Powering Future Transport in Scotland

A Review for the Scottish Association for Public Transport

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Abstract: This report discusses energy costs and emissions associated with transport in Scotland and reviews options for future power sources for different modes of public transport. Transport provides a major contribution to greenhouse gas and other harmful emissions worldwide and efforts to reduce these are important for all forms of public transport, as well as for private cars and for the movement of freight. The effects of transport policy decisions are recognised, increasingly, as being very important for the electricity supply industry at national and local levels, largely because of the growth in the numbers of electric and hybrid road vehicles. Moving from oil to low carbon energy for transport raises important issues for electrical power generation and distribution systems in addition to challenges already being faced by the electrical power industry as the proportion of generating capacity involving renewables increases. The report starts by considering current energy costs and emissions for different forms of passenger transport and then outlines some current developments in areas such as internal combustion engine technology, battery storage systems and hydrogen fuel cells. Systems involving short-term energy storage and recovery of energy that would otherwise be dissipated as heat during braking are also discussed. Such systems generally involve the use of super-capacitors, flywheels or hydraulic devices. References are provided to the sources of data used in the analysis carried out for this review and, also, to sources of information about relevant developments in science and engineering. For all the new developments mentioned, there is a brief review of some transport applications in the United Kingdom and elsewhere. The possible impact of autonomous vehicles on future car ownership is still not known and the effects of this technology on public transport remain uncertain. As well as discussing autonomous road vehicles, the report makes brief mention of the potential of autonomous systems and increased automation for rail transport and for tramway operations. The benefits of further conventional railway electrification are reviewed in terms of energy usage, costs and emissions and the advantages of a more integrated approach to the provision of public transport in Scotland are emphasised. The value of using mathematical modelling and simulation methods to explore options in transport systems developments and planning is discussed, and the importance of testing simulation models in ways that are appropriate for the intended application is emphasised. This review presents the first results from a continuing study which was started in 2018 and is intended to provide information that should be relevant for those involved in decision-making in Scotland at the time of publication. The quantitative information contained within it clearly needs to be updated on a regular basis. The review concludes with recommendations for the Scottish Association for Public Transport about possible priorities for its efforts to increase public awareness about transport issues and is intended to be the first of a series of publications on transport and energy issues in the Scottish context. The references form an important part of the report and provide a potentially important bibliography which must be augmented and updated regularly.

Keywords: Energy; transport; emissions; electrical power generation; distribution; battery; hydrogen; short-term energy storage; railway electrification; modelling; simulation.

1. Introduction

The possible impact of electric, hybrid and autonomous vehicles on our roads has attracted much attention in the media in recent months. The discussion has been focussed mainly on developments in battery and hydrogen fuel-cell technology (especially for road vehicles) and on targets in terms of reductions of emissions. However, it is important that these developments do not simply shift emissions of greenhouse gases and other substances that are known to be harmful to the health of humans from the vehicles themselves to electricity generating stations.

While the increased demand from the transport sector will be significant for the electrical power industry these developments in the transport sector must be looked at in the context of changes already taking place in the power industry, where there has been a rapid movement from a system dominated by a small number of very large power stations to a distributed generation network with much more emphasis on renewables and energy-storage. Problems of robustness and stability are now giving serious cause for concern as the more distributed network currently operates with safety margins that are regarded by many in the industry as being smaller than desirable [1]. The additional demands on the network of the large-scale use of electrical power for transport applications would certainly be significant, but quantitative estimates of the level of additional demand vary greatly at the present time (from about 10% to over 40%) (see, e.g., [2]- [4]).

Information about the emissions from internal combustion engines is widely available in many recently published reports from relevant academic and government sources, as well as from many non-governmental organisations and groups. The effects of greenhouse gases on the atmosphere are of great concern and the effects on public health of other emissions from internal combustion engines are being recognised increasingly. Data quantifying the contribution made by transport to these problems may be found at global, European, United Kingdom and Scottish levels in many published papers and reports (see, e.g., [5]-[36]). Some of these publications are concerned mainly with greenhouse gas emissions, both in general terms and in connection with transport (e.g. [5]–[21]), while others address issues within specific transport sectors such as road (e.g. [22]–[24]), rail (e.g. [25]–[32]) and shipping (e.g. [33]–[36]).

Although the UK is far from being the largest market for electric vehicles in Europe, the total number of new registrations of plug-in hybrid and battery-electric vehicles increased from just over 2000 in 2012 to approximately 50,000 in 2017. However, overall registrations show that at present, in the United Kingdom, less than 0.5% of cars are electric vehicles and plug-in hybrids represent about 70% of the growth in electric vehicles. For road vehicles powered only by batteries the number of new annual registrations has remained at about the same level each year since 2016 [37].

Information about energy costs and emissions can be very confusing. For example, in terms of total global emissions, some countries such as China, the USA, India, Russia and Japan are contributing much more in terms of CO_2 (measured in metric tonnes per year) than most others. On the other hand, if these emissions are expressed as the amount of CO_2 produced per head of population the results are very different, with the USA, Australia and Canada heading the table and countries in Europe overtaking India and China [38]. This is not surprising since people in countries with relatively high real incomes use more fuel and have more industrial production. On a per capita basis the figures for the UK are close to those for China while the level for India falls to about one quarter of the UK figure. However, there are interesting exceptions and the Netherlands, for example, has twice the CO_2 emissions per capita compared with France which has similar gross domestic product per head of population. Economies based on oil, such as Qatar and the United Arab Emirates, have exceptionally high levels of CO_2 per head of population. The burning of fossil fuels (e.g. in coal-fired electricity generating stations) is undoubtedly one of biggest causes of CO_2 emissions and is one of the main reasons for high CO_2 emission levels in China. Rates of change of output are another important factor, with developing countries showing much more rapid increases than more highly developed parts of the world where greenhouse gas emission levels are stable or decreasing.

For the transport sector, published comparisons between different modes of travel are often impossible to interpret objectively because details of assumptions made in energy calculations are missing. For example, some figures may be presented as energy cost per passenger km while others may involve costs per seat km and proper interpretation of the figures cannot be carried out without knowledge of the assumed load factors. Other comparisons may use the total energy or emissions for specific journeys (such as Edinburgh to London) but without information about load factors, or other important details such as the type of car, coach, train or plane being considered. Also, cases are often made using figures and assumptions that do not reflect real-world situations. For example, the stopping density for a specific train or bus service can have a large effect on energy usage and thus on the associated CO_2 and other emissions. It is important that more reliable figures relating to energy usage and total emissions should be made readily available for all forms of transport.

Current Government targets for emissions from private cars mean that in Scotland from 2032 new vehicles cannot depend only on conventional diesel or petrol internal combustion engines. Low-emission zones are already being introduced progressively in Scottish cities, with restrictions being imposed on certain types of vehicle. The aim of these developments is to ensure that over the next 10 to 20 years the more polluting vehicles are steadily replaced by cleaner types, based on battery-electric and other forms of traction producing less pollution than the internal combustion engines currently in use. Statements from the UK Department for Transport in 2018 about the elimination of diesel-only trains across the UK rail network by 2040 also have important implications.

Clearly, railways need to be seen by the public and by politicians as a clean and sustainable modal choice and the drive for more environmentally friendly forms of transport make the choice of future rolling stock for the non-electrified parts of the Scottish railway network a potentially sensitive issue. It is important, therefore, that those who are interested in public transport issues in Scotland should be fully aware of the facts regarding energy usage and emissions.

Trends in the usage of private cars and public attitudes in terms of transport options must also be given careful attention, together with the rapid developments taking place in autonomous road vehicles. Some would claim that the concept of private car ownership needs to be challenged and that the future lies in a combination of much-improved public transport and, possibly, self-driving cars that could be booked, as needed, by members of the public for local journeys to provide links to faster and more-efficient public transport for longer distance travel. The developments in autonomous cars must also be considered for other road vehicle applications and increased use of automation and autonomy must be assessed carefully for railway, light rail and tramway applications.

