 compared to 1990 levels using known technologies and projected current investment plans and equipment age and life profiles. These projections estimate a minimum ~23% reduction in emissions under the consumer evolution scenario by 2032, meaning that generation scenario, driven by policy, may be key to meeting the targets set out by the CCC. Technologies, such as hydrogen and CCS would enable the reduction or removal of remaining residual emissions (National Grid, 2019).

In December 2018, the EU European Energy Directive (2018/2001/EU) set a new and binding target for at least 32% of energy to be generated from renewable electricity by 2030. This target also encompassed a sub-target of a minimum of ~14% of renewable energy to be consumed in the transport sector by 2030 (Clancy et al., 2018; Prussi et al., 2019). The UK Government is committed to achieving this target in the most cost effective way and expects a shift towards renewable energy with an increase of ~16% by 2035 (See Appendix A). This has been achieved with the support of administrations in Scotland, Wales and Northern Ireland setting their own independent targets for generating renewable electricity by 2020. These are: Scotland 100%; Northern Ireland, ~40% of renewable electricity and ~10% of renewable heat; and Wales around twice the levels generated in 2011 (DECC, 2011). To meet the UK net zero emission target, additional low carbon electricity infrastructure will be needed beyond the National Grid's current horizon of 2035, especially to power the decarbonisation of transport and heat.

The UK transition away from coal has led to a rapid increase in gas generation infrastructure for electricity generation to provide dispatchable power for times when renewables cannot match demand. This type of network arrangement will be needed until storage technology coupled with greater renewable capacity can be developed. Although gas generation using combined cycle gas turbine (CCGT) technology produces less than half the GHG emissions of thermal coal per megawatt of electricity, it is not zero carbon. This means that CCS is required to remove CO₂ that would otherwise be emitted from gas power stations and from other industrial processes by transporting it to geological storage. Limitations for carbon storage would suggest that the UK will need to further develop renewables using technologies like offshore wind, wave and tidal power alongside a means of storing energy. Interconnected power grid management systems between the UK and other European countries such as the Netherlands, Norway and France, will encourage peak sharing between different time zones. To decarbonise the rail system to contribute to the UK's transport emissions reduction, a decarbonised electricity generation mix is essential, assuming that H₂ is generated by electrolysis.

1.3. Hydrogen generation for fuel

To decarbonise gas for transportation and to provide an energy storage medium, extensive research has been performed into the use of H₂ as a fuel. H₂ offers many advantages as an alternative energy source as the energy content of H₂ at 118 MJ kg⁻¹ at 298 K is much higher than most fuels, for example petrol at 44 MJ kg⁻¹ at 298 K (Revankar et al., 2010; Vincent and Bessarabov, 2018). ETs and HTs do not produce GHG emissions directly during operation but they can still produce emissions indirectly from the production of electricity and H₂ (Correa et al., 2017; Mekhilef et al., 2012). By properly utilising H₂ as a fuel for rail and other vehicles, significant environmental benefits will be seen after transitioning, assuming the hydrogen generation process is from a sustainable source (Kopasz, 2007; Vincent and Bessarabov, 2018).

Unlike fossil fuels, H₂ is not readily available in nature. It can be produced from any primary energy source, to be used as a fuel either for direct combustion or in a fuel cell, with only water as a by-product (Granovskii et al., 2006; Marbán and Valdés-Solís, 2007; Nikolaidis and Poullikkas, 2017; Shinnar, 2003; Van Mierlo et al., 2006). There are several main production methods which can be generalised into three broad categories: thermal, electrolytic and photolytic (Vincent and Bessarabov, 2018; Washing and Pulugurtha, 2016).

Thermal generation uses high temperatures, partial oxidation and reaction with steam to separate elemental H₂ from carbon compounds and water molecules. SMR using natural gas is the most common method of producing bulk H₂ (Haseli et al., 2008; Washing and Pulugurtha, 2016), however, similar methods (e.g. partial oxidation, gasification) can also use other raw materials such as other gases, liquids, and solids, containing various combinations of hydrocarbons (Nikolaidis and Poullikkas, 2017).

Electrolytic methods involve separating water into its constituent hydrogen and oxygen molecules using electricity through a process called electrolysis (Gandía et al., 2013; Senftle et al., 2010; Vincent and Bessarabov, 2018; Washing and Pulugurtha, 2016). This process is endothermic and therefore requires energy input from a combination of electricity and heat to produce H₂ and oxygen as a by-product (Bamberger and Richardson, 1976; Haseli et al., 2008; Nikolaidis and Poullikkas, 2017; Rossmel et al., 2005). Only indirect emissions from the energy and materials used to manufacture the power facilities are produced (Haseli et al., 2008). Electrolysis using electricity from renewable sources such as wind and solar energy will produce H₂ with low GHG emissions. Although this would be an ideal way to produce H₂ as a low GHG fuel source for transport, electrolytic H₂ production is not presently available at a reasonable cost due to the cost of electricity (Dincer, 2012). However, due to intermittent renewable electricity

generation, it may become a plausible solution to store energy.

Photolytic production of H₂ also splits water to produce H₂ but relies on sunlight to supply the energy (Ban et al., 2018; Peter, 2015; Washing and Pulugurtha, 2016). During this process, solar energy is converted into chemical energy, in the form of H₂, by using a photocatalyst. This method of H₂ generation is considered 'clean' and is of significant interest to policymakers (Dincer, 2012), but is highly inefficient. An example of biological H₂ production is through efficient utilisation of cyanobacteria and some other green algae as they have a strong potential as a source of renewable biofuels, such as bio-diesel, biogas, bio-oil and bio-hydrogen; cyanobacteria are considered a waste product resulting from eutrophication (Khetkorn et al., 2017, 2013; Maneeruttanarungroj et al., 2010; Parmar et al., 2011; Skjånes et al., 2013; Zhang et al., 2020). This method of H₂ generation is considered sustainable due to requiring sunlight, CO₂ and nutrients including nitrate, phosphate and potassium. However, even with analysis under optimistic conditions, the cost of H₂ through cyanobacteria is extremely high and cannot compete with the comparatively low costs of conventionally fuelled transport (Kolbe et al., 2019). Further improvements could be made through genetic engineering or further optimisation of the production process.

All methods of H₂ generation have potential to contribute to the UK meeting net zero emissions, creating a fundamentally different energy system, incorporating different renewables in the electricity generation mix (Ball and Weeda, 2015). For the purposes of this paper, although there are many methods of H₂ generation, electrolysis and SMR using natural gas and SMR using coal gasification were the primary focus for analysis. These methods were chosen as whilst electrolysis, if scaled up, is a low GHG method of H₂ production it is difficult to mass produce whereas both SMR methods are cheaper and more widely used. Coal gasification was also analysed as this method remains one of the most popular methods of H₂ generation worldwide and with the addition of CCS can have a significant reduction in CO₂ emissions (Kalamaras and Efstathiou, 2013) with this method being potentially used for future UK coal resources.