Transport in Scotland is highly influenced by geographical factors. There is a relatively low population density overall, but the central belt is home to a high proportion of the total population. However, some important centres of population are not well served in terms of public transport links. As pointed out recently by Harris and Payne [39], projected population trends in Scotland show significant increases in some areas, with Edinburgh, Aberdeen (both 28%) and Perth and Kinross (24%) showing especially large increases. However, Perth and Aberdeen are, at present, not well served in terms of fast rail connections to other parts of the country, including central Scotland. Another important point to note is that there are island communities in Scotland that can be reached only by ferry or by air at present, although recent suggestions about the possible construction of tunnels (as in Norway and in the Faroes) have been the subject of some publicity [40]. Public transport issues in Scotland are therefore different, in many respects, from those in other parts of the United Kingdom and require a different strategy in terms of transport planning. Much useful information relating to all forms of transport in Scotland can be found in the annual statistical reports published by Transport Scotland (see, e.g., [41]). Electrical power generation and distribution in Scotland is also influenced by many of the same geographical issues. The uneven distribution of the population and the fact that the best conditions for renewable power generation are found in some of the most remote parts of the country are two obvious factors.

Another important factor in considering transport issues in Scotland is the devolved administration, which takes full responsibility for transport within the country. Although there are many high-profile road projects being undertaken in Scotland it must be recognised that, unlike the situation south of the border, Scottish governments have supported an on-going programme of rail electrification since 2005. This policy in Scotland differs from the stop/go approach to rail electrification adopted by the UK Government and the Department for Transport (DfT), as was highlighted in papers presented at an event on railway electrification held in Birmingham in April 2019 [42]-[45]. Costs of current and recently completed electrification projects in Scotland are lower than costs for projects under way elsewhere in the United Kingdom. Hopefully, with the experience gained and lessons learned in recent and current electrification projects in Scotland, further cost reductions might be achieved in future, provided the momentum is maintained and the skills and expertise presently available are not lost ([43], [45], [46].

This review presents the results of a study that was started in spring 2018 and is intended to provide information that should be relevant to decision-making in Scotland at the time of publication. However, this is a continuing process and the report requires regular updating when new information becomes available. There is a need for increased public awareness of the close links between transport and issues concerning future power generation and public discussion of long-term transport options must take proper account of energy requirements and emissions. Developments in battery technology and hydrogen fuel-cells are considered within the review, as well as methods for short-term energy storage (such as supercapacitors and hydraulic energy storage systems) which are important for recovery of braking energy in trains and for bus, tramway and light rapid transit system applications. The main emphasis is on land passenger transport, but ferry, air and freight transport are also discussed briefly. The references form an important part of the review and thus provide a potentially important bibliography which should be augmented and updated regularly if the report is to have continuing credibility. The report includes material presented by the author at a seminar meeting organised by the Scottish Association for Pubic Transport (SAPT) in Perth on 5th April 2019 which covered options within the transport and electrical power generation and distribution fields. It is hoped that this will be the first of several SAPT publications on questions relating to transport, energy and emissions

2. Energy costs and emissions in transport

Information currently available about energy costs and emissions can be very confusing. Objective comparisons between different forms of transport are often made impossible because details of energy calculations, such as assumed load factors, are missing. Bus and rail passenger numbers vary greatly depending on the route and time of day, so load factor information is of critical importance, as outlined in Section 1. For example, for rail travel in the UK, some published figures suggest a median load factor of about 30% but a single figure of this kind can present a very misleading picture as load factors may be 100% or more for part of a route and much lower for other sections.

Occupancy of road vehicles is traditionally calculated from surveys and figures within the Scottish Household Survey in 2004 suggest that the estimated average number of people per car journey is 1.61, giving an average load factor of 32.2%, on the assumption that typical vehicles have five seats. There is no available evidence to suggest that the figures have changed significantly during the period since the data were collected. Aircraft load factors can vary considerably depending on the route and time of year, but it has been assumed that load factors for domestic services fluctuate around the 70% level. However, it must be recognised that most airlines use pricing policies that involve selling surplus tickets at low prices and they can therefore improve their load factors significantly at off-peak times. For this review the load factors adopted are as follows: car 30%, urban bus 20%, inter-city coach 60%, inter-city rail 40% and other rail services 30%. These values are consistent with figures used in previous UK studies (e.g. [26], [27]).

Another important point is that energy costs for road transport (and for rail transport powered by diesel engines) are normally quoted in units that are different from those used for transport systems involving electrical traction. This issue is considered further in Section 2.2.

2.1 Emissions

Atmospheric pollutants from transport can be divided conveniently into CO_2 emissions (which are of concern because levels of CO_2 in the atmosphere are linked to climate change issues) and other types of emission (which are important because of established links to human health and damage to the natural environment).

a) CO_2 emissions

On a global basis, transport in 2010 accounted for 23% of emissions of carbon dioxide (see, e.g. [11]). As shown in Figure 1, European statistics for 2014 suggest that road vehicles account for about 74% of the total with aircraft and shipping both at about 12% and trains producing less than 2% (see, e.g. [11], [26], [27]). Figure 2 gives global carbon dioxide emissions for different modes of transport (gCO2/passenger-km), showing also the average (UK) passenger numbers for each mode.

For vehicles with internal combustion engines (e.g. most cars, buses, freight road vehicles and diesel-powered trains) the primary fuel is crude oil entering a UK refinery. A standard efficiency figure of 90% is commonly used to account for refinery and transport losses and the conversion factor used by car manufacturers carrying out tests in accordance with appropriate EU directive (1999/100/EC) assumes that the use of x litres of diesel fuel per 100km of travel gives 26.5x g CO2 (see, e.g. [12]).

Energy costs for electric trains are quoted in units that are different from those used for transport powered by internal combustion engines and the relationship between electrical power output and associated CO_2 emissions depends on the method of power generation. This also applies to battery and plug-in hybrid vehicles for road transport, and electrical power generation methods must be considered in discussing hydrogen produced for use in vehicles powered by fuel cells. The factors used to determine the emission levels associated with an electrical generator depend on the fuel and therefore, at any specific time, the carbon dioxide and other emissions from electrical power stations across the country depend critically on the mix of generation methods being used. At best, only an average conversion factor can be used to relate quantities of greenhouse gases in grams to the generated energy in kWh. Carbon dioxide is the most important greenhouse gas in terms of transport and figures are normally expressed as a carbon dioxide equivalent mass [47]. The figures range from 870 g/kWh for coal fired stations to below 25 g/kWh for nuclear, wind and hydro-electric power [48]. Within the UK (and especially in Scotland) the situation is changing rapidly, with the elimination of coal-fired power stations as more and more renewable energy sources are connected to the distribution network. The situation also varies significantly from hour to hour and day to day and the average must be updated to take account of the situation as the generating mix changes. Forecasts from the UK Department for Transport suggest that, for the rail sector, the 2010 value of 0.363 litres of fuel burned per kWh of electricity used would fall to 0.285 in the year 2019, 0.203 in 2025, 0.120 in 2030 and 0.026 in 2050 [49]. Expressed in g/kWh the equivalent figures for consumption-based emissions (GHG emissions per unit of final energy used) are 382 g/kWh in 2010, 300 g/kWh in 2019, 214 g/kWh in 2025, 126 g/kWh in 2030 and 27 g/kWh in the year 2050. A value of 320 g/kWh has been used in this study, but it is recognised that this may be on the high side, given the increasing proportion of renewable energy often available.

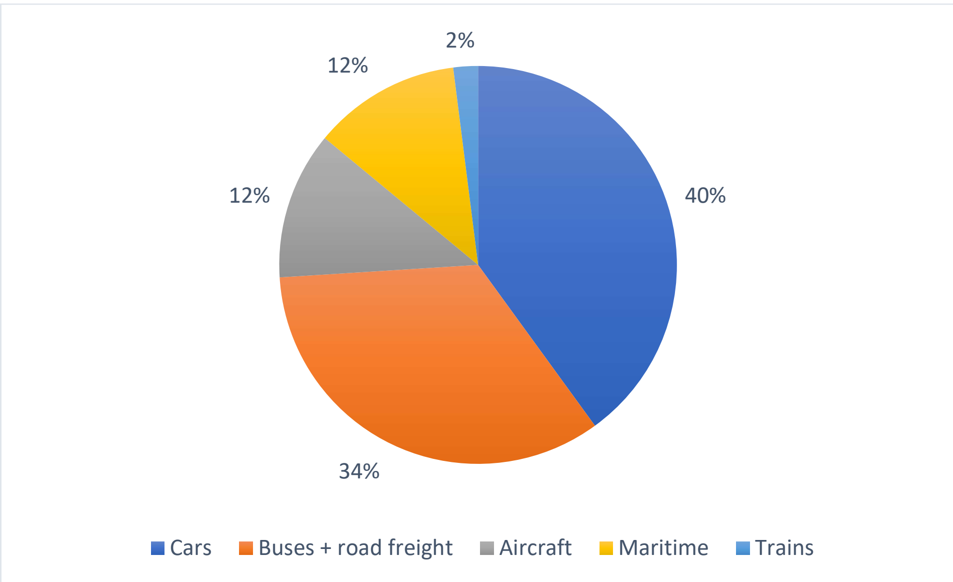

Figure 1: Total emissions of greenhouse gases attributed to the transport sector (based on percentage figures for EU countries (e.g. [11], [26], [27]).