Currently, the investment and policies surrounding H₂ and technology development are unknown. We acknowledge that initial financial implications and GHG emissions of ET and HT infrastructure, including train carriages will be high, but with the anticipated reduction in emissions from hydrogen technology compared to fossil fuel technology these emissions will amortize over time with net overall benefits being substantial. Therefore we have chosen to focus on operating emissions within our analysis which, although a simplified methodological approach, currently offers the most meaningful discussion regarding how to decarbonise our transport options.

2. Methodology

We have analysed the operating emissions of CFTs, ETs and HTs using several equations presented below. Results of this analysis was also compared with CFVs and EVs to highlight the importance of switching to sustainable public transport over personal vehicles.

Due to the lack of long term measurements and monitoring, the focus of this analysis is on the operating emissions of rail and does not focus on emissions produced from a life cycle analysis (LCA) (Egede et al., 2015). As the largest change in emissions is related to the energy that is used to power the train system and as we assume that the infrastructure and rolling stock embedded carbon cost is roughly similar between electrified and hydrogen rail to conventional diesel rail, we have chosen to focus on operating emissions within our analysis. Although this is a simplified methodological approach method, it focusses on the largest component in the change in emissions which is the energy to drive the system. We acknowledge that the initial financial cost and embedded emissions of hydrogen and electric infrastructure, and train rolling stock, will be high. However, with the anticipated reduction in operating emissions from hydrogen technology compared to fossil fuel technology, these infrastructure emissions will amortize over time with the net overall benefits being substantial, especially considering current railways run on Victorian infrastructure.

When defining an LCA system boundary, the manufacture, maintenance and development phases are often not fully accounted for, particularly if it is assumed they do not significantly contribute to the outcome. However, the design of the train can influence greatly the environmental impact of other stages within the LCA. For example, if the design is determined by the fuel consumption and emissions per kilometre driven when the vehicle is in use, then this may not influence the GHG cost of construction or the reusability of materials within the end-of-life phase; this is currently difficult to project due to the evolving technology of H₂ trains (Rebitzer et al., 2004). Nevertheless, only recently, decision making bodies, including Governments, are looking at LCAs for critical inputs related to transport fuels (Chester and Horvath, 2009). LCA models need to consider both direct and indirect processes and services required to operate the transport mode. This includes raw material extraction, manufacture, construction, operation, maintenance, scrappage, infrastructure and fuels (Chester and Horvath, 2009; Hawkins et al., 2013; Helms et al., 2010). To provide an accurate parameterization for an LCA it is important to consider fuel consumption or the train weight which can vary widely between types and locations, producing different results and interpretations of the data (Messagie, 2014). Therefore with the current paucity of information, and to allow a fair comparison, we have focused on the operating emissions of these train types.

2.1. Data collection

Data was obtained from a range of local authority, regional and national databases including the UK Government and National Grid and then extrapolated, taking into consideration current policy to allow projections between 2017 and 2050 (BEIS, 2018b; National Grid, 2018) and used to predict the CO₂ emissions produced for three differently fuelled trains in the UK (ETs, HTs and CFTs).

To estimate the projected number of trains and distance travelled between 2017 and 2050, the Transport Energy and Air Pollution Model (TEAM-UK) was used (Brand et al., 2019, Brand et al., 2012; Brand and Anable, 2019). TEAM-UK is a disaggregated, bottom-

up modelling framework of the UK transport-energy-environment system, built around a set of exogenous scenarios of socio-economic, socio-technical and political developments (Brand and Anable, 2019). Using projections from TEAM-UK, rail travel was disaggregated into four categories of services: urban, regional, intercity and high speed. These four categories were broken down for analysis separately to allow for better comparison; for example, shorter rail journeys through the urban rail network could be more comparable to private CFV journeys (such as the journey to and from work). A full breakdown of the projected number of trains and their projected distance travelled in the period under investigation can be seen in **Appendix B**. Between 2017 and 2050, for all four rail service categories, there will be a slight increase in the total number of trains required as well as a ~12.3% increase in the distance travelled for all trains for all service types.

For both ETs and HTs, our model was run using all four of the National Grid electricity generation mix scenarios: two degree, steady progression, community renewables and consumer evolution (**Appendix C**). The National Grid generates these scenarios to provide a continually updated reference point for environmental, network and use analyses. It reflects annual changes from various stakeholders including production, sale and end-use of electricity generation with consideration of uncertainties. These scenarios can therefore be used to quantify likely societal behaviours that could be related to transport emissions.

2.2. Estimating total conventionally fuelled train emissions and grams of carbon dioxide produced per kilometre travelled

To estimate the total CO₂ emissions produced for diesel trains in the UK, Equation (1) was used:

$$\text{Emissions}_{\text{Train}} = B_{\text{T}} * D_{\text{T}} * C \quad (1)$$

Where B = the total number of trains, D = the distance travelled (km), _T = train type and C = grams of carbon dioxide per kilometre (gCO₂ km⁻¹) travelled by train. Data units are then converted to MtCO₂.

C represents the gCO₂ km⁻¹ travelled per train and was estimated by Pridmore (2009) who gave a value of 2,870.2 gCO₂ km⁻¹ for rail travel. When taking into consideration technological improvement, an assumed decrease of 5 gCO₂ km⁻¹ per annum decreased to 2,705 gCO₂ km⁻¹ by 2050.

2.2.1. Emissions per person for electric, hydrogen and conventionally fuelled trains versus conventionally fuelled cars

Equation (2) was used to calculate GHG emissions per passenger km and to determine the difference in GHG emissions intensity for rail transport options compared to CFVs. Emissions were estimated in gCO₂ km⁻¹ and then weighted depending on the number of individuals travelling. TEAM-UK assumed a full capacity of 468 passenger seats per urban train, 447 passenger seats per regional train, 250 passenger seats per intercity and 750 passenger seats per high speed (Brand et al., 2019). These values were then used to estimate the total emissions per kilometre (gCO₂ km⁻¹) per person for CFTs, ETs and HTs at five different capacity levels (125%, 100%, 75%, 50% and 25%). We also included the overcapacity value of 125% to give a realistic overview of the UK rail system during rush hour, assuming these additional passengers stood for the duration of their journey. This analysis was compared to private CFVs and EVs to analyse the emissions produced and to highlight the need to switch to sustainable public transport.

$$\text{Emissions}_{\text{Per Person}} = \frac{EC}{\left(N * \left(\frac{A}{N}\right)\right)} \quad (2)$$

where EC = total emissions per train, N = total number of seats, and A = number of seats occupied. Data units are then converted to gCO₂ km⁻¹ per person.