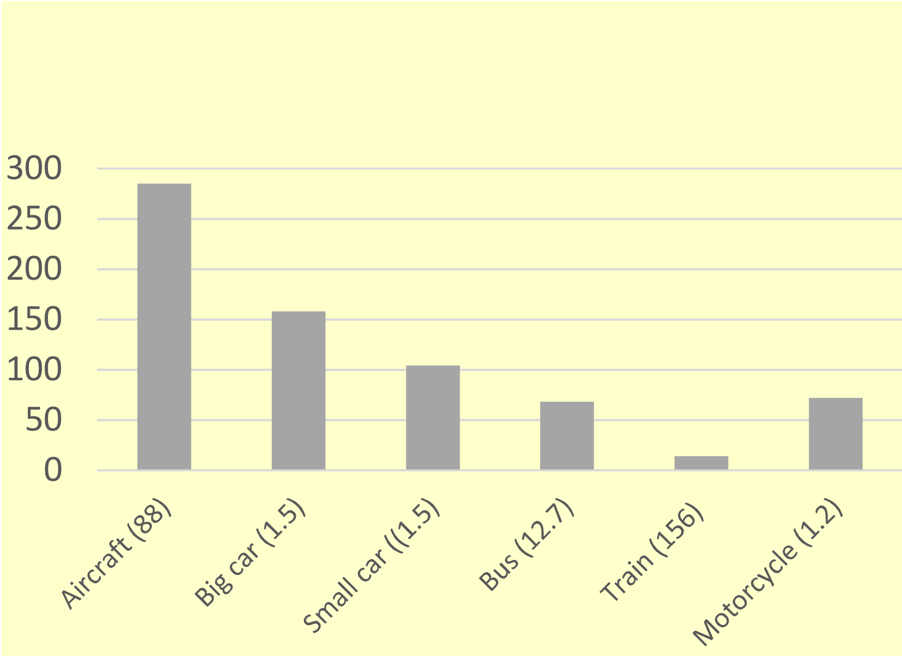

Figure 2: Global carbon dioxide emissions (gCO2/passenger-km), showing also average (UK) passenger numbers for each mode (e.g. [7], [11], [26], [27]).

Market pressures mean that more information is available about fuel consumption for road vehicles than for trains. Again, this is not a steady-state situation as manufacturers are making steady improvements in engine performance. Such developments are likely to have a more significant effect for road transport than for the railways due to the longer average life of rail vehicles. Developments in aircraft engine performance also need to be kept in mind when comparing land-based transport methods with air transport.

Another factor that has made comparisons and analysis of the contribution of railways to climate change difficult is the growth of passenger numbers. In 1960, 40 billion passenger-km were carried on the UK rail network, but this declined to 35 billion in 1980. Since that time rail passenger numbers have increased markedly and had reached 55 billion by 2006. The demand for rail travel has continued to increase over the past decade in terms of passenger numbers, but the demand for other transport modes has also increased. Analysis of published figures suggests that, for the U.K., the share of rail passenger-km transport in 1960 was 15%, which declined to 7% in 1980 and remained at 7% in 2006. Thus, an important part of the change in demand for rail has come from new demand and not demand shifted from other modes. Thus, one of the challenges in making the railways more climate friendly lies in finding ways of shifting the demand from road and plane to rail and by increasing the load factors that rail operators achieve, thus making better use of available infrastructure capacity [50]. It is also important that improved operational measures be implemented and that engineering developments should be fully exploited to improve energy efficiency of rail operations.

Aviation represents a sector where, because of a sustained increase in air travel, emissions are continuing to grow steadily. However, it must be recognised that most flights leaving Scottish airports have destinations that lie outside Scotland. Figures published by major airlines are therefore determined largely by international flights. Emissions from long-haul flights are known to cause significant environmental damage, but most of their emissions are at high altitude. Thus, although very important globally, aircraft emissions are of less importance when we are comparing transport modes for travel within Scotland.

b) Other emissions

Apart from CO_2, there are serious concerns about the levels of other emissions of potentially harmful gases and of particulate matter (see, e.g., [51]-[54]). Oxides of nitrogen such as nitrogen dioxide (NO_2), which are collectively referred to as NOx, are known to be a health hazard. Air containing a high concentration of NO_2 can, even over short periods of time, aggravate respiratory diseases, particularly asthma, and potentially increase susceptibility to respiratory infections. The acceptable threshold level in the UK below which there are no known adverse health effects is an annual mean of 40 $\mu g/m^3$. Oxides of sulphur (SOx) are also emitted but improvements in internal combustion engines in recent years mean that these are now significant only in shipping and are no longer viewed as being so important in other forms of transport.

Emissions of particulates are assessed using two figures based on the size of particles involved. These are the $PM_{2.5}$ measure (particles up to 2.5 micrometres (μm) in size, for which an acceptable annual mean of 10 $\mu g/m^3$ has been defined. For larger particles the measure is known as PM_{10} (particles up to 10 micrometres in size) and the acceptable annual mean for these is 18 $\mu g/m^3$. The effects of particulates and especially $PM_{2.5}$ are well documented, causing respiratory and cardiovascular problems particularly for children and the elderly. These tiny particles can penetrate deep within our lungs, and potentially even into the bloodstream and brain. The $PM_{2.5}$ measure is generally viewed as being particularly important due to the level of evidence of serious health issues that these particles can cause and many would argue that there is no is no safe level of exposure or any threshold below which adverse health effects do not occur. It should be noted that the PM figures include tyre-wear, brake-wear and road surface particles as well as particles from exhaust gases. In the case of road vehicles, the contributions from particulates in exhaust gases and the total particulates arising from these other sources are generally thought to be about equal for PM_{10} particulates. The largest component of non-exhaust PM_{10} particulates is associated with brake wear (about 55%) while estimates of the contributions from road dust vary between 28 and 59% and tyre wear from 5 to 30% of the total [55]. Particulates from diesel engine exhausts and from brake wear are also significant in rail transport, especially in the vicinity of stations (see, e.g., [56], [57)]. They are a special problem for diesel engines in transient conditions (e.g. starting and accelerating).

Overall, within Europe, emissions from transport sources are declining despite an increase in activity and all transport sectors have been reducing levels of emissions associated with health problems since 1990, apart from international aviation and shipping where levels have continued to rise for some emission categories. However, it should be noted that transport is still responsible for more than half of all NOx emissions.

Biomass and biofuels are often discussed in the context of emission reductions. Biomass is a term used to describe solid fuels derived from biological sources such as wood pellets, wood logs and wood chips while biofuels are liquid or gas fuels produced from organic materials using anaerobic digesters and recycled vegetable or animal oils (biodiesel, bioethanol, biomethane etc). Developments of that kind can certainly help reduce emissions that are directly harmful to health and some forms of biofuel may reduce greenhouse gas emissions. However, any claim that biomass is a "low carbon" fuel is not correct since biomass power plants can emit one and a half times the CO_2 of coal, and up to four times the CO2 of natural gas, per unit of energy produced [58]. Another factor is that, in the United Kingdom, biomass raw material is mostly imported and transport of these raw materials by sea and land can be a very significant item in terms of overall emissions [59].

2.2 Making comparisons

Different types of vehicle involve different measures of fuel consumption or energy usage. For example, car fuel consumption has been measured traditionally in this country in terms of miles/gallon of fuel or, more recently, in terms of litres/100km. Fuel consumption in aircraft, buses and diesel trains is normally expressed as litres/100 seat-km while in electric trains the usual measure of energy use is kWh/seat-km. In order to compare different transport modes, the figures being used must be based on a common reference. One widely used measure for CO_2 and other greenhouse gas emissions involves the total mass of gases emitted, often measured in units of thousands of tonnes per year. An alternative is to consider the mass of gases emitted in grams of CO_2 emissions per seat-km or per passenger-km (or per tonne-km for freight). Use of the measure involving g CO_2/passenger km requires some assumption about load factor. As mentioned at the start of Section 2, widely-used load factors are (for UK): car –30%, urban bus –20%, intercity coach –60%, intercity rail –40%, other rail –30%, domestic airlines –70% and these have provided a basis for calculations carried out for this report.

Figure 3 shows indicative CO2 emissions per passenger on the load-factor assumptions above. Road, air and diesel-powered rail vehicle emissions have been increased to take account of refinery losses and the figures for electric trains allow for losses from the site of power generation through the electrical transmission network to the train itself. The bar length represents the CO_2 produced (g/passenger-km) based on the assumptions given above and in Section 2.1a).

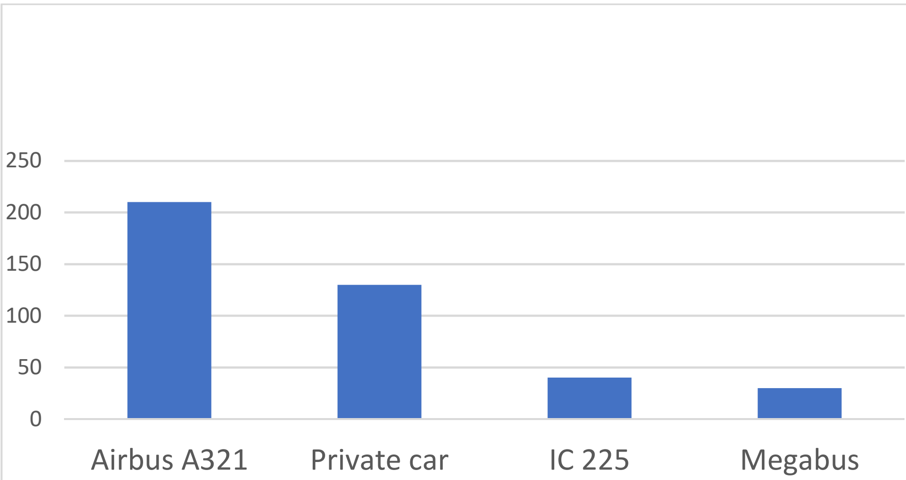

Figure 3: CO_2 produced (g/passenger-km) for different forms of transport for typical load factors for a 600km journey. [26], [27]

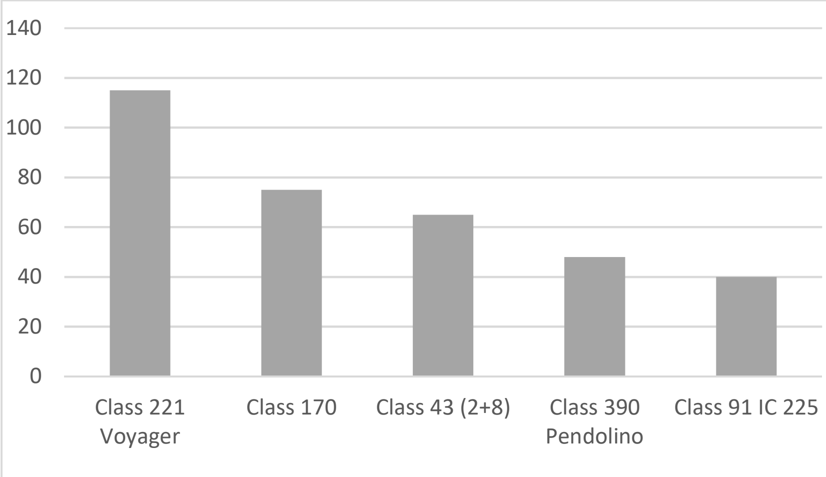

Figure 4: CO_2 produced ((g/passenger-km) by different types of train for a typical inter-city journey [26], [27].

Figures 4 and 5 show levels of CO_2 produced by different types of train for a typical inter-city journey using two different measures (g/passenger-km and g/seat-km). It can be seen, from Figure 3 that the least polluting means of transport are electric trains, and Megabus type intercity buses. The difference between them is small in comparison with the likely variations in load factor. In descending order, the worst polluters are planes, followed by private cars, with local buses and diesel-powered trains giving figures that are quite similar but below those for cars. However, it must also be recognised that for most intercity routes in the United Kingdom the journey time is less by train than by bus or car and this factor is seldom accounted for in this type of analysis.

Although CO_2 emissions from diesel trains are significant, the recent *Clean Air Strategy* document published by the United Kingdom Government [60] suggests that railways contribute just 4% of NO_x and 1% of particulate emissions nationally. These emissions can cause problems in station areas and the documents includes a call for the use of alternative fuels for routes where diesel trains currently run.

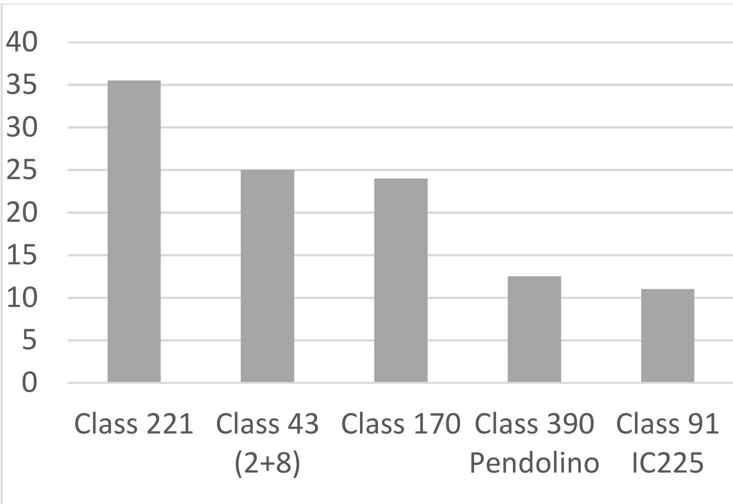

Figure 5: CO_2 produced (g/seat-km) by different types of train for a typical inter-city journey [26], [27].

For the main domestic air routes from London to Glasgow or Edinburgh, figures for an Airbus 321 have been used for making comparisons, since this type of aircraft is typical for a route of that type [26], [27]. Turbo-prop aircraft are used on many routes for services within Scotland and the specific types of turbo-prop aircraft considered are the 70-74 passenger ATR 72 and Bombardier Q400. These are similar to the types of aircraft currently used on the longer internal Scottish routes and on routes between Scotland and many destinations in England and Wales, other than routes to London. Carbon dioxide emissions for such aircraft for a typical flight of 200km are approximately 150 g/passenger km. The corresponding figure for the Airbus A321 aircraft on a 600km route (such as Edinburgh or Glasgow to London, as shown in Figure 3) is considerably more at about 210 g/passenger km [26], [27]. It should be noted that in general, the longer the route the lower are the emissions per passenger km.

NOx emissions from international aviation have increased by more than 140 % over the twenty-five-year period since 1990, due largely to the increase in air traffic over that time. The NOx emissions of associated with short-haul routes are also important but are not growing as rapidly.

In Europe, ships account for 25 % and 13 % of all NOx and SOx emissions, respectively (see, e.g., [33]-[36]). To put the SOx emissions in a more familiar context a typical modern car produces only about 100 g of SOx annually (for 15000km of travel), but a large marine diesel generates 5,200 tonnes of SOx per year. Ships now use low sulphur fuel in the North Sea and other European waters such as the coastal waters around the United Kingdom and the English Channel. Regulations imposed in these and some other coastal waters around the world mean that the sulphur content of marine diesel fuel used by ships in the areas defined by those rules, fell from 1.5% to 1% in 2010 and to 0.1% in 2015. It has been suggested that these standards, which were agreed by the International Marine Organisation in 2008, will have been responsible for saving up to 26,000 lives per year in the EU by 2020 (see, e.g. [33]-[36]). While they are in harbour, ships are required to use fuel with a maximum of 0.1% sulphur content and there is growing interest in the use of other forms of energy to supply power from the dockside for various purposes such as ship auxiliaries and lighting.