It was also assumed that the average CFV and EV had a full capacity with four individuals on board, which enables a conservative estimate of the benefit of public transport. Analysis was also completed with personal vehicles having the average UK occupancy of ~1.6. Equation (2) was also used to estimate the gCO₂ km⁻¹ per person for CFVs to draw conclusions as to which point rail-based public transport can be considered a lower emission alternative.

2.3. Electric and hydrogen train emissions

To estimate the total level of emissions produced from a full fleet of ETs and HTs, Equation (3) was used:

$$\text{Emissions}_{\text{T}} = ((B_{\text{T}} * D_{\text{T}}) * (G_{\text{s}} * P_{\text{s}})) * I * CI \quad (3)$$

where G = the annual train energy consumption (kWh km⁻¹), P = correctional factor for fuel cell inefficiencies dependent upon source of power, _s = value dependent on source of power, I = correctional factor for grid inefficiencies and CI = the carbon intensity of electricity generation (gCO₂ kWh⁻¹). Data units are converted to MtCO₂.

In Equation (3), P is dependent on the source of power of the analysed train fuel type, i.e. hydrogen or electric. For ETs this value was given as 1 as no electric fuel cell inefficiency value is needed whereas HTs were given a value of 1.25, based on a fuel cell efficiency of 80%.

G represents the fuel consumption per km by the given train power source, with the average electric train energy consumption ranging between 3.5 and 5.5 kWh km⁻¹ (Gattuso and Restuccia, 2014; Jong and Chang, 2005). As we are implementing a worst case scenario approach the maximum annual vehicle energy consumption was chosen at 5.5 kWh km⁻¹ for the UK. For HTs, the consumption value for the UK was 10 kWh km⁻¹ (Progressive Energy Ltd, 2019). We have used the same value for all four rail service categories, however with the further development of high speed trains in the UK, the value may decrease over time resulting in trains

Table 1

The carbon intensity of producing hydrogen through steam methane reform using natural gas, steam methane reform using coal gasification and electrolysis with and without carbon capture and storage ($\text{gCO}_2 \text{kWh}^{-1}$) in 2018 (Source: Brukner et al., 2008; CCC, 2018).

| | Without carbon capture and storage ($\text{gCO}_2 \text{kWh}^{-1}$) | With carbon capture and storage ($\text{gCO}_2 \text{kWh}^{-1}$) |
|--|---|--|
| Steam methane reform using natural gas | 285 | 25 |
| Steam methane reform using coal gasification | 675 | 34 |

becoming more energy efficient.

To account for losses due both to electricity distribution and transmission, for ETs, I was given the inverse value of 18%. This value was estimated as $\sim 8\%$ of electricity lost through transmission and between $\sim 3.1\%$ and $\sim 10\%$ lost through distribution network operators (The UK Parliament, 2014). The higher value was chosen as this would be a precautionary approach to the estimation of the total level of emissions produced and the required level of electricity generation, thereby enabling conservative conclusions. For HTs, the grid inefficiency of 1.18 was multiplied by an additional 1.72 inefficiency factor accounting for hydrogen generation electricity requirements giving an efficiency value of 2.03 for HTs. To estimate this factor, for every 1 GJ of H_2 to be produced, 479 kWh of electricity needs to be generated from the energy source (specific sources or general market can be used in the estimation). The 1 GJ of H_2 was converted to kWh by dividing this by 3,600, implying 277 kWh equivalent of H_2 had been produced. This therefore gave an inefficiency correction factor of 1.72.

Current and future years considered the same grid inefficiency correctional factor for the UK. This is because as the UK electricity generation mix expands from less centralised CCGT and nuclear towards offshore and remote renewables, transmission losses could increase. The influence of small-scale and decentralised energy production may counter this, however the estimation of this is out with the scope of this research and may require further examination.

CI describes the carbon intensity of electricity generation using data from the UK's National Grid as seen in **Appendix C**.

2.3.1. Alternative hydrogen production using steam methane reform with natural gas or steam methane reform with coal gasification

For HTs, the carbon intensity of electricity generation from the four National Grid scenarios was used for H_2 production by electrolysis. In addition, the carbon intensity of two H_2 reforming processes with and without CCS was used. The carbon intensity of these methods obtained from the literature are tabulated in **Table 1**. These values were used instead of the carbon intensity of electricity generation within Equation (3) to estimate the projected level of emissions from generating H_2 through SMR with natural gas and coal gasification with and without CCS.

3. Results

The results of the analysis of different energy sources to power trains are presented below, with the analysis of the emission levels of the four different rail service categories for the four different electricity generation scenarios between 2017 and 2050. Passenger emissions per person per kilometre for urban, regional, intercity and high speed services are compared. Results from urban rail are also compared to personal vehicles (CFVs and EVs) in **Section 3.5** to determine whether trains are the more favourable method of transport in terms of reducing emission levels.

These results were also compared to determine the lowest emitting fuel type for trains to help allow the UK to meet the net zero

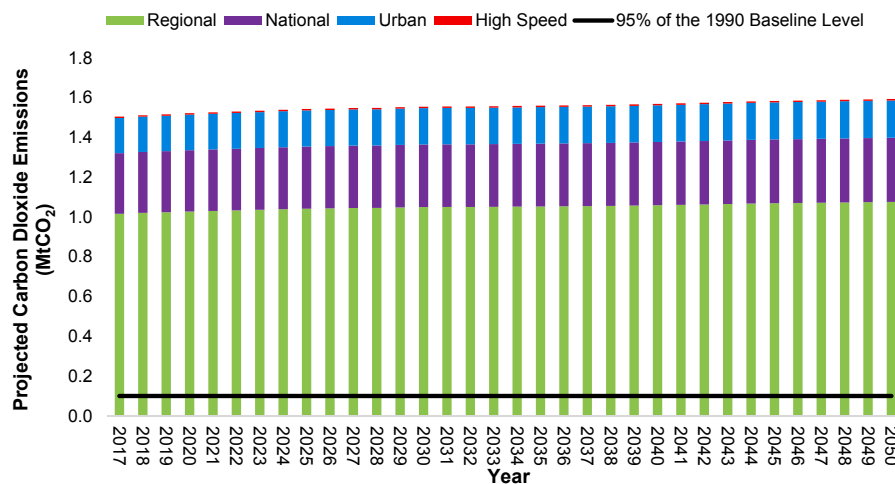


Fig. 1. Projected carbon dioxide emissions for conventionally fuelled urban, regional, intercity and high speed rail services in the UK between 2017 and 2050. The black line indicates 95% of the 1990 baseline emissions.