It has been calculated that a typical car ferry produces more NOx emissions and particulates than the vehicles it is carrying would for a journey of the same distance by road. An investigation for the ferry routes across the Irish Sea has provided detailed quantitative information and published figures suggest that taking an average car on the return trip between Dublin and Holyhead (200km) produces CO_2 emissions equivalent to driving 1400km [61]. It has also been suggested that reducing the speed of a ferry by 10 per cent would cut emissions by at least 19 per cent. High speed ferries inevitably produce a much higher level of greenhouse gas emissions than conventional ferries. The use of liquified natural gas and biofuels could reduce toxic emissions from ferries, although it is not clear that significant reductions in carbon dioxide emissions would result from the use of such fuels and further research is clearly needed. Developments in terms of the "more-electric" ship are also of potential interest (see, e.g. [62], [63]).

3. Current developments relevant to transport

3.1 Developments in internal combustion engine technology

Developments continue concerning the technology of internal combustion engines and these should certainly not be discounted as a future power source for transport, especially in hybrid form. The introduction of EURO VI regulations for heavy duty vehicles of all types, including buses, and the Euro 5 and 6 standards for other road vehicles is very important and should lead to reductions in the emissions that are potentially damaging for health [64]. There are also continuing developments in marine diesel engines and in aero engine technology which are producing steady improvements.

Engineering developments in internal combustion engines for road vehicle and marine applications also provide scope for developments in diesel engines for railway applications. One example is in North America, where GE Transportation has developed the Evolution Tier 4 diesel engine, designed to meet US Environmental Protection Agency regulations on emissions, with tests being completed on this engine in 2015. The company claims that it can reduce nitrogen oxides (NOx) and particulate matter (PM) emissions by at least 70% [65]. In July 2016 GE celebrated producing the 1,000th Tier 4 locomotive [66].

In Europe, the Alstom Prima H3 and H4 locomotives, designed for shunting purposes, are intended to reduce fuel use and emissions in built-up areas [67]. They can be operated in single or double-engine modes with either one 1,000KW diesel generator or two 350KW diesel generators. Alstom claims the H4 double engine can cut diesel fuel consumption by up to 15%. They are also available in hybrid and battery configurations. The H3 hybrid can reduce fuel use by 30% to 50% as it incorporates a battery alongside the diesel generator. The full battery mode, designed for more populated areas or use in tunnels, can operate emission-free. The H4 battery version involves a combination of a battery and catenary systems. Deutsche Bahn has introduced five H3 hybrids to its fleet.

Liquefied natural gas is being considered in the rail industry as an option for dual-fuel locomotives and in 2015 Russia unveiled what it claimed to be the world's first locomotive of this kind, the TEM19 [68]. Russian Railways, Gazprom, Transmashholding and the Sinara Group signed an agreement in 2018 to develop the necessary infrastructure to support the use of liquified natural gas to power locomotives. Also, in 2017, Spanish operator RENFE announced it was to replace a diesel engine in a Class 2600 diesel multiple unit with a liquified natural gas equivalent. Plans were announced to compare the performance of this modified unit with a diesel version using a specific 20km section of track for trials [69]. In North America, GE Transportation has claimed that it can convert its Evolution series locomotives to operate on a mixture involving up to 80% natural gas.

3.2 Developments in battery technology

There is much research and development effort being applied at present to battery technology. Falling costs have been accompanied by marked improvements in range. In 2011, the greatest range an electric vehicle could achieve was about 90 miles, compared to more than 330 miles in 2018. Although battery technology is advancing rapidly, it is important to note that most forms of battery continue to depend on materials that have some unfortunate properties from an environmental viewpoint. There are several areas of concern including total energy efficiency, availability of the materials required and the environmental effects of mining and processing of those materials, as well as end of life disposal issues. Battery life expectancy is another issue that may deter some potential purchasers of electric vehicles as the cost of battery replacement remains high.

Apart from continuing research and development effort in the field of lithium-ion batteries (the current choice for almost all transport applications), there are important developments taking place with other forms of battery which show promise but have not yet been fully tested and evaluated for transport applications. These include lithium-metal batteries and lithium-sulphur batteries which have properties that could give them advantages over currently available lithium-ion batteries, especially in terms of capacity and charge time (see, e.g. [70], [71]). One other important development involves the concept of a “structural battery” in which the vehicle itself becomes a large battery (see, e.g. [72]). This involves the use of carbon fibre technology, which is already starting to be used in aircraft, in road vehicles and in at least one design of rail vehicle.

Applications of modern battery technology in transport are now widespread and have been widely reported. Battery-powered buses have been in use in the central area of Vienna for several years [73] and such vehicles also form part of an ambitious plan in Milan to make city-centre public transport entirely electric by 2030 [74]. Fleets of battery powered light goods vehicles are appearing in various cities and there are many examples of tramway systems with hybrid vehicles that use batteries for some sections of their routes. Examples include some modern tramway and light rapid transit systems in the USA (e.g. Oklahoma City and Milwaukee) and some European cities, where concerns about the introduction of catenary in historic areas have led to designs involving a mix of conventional catenary and battery power. In some cases, such as the new tramway in Doha (in Qatar) which was opened in 2018 and a demonstrator line in Busan, South Korea, only battery-powered electric traction is provided.

Although marine applications of batteries are expected to remain limited to relatively small vessels, there are examples of hybrid systems involving the use of batteries that are under development in several countries. Research is also taking place on electrically powered aircraft for short flights. The share of greenhouse gas emissions associated with aircraft is expected to reach about one quarter of the total by 2050 and there is therefore considerable interest within the industry about the potential of batteries in developing a more-electric form of aircraft Structural batteries are of particular relevance for aircraft applications [72].

One example of special interest in Scotland is the successful demonstration by Vivarail (Figures 6, 7 and 8) in October 2018 of its battery powered Class 230 unit on the Bo’ness and Kinneil Railway [75]. Vivarail has recently announced that it is supplying five diesel-battery hybrid three-car units for use by Keolis-Amey on the Wales and Borders franchise. On these hybrid sets use will be made of GPS systems to cut out the diesel engines in stations and environmentally sensitive areas.

Figure 6: Vivarail battery powered Class 230 unit at Bo’ness station on the Bo’ness and Kinneil Railway during a short visit for demonstration trips on 11th October 2018. (Photograph D. Murray-Smith).

Figure 7: The Vivarail Class 230 unit at Manuel. (Photograph D. Murray-Smith).

Figure 8: The Vivarail Class 230 battery-electric unit at Manuel prior to departure for Bo'ness (Photograph D. Murray-Smith).

Among other recent announcements by manufacturers and vehicle leasing companies is a statement that Class 319s EMUs are currently being rebuilt by Brush to include battery technology. A leasing company (Porterbrook) has also announced that Class 455 4-car EMUs could be rebuilt with battery packs to allow use on non-electrified routes [76] and that design work is being undertaken to convert Siemens Class 350/2 EMUs into "BatteryFLEX" trains capable of working away from 25kV overhead routes. An item in the issue of the *Scotsman* newspaper of 25th March 2019 included an announcement by Hitachi of plans for the addition of batteries to Class 385 units to allow their use to destinations currently beyond the electrified network in Scotland (e.g. lines from Dunblane to Perth, Glasgow to East Kilbride etc.) and this information is consistent with an item on the Hitachi website [77]. It is of interest to note that the news item in the *Scotsman* included the statement that "Scottish passengers would be among the first in the world to ride on battery-powered trains under plans unveiled by Japanese firm Hitachi", thus neglecting completely the use of the experimental battery electric multiple unit (Figure 9) that ran in regular passenger service between Aberdeen and Ballater during the period from 1958 to 1966 when the branch was closed [78]. It also neglects important developments in the 1950s and 1960s in other countries and the much earlier experiments on the route of the Edinburgh and Glasgow Railway in 1842 with Robert Davidson's battery-electric locomotive (named *Galvani*) [79].

Figure 9: View of the BR Scottish Region battery-electric multiple unit departing from Aberdeen on its first day of passenger-carrying service on the Aberdeen – Ballater line (April 1958). The compartments holding the lead-acid batteries are visible below the body of each of the vehicles of the two-car set. (Photograph D. Murray-Smith).

3.3 Developments in hydrogen fuel-cell technology

Hydrogen fuel cell technology is still at an early stage and it is likely to be some time before hydrogen is widely used as a fuel [80]. Today, hydrogen gas is usually produced either by a process that gives 'brown' hydrogen made by reforming of non-renewable fossil fuels using steam and the currently more-expensive 'green' hydrogen produced by electrolysis. Other methods of production are under development using domestic waste or discarded plastic but have not yet been applied on a commercial scale in this country.

Transport is an obvious application and progress is being made with buses, trains and ships, but it is not yet clear what the implications might be for the electricity supply industry. The production of hydrogen by electrolysis could require large quantities of electrical energy but there are economic factors and issues of scale that are still not well understood. For example, are there advantages in developing large electrolysis plants close to areas where there are good supplies of renewable electrical energy and then transporting the hydrogen to the point of use? Or is a network of (possibly smaller) electrolysis machines distributed across the country more viable? The answer clearly has important implications for the electrical distribution network. An additional important point is that the storage of hydrogen requires significantly more space than diesel fuel and there are safety concerns, both about the movement of hydrogen in bulk and about storage in general. These safety concerns are especially important for transport applications where structural integrity of vehicle storage tanks becomes an important issue. Hydrogen-power sources convert the stored chemical energy to mechanical energy, by burning the gas within an internal combustion engine or by a reaction with oxygen within a fuel cell to produce electricity and water.

The hydrogen internal combustion engine is simply a modified version of a traditional internal combustion engine and has a cost believed to be about 50% more than the current cost of a petrol engine. Currently available hydrogen engines are designed to use about twice as much air as theoretically required for complete combustion since a high air/fuel ratio can help to limit the formation of NO_x. Unfortunately, the corresponding power output falls to about half that of a similarly sized petrol engine and in order to make up for the power loss, hydrogen engines are usually larger than petrol engines.

Hydrogen fuel cell technology is generally regarded as a promising approach for many transport applications and has made major advances in recent years. Although research and development in fuel-cells continues, there have been several important applications in the transport sector involving hybrid systems that include batteries as well as fuel cells. Essentially the hydrogen fuel cell is the primary source of energy and this charges the battery which then provides power to the traction motors. Examples include bus trials in Aberdeen (Figure 10) and several other European cities [81] and both Tesla and Hyundai have produced prototype heavy goods vehicles [24]. Hydrogen has even been considered as a fuel for aircraft and this is the subject of the "Enable H2" research project involving Cranfield University, GKN Aerospace and other partners [82].

Figure 10: Hydrogen-powered bus in service in Union Street, Aberdeen (May 2019). (Photograph: D. J. Murray-Smith).

Since September 2018, the world's first hydrogen-powered commuter trains have been in service in Germany. Operating costs are said to be lower than those of an equivalent diesel unit. In the United Kingdom Vivarail claims to be the only manufacturer offering a hydrogen power train of proven design and ready for use on the mainline network [83]. This is a hydrogen/battery-electric version of the diesel/battery-electric Class 230 announced earlier. It has hydrogen fuel cell and hydrogen storage tanks below the floor in an intermediate vehicle instead of the diesel engine and diesel fuel tanks. The unit has a range of 650 miles and incorporates regenerative braking. Since these two types of power unit and storage tanks occupy the same space, the modular approach that has been adopted by Vivarail is claimed to allow easy transition from a diesel/battery to a hydrogen/battery hybrid configuration.

Other projects announced in the United Kingdom include the Porterbrook 'HydroFLEX' demonstration project which will be based on a Class 319 unit. This involves collaboration with the University of Birmingham's Birmingham Centre for Railway Research and Education

('BCRRE') [84]. A hydrogen-powered train for the UK market is also under development by Alstom in collaboration with and the rolling stock leasing company Eversholt Rail. Known as the "Breeze" this vehicle will be based upon an existing Class 321 multiple unit [85].

Interest in hydrogen power for transport is not new and it is interesting to note that a very comprehensive review of possibilities for the use of hydrogen for powering trains and for many other railway applications was published in 2005 by the UK Rail Systems and Safety Board [86]. Comparisons of fuel economy in hydrogen powered buses, as compared with equivalent diesel-powered equivalents, have been made (e.g. [87]) and an up-to-date report, entitled *The Future for Hydrogen Trains in the UK,* was published by the Institution of Mechanical Engineers in February 2019. This builds on earlier studies and states that the current overall efficiency of a hydrogen train is about a third that of a conventional electric train. This because hydrogen traction requires 3 kW of electricity to deliver 1 kW of power to the wheel while a conventional electric train needs 1.2 kW [88]. A further problem is that the low energy density compressed hydrogen means that a fuel tank is needed that is eight times the size of a diesel tank for the same range**.** The report suggests that there may, therefore, be strong economic and practical arguments against the general use of hydrogen power for railways and that its use should be considered mainly for parts of the country where hydrogen production already occurs (e.g. from renewable energy sources) and where there are opportunities to support integrated rail, bus and electrical power systems using this fuel. It is suggested, therefore, that hydrogen might be best used in more remote areas, such as island communities, which have electricity supplies based, mainly, on relatively inexpensive renewables and also poor transmission links to the remainder of the national grid. This could lead to the creation of 'clusters' of hydrogen-related businesses where the gas is produced and could, perhaps, help local train and bus operators to decarbonise by reducing or sharing the distribution costs involved. On the other hand, a recent study concluded that the business case for conventional electrification of the single-track Trondheim-Bodø line in north Norway was poor and that hybrid hydrogen fuel-cell and battery locomotives might be a better option [89]. Design issues for hydrogen powered trains are also discussed in a 2016 paper by Hoftrichter, Hillmansen and Roberts [90] which also provides some comparisons in terms of energy costs for diesel trains with two possible traction options involving hydrogen.

There has also been recent publicity concerning the use of surplus wind and tidal energy in Orkney to produce hydrogen. A 500kW electrolysis machine is being used on the island of Eday, with hydrogen being transhipped to Kirkwall where it is used to supply the port's hydrogen fuel cell. The cell produces electricity for shore-to-ship power [91]. The process is claimed to reduce pollution and is also seen as a basis for hydrogen bunkering facilities in the future. However, the technology is still expensive and the electricity cost from a fuel cell is currently about double or triple that from a diesel generator. Marine applications of hydrogen are discussed in several recent papers (e.g. [92], [93]).

3.4 Other methods of energy storage

Recovery of energy currently dissipated in braking in all forms of transport could help to reduce energy usage and also the emissions produced. One widely used form of energy recovery is regenerative braking where, in electrical transport systems, traction motors act as generators to convert part of the kinetic energy back into electrical energy. This may be fed back to the power grid or stored in some way for later use. Although this is a relatively straightforward process on conventional electrified railways, other forms of transport require components that can store energy quickly and release it over longer periods of time and repeat the process on a regular basis with a high cycle rate. Various approaches are possible, including mechanical systems based on flywheels, hydraulic systems and electrical systems involving batteries or supercapacitors [94].

a) Flywheel energy storage systems

Flywheel energy storage systems work by storing kinetic energy in a rotating mass. In some modern systems of this kind the rotors are made of high strength carbon-fibre composites, suspended by magnetic bearings, and spinning at speeds from 20,000 to over 50,000 rpm in a vacuum. Such modern systems can reach full speed in a matter of minutes. One well-known example in the UK is the hybrid Parry People Mover system used in Class 139 railcars which involves the use of an LPG engine and a flywheel. Some electric locomotives have also incorporated flywheels, including examples built by the Southern Railway in 1942 (later designated as BR Class 70 locomotives), and also a later type designed for British Railways in the 1950s (Class 71). Both these types of locomotive were designed for use on electrified routes based on the third-rail system and used flywheels to ensure that power was not lost over short sections where there were gaps in the third rail. Such gaps are inevitable when electrification is based on the third rail system and do not present problems for multiple unit electric trains which have several pickup shoes.

b) Hydraulic energy storage systems

Although energy recovery through regenerative braking is well-established for electrified railways there has, until recently, been no equivalent for conventional diesel traction. However, recent development work by Artemis Intelligent Power using their Digital Displacement® pump technology involves kinetic energy being directed into an onboard energy storage system, thus braking the vehicle. It has been demonstrated, in trials in Scotland (Figure 11), that it is possible to accelerate a train from standstill using only that stored energy from braking. This means that the diesel engines need not be run in station areas, thus eliminating potentially harmful diesel emissions. During travel, the stored energy can be used to increase acceleration and reduce journey times without the use of more fuel [95].

Figure 11: Artemis Intelligent Power test vehicle at Bo 'ness, October 2018 (Photograph: D.J. Murray-Smith).