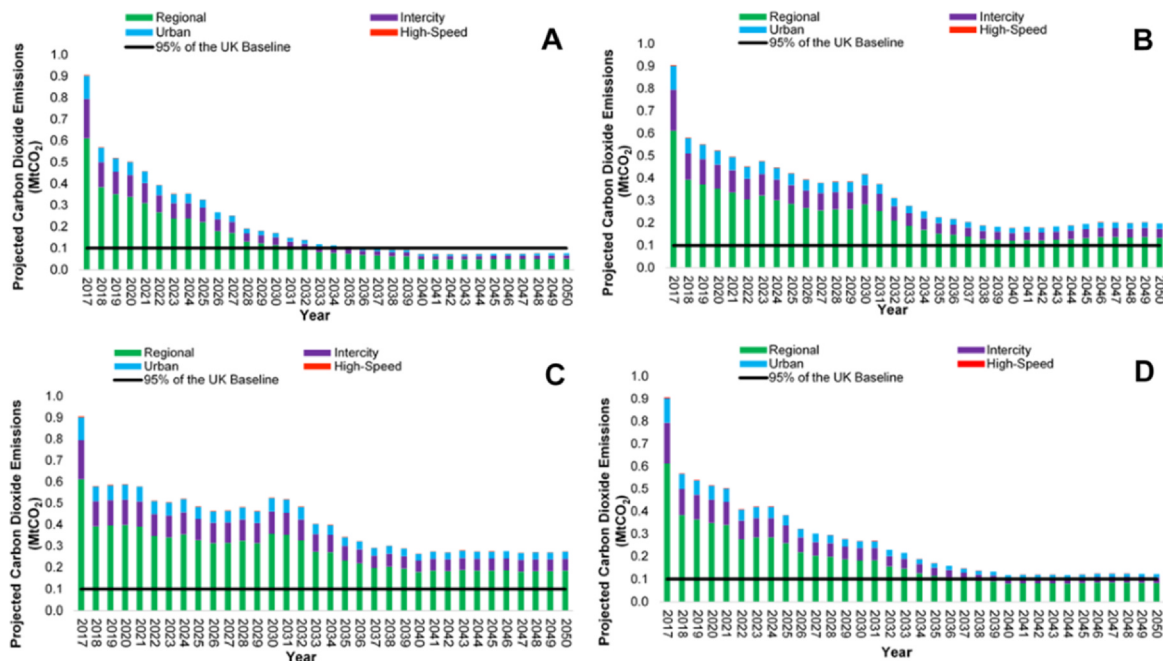


Fig. 2. Electric train emissions Between 2017 and 2050 for urban, regional, intercity and high speed under the four electricity generation scenarios as follows: two degree (A), steady progression (B), consumer evolution (C) and community renewables (d) in the UK. The black line indicates 95% of the 1990 baseline emission.

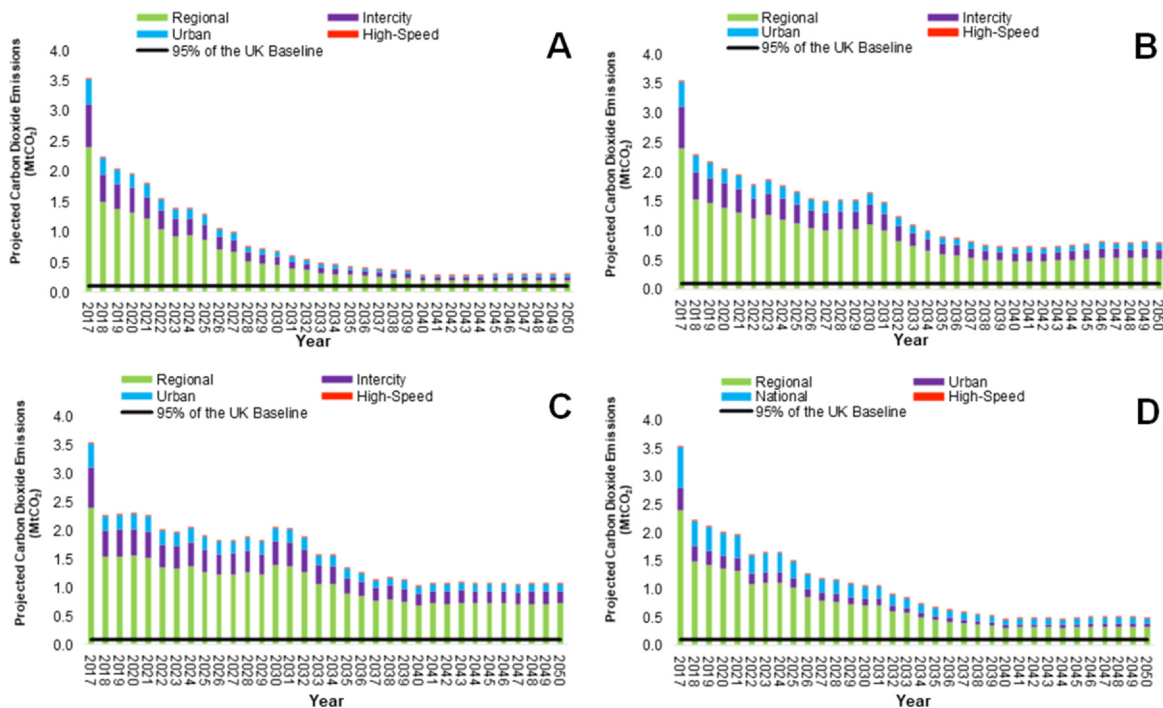


Fig. 3. Hydrogen Train Emissions Between 2017 and 2050 for Urban, Regional, intercity and High Speed under the four electricity generation scenarios as follows: two degree (A), steady progression (B), consumer evolution (C) and community renewable (D) in the UK. The black line indicates 95% of the 1990 baseline emissions.

Table 2

Overview of projected carbon dioxide emissions for electric rail in 2017 and 2050 under all four National Grid energy scenarios.

| | 2017 (MtCO ₂) | Two Degrees (A) (MtCO ₂) | Steady Progression (B)(MtCO ₂) | Consumer Evolution (C) (MtCO ₂) | Community Renewables (D) (MtCO ₂) |
|-----------------|---------------------------|--------------------------------------|--|---|---|
| Urban Rail | 0.11 | 0.001 | 0.02 | 0.03 | 0.01 |
| Intercity Rail | 0.18 | 0.02 | 0.04 | 0.06 | 0.03 |
| Regional Rail | 0.61 | 0.05 | 0.13 | 0.18 | 0.08 |
| High Speed Rail | 0.0003 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |

emissions target by 2050. To compare results with the targets, the 95% reduction of the 1990 baseline levels to 0.1 MtCO₂ (DfT, 2018b) has been highlighted on Figs. 1–3.