There is a second area in which the digital hydraulic pump has potential benefits. Powering of cooling fans and generation of electricity in diesel multiple units can use up to 15% of the engine fuel. ScotRail is working with Artemis Intelligent Power to test the use of the company's digital hydraulic pump technology as an alternative to conventional methods for this type of application. Tests on a Class 170 diesel multiple unit suggested that savings could exceed 1.5 million litres of diesel fuel per year if this technology were to be applied to the whole fleet of Class 170 units operated by ScotRail at the time of the tests [96].

c) Electrical energy storage systems using supercapacitors

Supercapacitors have electrical properties that are like those of conventional capacitors used in electronic circuits but, as the name suggests, can have very much larger values of capacitance. They are high-power energy storage devices that store charge at the interface between porous carbon electrodes and an electrolyte solution and have favourable properties as devices for short-term energy storage, such as regenerative braking in transport applications. Although it is possible to apply conventional battery technology to regenerative braking, there are potential advantages in using supercapacitors.

The specific power (power output per kg) of a supercapacitor is typically 10 to 100 times greater than that of currently available batteries, although batteries can store more energy for a given weight and volume. Supercapacitors also have superior characteristics in terms of their overall energy efficiency compared with batteries (about 95% compared with an equivalent battery system which is typically 75-90%). A further advantage of supercapacitors for short-term energy storage applications is that they can be charged very quickly and discharged in a controlled fashion. The number of charge/discharge events over the lifetime of a supercapacitor is almost unlimited and the life of such devices is estimated as being about 10 and 15 years, compared with a typical battery life of between 5 and 10 years. However, supercapacitor costs remain significantly greater than the cost of equivalent batteries, although the difference is becoming smaller. While supercapacitors are not a recent development, their practical use has only been reported over the past two decades. Research and development activities aimed at improving the characteristics of these components and increasing our understanding of their properties continues (see, e.g. [97], [98]).

In railway or tramway applications supercapacitors can be used at the trackside (see, e.g. [99], [100]) or can be based within the vehicle (see, e.g. [101]). Early applications of supercapacitors in public transport were in the bus industry with MAN's so-called "Ultracapbus" being tested in Numerberg about 2001or 2002. That involved a vehicle with a diesel-electric drive system and results showed a fuel consumption reduction of between 10 and 15% compared with an equivalent conventional diesel vehicle. Anther subsequent application involved the "Capabus" which was first tested in Shanghai in 2005 and is now in service in various places within China, including Hong Kong.

Light rail and tramway use of supercapacitors appears to date from 2003 when the city of Mannheim in Germany tested a prototype light-rail vehicle from Bombardier. This could provide 600kW in the starting phase of operation and could drive the vehicle up to 1 km without overhead line supply. It was claimed that onboard energy storage could save up to 30% of energy costs and could reduce the peak demand by up to 50%.

In August 2012 the CSR Zhuzhou Electric Locomotive Corporation of China presented a prototype two-car light metro train equipped with a roof-mounted supercapacitor unit. The unit can travel up 2 km without wires, recharging in 30 seconds at stations via a ground mounted pickup. In 2014 China also began using supercapacitors for tramways with seven trams powered by supercapacitors being supplied for operation in Guangzhou. The supercapacitors are recharged in 30 seconds by a device positioned between the rails and this can power the tram for up to 4 kilometres. Wuhan also has a fleet of 21 CRRC designed four-section supercapacitor trams with Siemens traction and braking equipment. These have capacity for 400 passengers and a range of 3-km after each charge which typically takes between 10 and 30 seconds.

The possibility of eliminating catenary also means that supercapacitors can be an attractive proposition for trolley bus and tramway routes that pass through historical city areas and can thus help preserve architectural heritage.

In 2016 worldwide sales of supercapacitors was reported to be about US$400M which is significant and growing. This is still small compared with the market for rechargeable batteries which is worth tens of billions of US dollars, but it is likely that costs of supercapacitors will fall significantly as demand increases.

4. Electrical power generation and distribution issues

At present, in the United Kingdom, the use of electrical power for transport is mainly for railways. Network Rail procures electricity centrally and is one of the largest consumers of electrical energy in the country. Train operators are then charged for traction power and in 2013 Network Rail awarded EDF Energy a 10-year contract to supply electricity for the rail network. The total consumption in 2016-17 was around 3,400GWh at a cost of about £300M. The present contract runs to September 2024. and is supposed to link the energy supplied to Network Rail to output from EDF Energy's nuclear power stations across the United Kingdom [102].

The U.K. electricity system appears to be able to meet current demands, but with safety margins that are regarded by many in the industry as being smaller than desirable. We now have much less generation of electricity from fossil fuels than in the past and, also, less nuclear power. More and more of our power requirements are being met from renewable sources such as wind power, resulting in a supply system that is much more system more distributed. One important result of these changes is that there are new issues of power system stability and control that did not present difficulties in the past [103]. Fault conditions that would have had relatively minor consequences when the Scottish network benefitted from the presence of several large conventional generating stations are now seen as being potentially very damaging. It has been stated that a so-called “black start” situation in the United Kingdom, involving the sequential reconnection of the grid system following a major fault, could mean that in the worst-case scenario there could be a delay of several days before electricity users in Scotland would get supplies restored [1].

A pressing question is how the existing system can best be adapted to ensure that it can provide a robust and reliable supply at a time when there is a new and rapidly increasing demand from battery-electric vehicles. Estimates of the extra demand from vehicle battery charging range 10% to 40% [104]. In Scotland, the growth of renewable generation (dominated by wind energy sources at present) adds to the difficulties, since this major component is inherently variable and requires to be backed up by other energy sources [1]. One option would be to supplement supplies from renewable sources through the building of more conventional gas-burning power stations, but the counter argument is that such a policy would simply move pollution problems away from the end-user to the areas around generating stations. Another problem concerns the question of the ability of the grid to cope with the extra demand from a more-electric transport system and especially the demand from charging of vehicle batteries on domestic premises. Home charging suggests an immediate need for stronger local networks (and possibly enhanced domestic supplies) plus developments such as “lamp-post” or inductive charging facilities in the street to meet the needs of those whose properties do not have off-street parking. There is also a need for fast charging of batteries in places like conventional filling stations, motorway service areas and, possibly, in the workplace. Such developments suggest a significant investment in infrastructure.

From an electrical power systems perspective, the batteries within electric vehicles of all types may be considered as (a) simple passive loads, (b) flexible loads that may allow the charging process to be modified or controlled and (c) controlled storage devices that interact with the electrical distribution network to provide a controlled two-way flow of energy as and when required. This suggests that there are at least two ways to cope with the demand increase from electric vehicle battery charging. The first of these is a passive approach which would require the upgrading of the existing power system infrastructure to meet the additional demand in conventional ways. The second would involve an active approach to the control of electric vehicle battery charging and could reduce the costs of upgrading the power distribution network but would introduce the additional complexities of what is termed “demand side management” (see, e.g., [105] - [108]).

This demand-side management approach can best be understood from the example of some trials being undertaken in London where a fleet of battery-electric delivery vans is owned and operated by the UPS courier/delivery service. A project is under way involving UPS and some partner companies to provide “smart” charging facilities for these vehicles using “intelligent” charge-points. These communicate with the national grid and with local electrical storage facilities (i.e. fixed batteries installed within the depot). The configuration chosen is intended to provide minimum cost charging, at all times. Using this “smart” charging infrastructure, UPS has been able to increase the number of electric vehicles operating from its depot from 65 to 170 without any upgrade its electrical network connection. This raises interesting possibilities in terms of future methods for the charging of batteries for public transport vehicles and could also be relevant for the charging of batteries of private cars at the owner’s home, provided new and attractive forms of tariff could be introduced.

Thus, it could perhaps be argued that electric vehicles are not all bad news for the electrical supply industry. Some would suggest that they could be part of solution with “smart” charging and new tariffs allowing electric-vehicle batteries to provide some of the electrical storage capacity needed to maintain the necessary balance between supply and demand at all times.