3.1. Light, regional, intercity and high speed conventionally fuelled trains

Fig. 1 demonstrates the projected CO₂ emissions from all four CFT service categories between 2017 and 2050 for the UK. Results indicate that in this period, total diesel rail emissions are expected to increase by 5.2% from 1.51 MtCO₂ to 1.59 MtCO₂.

Therefore, this indicates that even with technological advances over the time frame of interest, including improvements to a diesel train's fuel consumption and emissions factor, as incorporated in the methodology, emission levels remain constant, with regional and intercity rail operating emissions increasing slightly over the time frame.

3.2. Electric trains

Using the four electricity generation scenarios from the National Grid: two degrees (A), steady progression (B), consumer evolution (C) and the community renewables scenario (D), total emissions from 100% ETs for urban, regional, intercity and high speed rail services are shown in Fig. 2.

Results of the four National Grid scenarios indicate that regional rail travel produced the highest level of operating emissions under all four electricity scenarios for ETs. As shown in Appendix B there is an expected change in the distance travelled between 2017 and 2050, which could be accounted for by the addition of the different train types. Results also indicated that the two degree scenario (A) produced the largest decrease in the level of emissions between 2017 and 2050 for all four rail service types. The highest level of emissions by 2050 was from the consumer evolution scenario (C). Table 2 provides a breakdown of results from Fig. 2.

Results from Table 2 indicate that under the steady progression and consumer evolution scenarios regional rail will fail to meet the 0.1 MtCO₂ emissions target. Therefore, decarbonisation of the electricity sector is needed for emission targets to be met. If the results for all rail service categories were combined, emissions would decrease overall by 92% from 0.91 MtCO₂ to 0.08 MtCO₂ between 2017 and 2050 under the two degree scenario. Under the steady progression scenario which is the most realistic in terms of future electricity generation, emissions decrease by 78% to 0.2 MtCO₂. For the consumer evolution scenario there was an 81% decrease to 0.3 MtCO₂. Finally, under the community renewables scenario, there was a decrease of 86% to 0.12 MtCO₂.

3.3. Hydrogen trains

Fig. 3 demonstrates the projected CO₂ emissions from HTs for urban, regional, intercity and high speed rail services under the four National Grid electricity generation scenarios: two degrees (A), steady progression (B), consumer evolution (C) and community renewables (D) between 2017 and 2050 using electrolysis.

Realistically, HTs will be more likely used for regional trains incorporating slow to medium speed regional services. However, regional rail services are likely to travel within rural areas where electrification may be difficult. Conversely, rail is much easier to electrify on urban, intercity and high speed routes and is therefore more likely to be utilised in these circumstances. Like ETs, operating emissions produced under the two degrees scenario (A) produced the largest decrease in the level of emissions between 2017 and 2050 for all four rail service categories. The highest level of emissions by 2050 was from the consumer evolution scenario (C). Although HTs produce higher level of emissions for regional rail, ETs will not be feasible within these areas and HTs will need to be implemented and will not meet the net zero emission targets. However, emissions remained significantly less than CFTs.

If all rail service categories were combined, under the two degrees (A) electricity generation mix, operating emissions would decrease overall by 91% from 3.5 MtCO₂ to 0.3 MtCO₂ between 2017 and 2050. Under the steady progression (B) scenario, the most realistic scenario in terms of future electricity generation, emissions decrease by 77% to 0.8 MtCO₂. For the consumer evolution (C) scenario there was a 69% decrease to 1.1 MtCO₂ in 2050. Finally, under the community renewables (D) scenario, there was a decrease of 86% MtCO₂ to 0.5 MtCO₂.

3.3.1. Alternative hydrogen production using steam methane reform with natural gas or steam methane reform with coal gasification

The results from using the values for SMR with natural gas and SMR with coal gasification with and without CCS in 2018 can be seen in Table 3 for each of the four rail service categories.

In 2018, if 100% of H₂ is generated from SMR using natural gas with CCS, trains are expected to produce 1.88 MtCO₂ less than the two degrees National Grid scenario. Without CCS, if H₂ is generated by SMR using natural gas, emissions would be 0.28 MtCO₂ higher

Table 3

Emission projections of producing hydrogen through natural gas using steam methane reform with and without carbon capture and storage and coal gasification using steam methane reform with and without carbon capture and storage (MtCO₂) in 2018 for hydrogen trains in the UK.

| | Natural gas SMR without CCS (MtCO ₂) | Natural gas SMR with CCS (MtCO ₂) | Coal gasification without CCS (MtCO ₂) | Coal gasification with CCS (MtCO ₂) |
|-----------------|--|---|--|---|
| Urban Rail | 0.45 | 0.04 | 1.06 | 0.05 |
| Regional Rail | 2.58 | 0.23 | 6.10 | 0.31 |
| Intercity Rail | 0.77 | 0.07 | 1.83 | 0.09 |
| High Speed Rail | 0.02 | 0.002 | 0.04 | 0.002 |
| Total | 3.82 | 0.34 | 9.03 | 0.45 |

than the two degree scenario. Furthermore, if 100% of H₂ is generated from SMR using coal gasification with CCS, 1.77 MtCO₂ less emissions would be emitted than the two degree scenario. However emissions would be 5.49 MtCO₂ higher if H₂ is generated from SMR using coal gasification without CCS. Results highlight the importance of CCS to help reduce emissions from H₂ generated for HTs, regardless of generation method. Furthermore, Table 3 indicates that SMR using natural gas without CCS and SMR using coal gasification without CCS will likely emit the higher levels of GHG emissions than from H₂ generated through electrolysis. Therefore, if the UK wants to meet its net zero emission targets incorporating CCS is essential as part of the switch away from non-renewable H₂ generation.

3.4. Electric trains versus hydrogen trains

Emissions from HTs in 2017 (for all rail service categories combined) demonstrated that operating emissions were 3.8 times higher at 3.5 MtCO₂ than those from ETs at 0.91 MtCO₂. By 2050, emissions under the two degree scenario demonstrated that HTs were still three times higher at 0.3 MtCO₂ than those from ETs at 0.1 MtCO₂. Under the steady progression scenario by 2050, emissions from HTs were four times higher at 0.8 MtCO₂ than those from ETs at 0.2 MtCO₂. Under the consumer evolution scenario by 2050, emissions from HTs were 3.7 times higher at 1.1 MtCO₂ than those from ETs at 0.3 MtCO₂. Under the community renewables scenario by 2050, emissions from HTs were five times higher at 0.5 MtCO₂ than those from ETs at 0.1 MtCO₂. Overall, results indicate that the level of emissions for HTs is higher than those produced from ETs by 2050.

3.4.1. Cumulative emissions

It is also important to consider the cumulative emissions produced from ETs and HTs as the UK works towards net zero. Cumulative emissions of all four CFT types indicate emissions would be 40.7 MtCO₂ between 2017 and 2050.

Table 4 highlights the cumulative emissions from ETs and HTs for all four rail service categories combined under the four National Grid electricity generation scenarios. Results indicate that under all four electricity generation scenarios cumulative emissions from ET were lower than for HTs. The lowest level of cumulative emissions was under the two degrees emission scenario for both ETs and HTs.

3.5. Conventionally fuelled trains versus conventionally fuelled vehicles

Table 5 compares the combined (i.e. all rail service categories) total operating emission of CFTs from Fig. 1 with the operating emissions produced from CFVs and EVs to better understand the need to encourage a modal shift towards public transport. Results for EVs when using the two degrees emission scenario highlight the best-case scenario outcome.

Results indicate that CFVs produced higher levels of emissions between 2017 and 2050 than all rail types (CFTs, ETs and HTs) and EVs. For CFVs, emission levels peak in 2020 before decreasing, whereas train emissions peaked in 2040 and remained relatively consistent. 100% EVs, under the two degree scenario, saw a rapid decrease in operating emissions within the time frame, however, even with this decrease emission levels remained higher than CFTs. Results indicated that the operating emissions from CFTs, ETs and HTs were significantly lower than from personal vehicles. Therefore, without a shift towards rail travel, transport emissions will not decline enough to achieve UK goals.

Table 4

Cumulative emissions of all electric trains and hydrogen trains under the four National Grid electricity generation scenarios between 2017 and 2050 in the UK.

| | Two Degree (MtCO ₂) | Steady Progression (MtCO ₂) | Consumer Evolution (MtCO ₂) | Community Renewables (MtCO ₂) |
|---------------------|---------------------------------|---|---|---|
| Electric Train (ET) | 7.3 | 11.2 | 14.0 | 9.1 |
| Hydrogen Train (HT) | 28.4 | 43.7 | 54.8 | 35.6 |

Table 5

The projected emissions from electric trains (ETs), hydrogen trains (HTs) and conventionally fuelled trains (CFTs) as well as 100% electric vehicles (EVs) and 100% conventionally fuelled vehicles (CFVs), between 2017 and 2050 in the UK, with five-year increments from 2020, using the National Grid two degree scenario.

| | 2017 (MtCO ₂) | 2020 (MtCO ₂) | 2025 (MtCO ₂) | 2030 (MtCO ₂) | 2035 (MtCO ₂) | 2040 (MtCO ₂) | 2045 (MtCO ₂) | 2050 (MtCO ₂) |
|--|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|
| Electric Trains (ETs) | 0.91 | 0.50 | 0.33 | 0.17 | 0.11 | 0.07 | 0.07 | 0.08 |
| Hydrogen Trains (HTs) | 3.54 | 1.96 | 1.28 | 0.67 | 0.42 | 0.28 | 0.29 | 0.30 |
| Conventionally Fuelled Trains (CFTs) | 1.52 | 1.52 | 1.54 | 1.56 | 1.56 | 1.57 | 1.58 | 1.59 |
| Conventionally Fuelled Vehicles (CFVs) | 41.8 | 41.5 | 40.8 | 39.8 | 38.6 | 37.3 | 36.0 | 34.5 |
| Electric Vehicles (EVs) | 20.97 | 11.64 | 7.63 | 4.00 | 2.53 | 1.71 | 1.73 | 1.78 |

Table 6

Point emission calculations for conventionally fuelled vehicles, electric vehicles, conventionally fuelled trains, electric trains and hydrogen trains under the two degree national grid electricity generation predictions in 2017 and 2050 for the UK (gCO₂ km⁻¹ per person, based on 100% capacity).

| | | Projected Carbon Dioxide Emissions (gCO ₂ km ⁻¹ per person) at different capacity levels | | | | | | | |
|------------------------------|------------------------|--|--------|--------|--------|----------------------|--------|--------|--------|
| | | 2017 Capacity Levels | | | | 2050 Capacity Levels | | | |
| | | 100 (%) | 75 (%) | 50 (%) | 25 (%) | 100 (%) | 75 (%) | 50 (%) | 25 (%) |
| Personal Vehicle (Car) | Conventionally Fuelled | 30.0 | 40.0 | 60.0 | 120.0 | 21.8 | 29.0 | 43.5 | 87.0 |
| | Electric | 15.0 | 20.1 | 30.1 | 60.2 | 1.1 | 1.5 | 2.2 | 4.5 |
| Conventionally Fuelled Train | Urban | 4.6 | 6.3 | 9.5 | 19.0 | 4.2 | 5.9 | 8.8 | 17.6 |
| | Regional | 5.0 | 6.6 | 10.0 | 19.9 | 4.6 | 6.1 | 9.2 | 18.4 |
| | Intercity | 8.9 | 11.9 | 17.8 | 35.6 | 8.2 | 11.0 | 16.5 | 33.0 |
| | High Speed | 3.0 | 4.0 | 5.9 | 11.9 | 2.8 | 3.7 | 5.5 | 11.0 |
| Hydrogen Train | Urban | 14.4 | 19.2 | 28.8 | 57.7 | 1.1 | 1.4 | 2.1 | 4.3 |
| | Regional | 15.1 | 20.1 | 30.2 | 60.4 | 1.1 | 1.5 | 2.2 | 4.5 |
| | Intercity | 27.0 | 36.0 | 54.0 | 108.0 | 1.6 | 2.0 | 2.7 | 4.0 |
| | High Speed | 9.0 | 12.0 | 18.0 | 36.0 | 0.7 | 0.9 | 1.3 | 2.7 |
| Electric Train | Urban | 3.7 | 4.9 | 7.4 | 14.8 | 0.3 | 0.4 | 0.6 | 1.1 |
| | Regional | 3.9 | 5.2 | 7.7 | 15.6 | 0.3 | 0.4 | 0.6 | 1.3 |
| | Intercity | 6.9 | 9.2 | 13.8 | 27.6 | 0.5 | 0.7 | 1.0 | 2.1 |
| | High Speed | 2.3 | 3.1 | 4.6 | 9.2 | 0.2 | 0.2 | 0.3 | 0.7 |

3.6. Grams of carbon dioxide emitted per person for train and private car

Table 6 demonstrates the per capita emissions (gCO₂ km⁻¹ per person) at four different capacity levels (100%, 75%, 50% and 25%) to highlight and compare the different level of emissions between CFTs, ETs, HTs with personal vehicles (CFVs and EVs) under the two degree scenario for all rail service categories combined. As mentioned in the methodology, the trains used for the four rail service categories had different carrying capacities, therefore the categories were projected separately by fuel type.

Results in Table 6 indicate that by 2050, ETs would be the most sustainable travel option for all four service categories, producing the lowest emissions under all four capacity levels. HTs produced higher level of emissions under all four capacity levels in 2017 than CFVs, however produced significantly less emissions in 2050 in comparison. This highlights that there will be a 'tipping point' where clean energy production emissions are less than cumulative conventional emissions.

To contextualise our results, the average person per vehicle (~1.6 individuals) is compared to urban train travel to identify the 'tipping point' at which the low carbon modes of rail transport become more environmentally friendly than personal transport using the two degree scenario. The results indicated that for CFVs, 75 gCO₂ km⁻¹ per person would be produced in 2017 reducing to 54.4 gCO₂ km⁻¹ per person in 2050. For EVs, 37.6 gCO₂ km⁻¹ per person would be produced in 2017 and 10.1 gCO₂ km⁻¹ per person in 2050. Urban ETs produced 1,730 gCO₂ km⁻¹ in 2017 and 128.5 gCO₂ km⁻¹ in 2050. An urban HT produced 6,750 gCO₂ km⁻¹ in 2017 and 502.3 gCO₂ km⁻¹ in 2050. Therefore, at least 23 people are needed to be on an urban ET in 2017 and three people in 2050. For urban HTs, at least 90 people on an urban HT in 2017 and at least ten people on an urban HT in 2050 are needed to make rail transport a more environmentally clean mode of travel than personal CFVs. For EVs, at least 46 people are needed to be on an urban ET in 2017 and 13 people in 2050 to make rail transport a more environmentally clean mode of travel. For urban HTs, at least 180 people are needed to be on an urban HT in 2017 and 50 people in 2050 compared to EVs.

These results highlight the importance of encouraging a modal shift towards public transport. Although EV emissions are lower than CFTs, emission levels remain higher than for ETs and HTs, especially when taking a more realistic approach to vehicle capacity levels.

Table 7

Point emission calculations for 125% capacity conventionally fuelled trains, electric trains and hydrogen trains under the two degrees National Grid electricity generation predictions in 2017 and 2050 for the UK (gCO₂ km⁻¹ per person).

| | | 2017 (gCO ₂ km ⁻¹ per person) | 2050 (gCO ₂ km ⁻¹ per person) |
|------------------------------|------------|---|---|
| Conventionally Fuelled Train | Urban | 3.8 | 3.5 |
| | Regional | 4.0 | 3.7 |
| | Intercity | 6.9 | 6.4 |
| | High Speed | 2.4 | 2.2 |
| Hydrogen Train | Urban | 8.2 | 0.6 |
| | Regional | 8.2 | 0.6 |
| | Intercity | 15.3 | 1.1 |
| | High Speed | 5.1 | 0.4 |
| Electric Train | Urban | 3.0 | 0.2 |
| | Regional | 3.1 | 0.2 |
| | Intercity | 5.5 | 0.4 |
| | High Speed | 1.8 | 0.1 |

3.6.1. Overcrowding: Carbon dioxide emissions emitted per person

Table 7 highlights emissions produced in 2017 and 2050 for all train types at overcrowding of 125%. Emission levels per person at 125% capacity are less than at full capacity and remain lower than personal vehicle alternatives.

Overcrowding estimations provide a realistic scenario that includes standing capacities. This further highlights that electric or hydrogen powered commuter rail transport will have significant emission savings over the current transport power regime in reality. Ideally, there would be an increase in service provision to increase consumer confidence in the rail network meaning these overcrowding values would not occur in reality, however under current circumstances these values could be viewed as more realistic.

4. Discussion

Results from this analysis demonstrate the need for widespread change in travel mode from private vehicles to trains. In addition, to achieve the UK net zero objectives, trains should be converted to ETs, or to HTs where this is not possible for economic or technical reasons. The analysis shows that both ETs and HTs produced significantly less emissions than CFTs between 2017 and 2050, however this is dependent upon the method of electricity generation, with emissions from HTs higher than ETs under all four National Grid electricity scenarios for all four rail service categories. Emissions per passenger per kilometre under the four electricity generation scenarios remained significantly lower for ETs and HTs than private vehicles and CFTs for all rail service categories. Although rail is considered a 'green' mode of transport, rapid electrification (or conversion to hydrogen) is required immediately as without this, negative environmental impact will be felt for decades. Trains have a technical life of around ~20–40 years with some models such as the Train à Grande Vitesse (TGVs) in France and UK 125s retiring aged > 40. Therefore, new trains entering service in 2020 will still be in service by 2040 or 2060, long after the net zero target. Therefore, maximising an early change to train technology is necessary and a clear policy imperative for the UK to meet its ambitious net zero emissions target. Furthermore, although this study focuses on the operating emissions of rail, current and future investments and policies surrounding new rail technologies remains relatively unknown. In addition, studies have highlighted that for all types of public and freight transport, by reducing the operating emissions of a transport type, the overall LCA emissions have significant reductions, as highlighted under EU policy for CFVs with its focus on reducing their tailpipe emissions (Moro and Helmers, 2017). In addition, LCAs are often not applicable due to data deficiencies and therefore operation-level based simple models have greater utility in international comparisons and at consumer levels. Therefore, by using our approach there is the opportunity for international comparisons and analysis which will allow countries to learn from one another as low carbon energy and transport is integrated into their transport networks.

While the model used in the analysis presented here does not detail hydrogen and electric LCA components with the inclusion of infrastructure, our work highlights a key progression point. Conventionally fuelled transport is unlikely to reduce its emissions by any significant percentage; therefore fuel options must be implemented that enable a reduction over time. The difference in operating emissions between fuel types will offset the initial embedded emissions during the transmission process, with the exact equalization point dependent on the manufacturing and development processes used which are as yet unknown.

For train services to be fully utilised several obstacles need to be overcome. For example, rail travel needs to remain appealing for consumers in terms of cost and convenience. Currently, due to the low cost of flying, especially for internal flights, individuals are choosing the cheaper travel option and (depending on distance) shorter travel time. With the construction and development of the third runway at London Heathrow Airport being ruled illegal it is possible that there will be a reduction of internal flights. Should this occur rail infrastructure and new ETs and HTs need to be introduced to fill this gap. In some countries internal flights are already rare; in France the high speed TGV was introduced in 1981. The TGV has a dedicated line with shared-use segments in urban areas, first running between Paris and Lyon and now most other major French cities, with these trains and lines being continually upgraded as needed. With the TGVs introduction, there was an associated decrease in communications and transport costs which allowed multi-office companies to create jobs in regional offices and enhance specialisation and productivity (Blanquart and Koning, 2017; Charnoz et al., 2018). Furthermore, newer high speed lines were designed to avoid tunnelling so as to allow the implementation of double

decker trains, to allow a higher capacity of users (Watson et al., 2017). With greater accessibility to parts of France, the TGV has become a more favoured mode of transport than CFVs and airplanes. Although trains have become a favoured transport option (as is the case in France), it is acknowledged that trains are not always the most flexible option. In this paper we have assumed that the distance travelled by CFV can be directly replaced by rail, however individuals may require multiple modes of transport to get to their destination due to the location of train stations and access opportunities. Transfer to local public transport to travel shorter routes (for first and last mile connections) are often part of commuter journeys, something not accounted for within this study, and highlights the need for connected services. By introducing TDM initiatives that encourage sustainable public transport solutions such as park and ride schemes with cheaper bus and train routes, this will reduce the need for CFV use and allow for reduced emissions through more sustainable, integrated public transport use (Logan et al., 2020).

With the development of new infrastructure projects such as HS2 the UK Government has promised improvements through track and signalling infrastructure allowing for enhancements in efficiency and decreasing travel time. For example, according to the Department of Transport (DfT) the journey between Birmingham and London (~160 km) which is currently 81 minutes would be expected to decrease to around 52 minutes with HS2. After stage two is complete the journey between Manchester and London (260 km) which is currently 67 minutes would decrease to around 127 minutes and the journey between Birmingham and Leeds (150 km) would decrease to around 49 minutes from 120 minutes (DfT, 2016). Therefore, although cost to the consumer may remain the same, the convenience of getting to a destination in almost half the time between city centres may increase the incentive for rail travel (Lalive et al., 2018). This may also deter individuals from flying and encourage train usage over longer distances within the UK and to Europe via the Eurostar.

Although there is scope for development and expansion, train service provision is limited by capital availability constraints for infrastructure investment. New infrastructure projects, including the HS2, are not considered to have kept pace with changing travel patterns over the past several decades (Blainey et al., 2016). For train operators, overcrowding can cause issues with delays boarding and en route making it difficult for operators to provide a reliable service (Preston et al., 2017) which may ultimately lead to the loss of revenue. Taking this into consideration train services on HS2 are expected to carry up to ~26,000 passengers an hour, the equivalent of ~85 million individuals annually.

To ensure enough trains are running sustainably, additional electricity will need to be generated from renewable to power new low carbon trains. During this transition the incorporation of CCS where possible will be necessary to reduce emission from non-renewable electricity generation. However, in some rural areas electrifying rail tracks may be too difficult, therefore using hydrogen generated by decarbonised electricity would allow a low emission alternative to CFTs. Although they are currently not in use in the UK, there are plans for HTs technology to be used from as early as 2022 and it is relevant to note that H₂ trams are already deployed in some Chinese cities (Staffell et al., 2019). With the introduction of TDM initiatives in rural areas to encourage train use, many disused lines and stations could be put back into passenger service as demographics change.

Considering realistic development, electrolytic H₂ generation will not rapidly meet demand as the applications of H₂ generated through electrolysis are limited to small-scale operations and is not possible or economical (Sharma and Ghoshal, 2015). Large-scale introduction of HTs will require H₂ produced with SMR in combination with CCS and results from this study indicated that this was the lowest GHG emitting method of H₂. Ideally, to keep costs low, electricity should be converted to H₂ and stored during non-peak electricity consumption periods during the night to allow HTs to fuel up during the early hours of the morning. This is not to say however that other H₂ generation types should be disregarded, other methods are currently small-scale but there is the potential to scale up through investment. Energy systems and technologies develop slowly, for example the combustion engine for CFVs took over a century to develop and is continually developing (Ball and Weeda, 2015). Like CFV technology, the infrastructure will take time to develop with the cumulative capital costs needed for H₂ transport not considered a deterrent relative to the estimated investments over the next decades in the energy sector in general (Ball and Weeda, 2015). Furthermore, H₂ should not be evaluated in isolation but in conjunction with other renewable energy technologies with methods of H₂ generation considered at the community to regional scale to ensure effective use of land and facilities throughout the UK.

In terms of fuelling HTs, by the end of 2020, there will be ~177 hydrogen fuelling stations in Europe, having increased from ~95 in 2016 (Kolbe et al., 2019; LBST, 2020). Despite an increase in hydrogen fuelling stations, demand remains low and it is not always economically feasible to build large-scale H₂ fuelling stations. Therefore adapting existing H₂ storage tanks for rail could allow costs to be kept at a minimum (Chan et al., 2013). Additionally, cost of trains has previously been considered an issue as H₂ trains are currently ~50% more expensive than diesel trains, however their economic viability is dependent on potential lower-fuel costs associated with overall cheaper H₂ production due to fuel cells having a higher efficiency (Hart et al., 2016; Staffell et al., 2019).

With the UK's legal commitment to meet net zero, investment should be diverted back into public transport as rail is the backbone for longer travel lengths. Rail travel needs to remain affordable and accessible to individuals through the introduction of TDM measures. For example, individuals living in rural areas have a more restricted access to rail travel and often require a secondary method of transport to get to a railway station which can increase the cost of a trip. Therefore, the introduction of park and ride facilities at rail stations, cycle rail schemes which allow passengers to load their bikes onto trains and cheaper train tickets should be encouraged.

5. Conclusions

Results from this study indicate that for the UK to meet its net zero emission targets, a modal shift away from personal vehicles towards sustainable public transport needs to occur. Even at full capacity, CFV emission levels per person per kilometre travelled remained significantly higher than for the worst emitting CFTs (irrespective of service category) and even an average capacity EV has

higher emissions than a CFT. Therefore, if proportionally more individuals chose to commute by train than personal vehicle, especially for longer distances, then the total level of emissions will reduce.

Several push and pull TDM initiatives need to be implemented to encourage a modal shift towards trains, including reduced cost and ensuring there are enough carriages to improve consumer experience as that remains a constraint. In addition, bus and train timetables need to be integrated to provide easy connections for seamless travel. However, for this to be achieved, significant funding needs to be implemented not only on a local level but on a much larger national scale to ensure this works collectively across the UK. Furthermore, introducing a UK-wide styled Oyster card, to allow individuals to use as much public transport, for both bus and trains, as needed with the maximum value spent being capped could further encourage the integration of sustainable travel types including rail and buses, thus allowing individuals to meet all their travel needs without cost being a factor.

From our study, we conclude that ETs produce the lowest level of emissions from the comparison of CFTs, ETs and HTs and that there should be wider implementation of the infrastructure required to electrify the rail lines. This strategy may benefit from the phased integration of HTs although the business case for the electrification of the railways remains strong. While other fuel sources are being used to generate the electricity required, the addition of CCS will be necessary as although this does not directly reduce operating emissions from different transport types, it remains an important aspect during the transition towards net zero for the UK.

Author contributions

K.G.L. led the writing, conceptualization of ideas and designed the methodology with contributions from A.H., J.D.N. and B.C.M.. K.G.L. gathered the data for analysis. All authors contributed to the drafting and revision of the article and gave approval of the final version of this manuscript before submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trd.2020.102523>.

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