However longer-term uncertainties concerning the impact of electric road vehicles on transport and the electricity supply system mean that there is a risk of over-investing in infrastructure, such as charging facilities, that may be under-utilised. On the other hand, this must be balanced against the potential benefits of encouraging faster electric vehicle uptake by investing in infrastructure ahead of need. Current electric vehicle owners are often referred to as “early adopters” who are relatively well-off and less risk averse than the population as a whole. Uncertainties about battery lifetimes and replacement costs, together with worries about the range of present-day vehicles and availability of charge points are some of the factors that tend to put off many potential purchasers. There should be more transparency about what will happen in terms of future road and fuel tax policies, what the likely depreciation rates will be for electric vehicles and what longer term government incentives may be offered. It is perhaps significant that the country with the highest level of electric vehicle registrations is Norway, but that this has been achieved only with major government incentives such as toll-free driving on motorways, toll-free bridge crossings, free ferry transport for electric vehicles and free parking. However, it should be noted that while the Norwegian Government is encouraging the uptake of electric vehicles through these generous incentives it is also investing heavily in public transport through major new rail infrastructure programmes [89].

5. Current trends in car usage and effects of possible developments in autonomous transport systems

In recent years it has been recognised that there are many factors, in addition to the growth of electric road vehicles, that are likely to be important in terms of modal choice for our transport needs in future. Frustration with traffic delays encountered on the roads, and a growing realisation that some forms of public transport make it easy to use travel time productively for work or entertainment, mean that driving has ceased to be the first choice for some. The rapidly increasing costs of car ownership for young people (and especially insurance) mean that some in their late teens or early twenties are deciding not to learn to drive at that stage in their lives. Reduced travel costs by public transport and especially by train through the availability of railcards that offer substantial discounts are also a factor in this. Similarly, older people in the U.K. are tending to drive less, even when a private car is available, because of the attractions of schemes such as the bus travel concession cards and the Senior Railcard.

The rate of development of autonomous vehicles is an additional factor that will influence future transport choices. Although the whole topic involves many uncertainties at present, we can expect the uptake of autonomous vehicles to start to increase significantly if the technology can be shown to be safe and reliable and production levels can reach a level at which both the initial cost and the cost of maintenance become acceptable for present-day car owners. Many suggest that autonomous vehicles could significantly reduce the demand for car ownership and that the future of local transport might lie in self-driving vehicles that can be booked, as required, from vehicle hire companies in much the same way that taxis can be ordered by telephone or over the internet. This type of service might well be used, primarily, for relatively short journeys and could then provide links to faster and more-efficient public transport for longer distance travel. Also, those individuals owning an autonomous vehicle could possibly benefit by allowing others (at an appropriate charge) to use the vehicle when it is not being used by themselves. Many reports and strategy papers have been produced which consider the growth of electric vehicles and the expected developments in terms of vehicle autonomy (see, e.g.[109]-[112]) and the effects that the trend towards electric vehicles will have on government policies on paying for road use (see, e.g. [112] – [114]).

There are, at present, too many unknowns concerning autonomous vehicles and their usage to make it sensible to include them in any numerical projections. However, this situation will certainly change within the next five to ten years and it is important to keep this area in mind in considering future transport developments.

Although most people associate autonomous transport developments with road vehicles, we should also be looking carefully at autonomous operation for other modes. Driverless trains have been a feature of transport systems in many cities such as Lille, Copenhagen and Kuala Lumpur, for some considerable time and many new automated systems are being introduced (including the Glasgow Subway). An autonomous tram is on test in Potsdam in Germany (a Siemens *Combino* 400) and in St Peterburg in Russia a similar project is under development (involving PK Transportyne Systemy and Cognitive Technologies). Driverless 160km/hour trains are planned for the New Airport line in Beijing which is due to open in September 2019. A form of automatic train control is being applied to part of Thameslink route (St Pancras Intl. to Blackfriars) to increase service frequency.

6. Using computer simulation methods to investigate options

Computer simulation techniques and related computer-based modelling tools have proved to be very important for many transport applications in recent years. The available computational methods can be divided conveniently into those that use discrete models and discrete-event methods and those that are based on continuous system simulation principles using mathematical models involving differential equations.

Discrete-event simulation tools are particularly useful in the modelling of traffic of all kinds and can, for example, assist in decision making about traffic light sequencing to avoid unnecessary delays. They are also very useful for investigations of complex networks (for example, in the transport context or in digital communications) and can be of great importance for overall optimisation of network performance where each object being considered (e.g. a vehicle or message) behaves in exactly the same way, or in one of a predefined set of different ways. Discrete-event simulation methods thus have a role in areas such as railway timetable development or air traffic control system design and airport or station management.

Continuous system simulation methods focus more on the prediction of the dynamic performance of a single object and can, for example, allow one to predict values of chosen system output variables (such as velocity or position at any instant of time) from a given input variable (such as a force or power level). Continuous system simulation methods are widely used in engineering applications of all kinds and have been applied to transport systems analysis for many years. Hybrid approaches, involving some sub-models based on discrete-event descriptions working together with other sub-models that involve continuous system simulation principles are becoming increasingly common. A hybrid approach may be useful in applications that involve separate elements, such as in road traffic analysis involving individual vehicles that interact in a dynamic fashion but where the main interest lies in overall patterns of traffic flow. Hybrid simulation methods are also useful in the investigation of complex systems involving computers, as are found in many modern transport systems. Studies involving the modelling of human activities provide an example of another area where hybrid approaches have been found to be useful.

Whatever the methodology, it is vitally important that a simulation model should be properly assessed and tested in ways that are appropriate for the intended application before it is used. This testing process is often termed simulation model "validation" and is an essential part of the model development process (see, e.g. [115], [116]).

Train performance system modelling methods are well established and are generally based on a mathematical model in the form of a set of ordinary differential equations and algebraic equations that represent the characteristics of the traction system, vehicles and route. Such a model is generally nonlinear in form and analytical methods of solution cannot be applied except in some special cases. Continuous system simulation methods can be applied to a problem of this kind and the use of well-established simulation software tools eliminates the need to develop numerical routines for each application considered. Many reports and papers are available which discuss mathematical modelling and simulation in the context of train performance, some of which were published some considerable time ago (see, e.g., [117]). Studies have also been published involving comparisons of simulation model results with measured data from train performance tests and these have helped to demonstrate the accuracy and value of the computer-based modelling approach (see, e.g. [118]). Modelling and simulation activities are now used to support engineering design and policy decision making processes in many different areas associated with transport and electrical power systems (see, e.g. [119]-[123], [62], [103], [107]). Such simulation-based activities reflect, among other things, current developments in inter-city travel (e.g. [119], [120]), new trends in terms of battery and hydrogen power (e.g. [90]) and the use of supercapacitors for short-term energy storage (e.g. [121], [122]).

One issue that arises in the modelling and simulation of traction motor drive systems is that some of the sub-systems being considered involve fast switching of power-electronic devices while other subsystems may involve relatively slow phenomena, such as battery discharge. This presents interesting challenges in terms of simulation because of the wide range of timescales involved. In this context, methods of multi-rate simulation which have been used successfully in the modelling and simulation of drive systems for marine applications are of direct relevance (see, e.g., [124]). Established software methods available through the use of high-level development tools, such as Matlab® and Simulink®, allow use of well proven numerical routines and allow a train performance simulation to be set up and used very easily on any small computer, such as a standard laptop. Such simulators can also be used for investigation of energy saving through the adoption of improved driving strategies.

The example considered here is illustrative of practice in the United Kingdom and involves a mathematical model of a Class 390 Virgin West Coast Pendolino set, as shown in Figure 12. The data used for the model were obtained from annexes to a UK Rail Safety and Standards Board Report [125] for the 9-car version of the Pendolino. Route information is based on a gradient profile that involves level track for an initial distance and then a constant rising gradient for the remainder of the route. The route has no significant curves so that curvature resistance can be neglected. There is an overall speed restriction in terms of a line speed limit. The length of the route has been chosen to be relatively short but includes four distinct phases: (a) the initial acceleration to the maximum allowed speed; (b) a phase where the speed is limited to the maximum permitted value but where the starting point for the rising gradient is encountered (c) a coasting phase and (d) a final braking phase to bring the train to rest.

Figures 13(a)-13(d) show plots of tractive force versus time, speed versus time, power versus time and distance travelled versus time for the simulation that was carried out. The initial phase shows the tractive force at the low-speed adhesion limit of 200 kN, with the maximum power being applied after about 80s. When the speed reaches the value beyond which limiting ceases to apply, the tractive force starts to fall and follows a characteristic hyperbolic curve for constant power conditions until the line speed limit of 200 km/h is reached at about 240s. The tractive force is then reduced to a value of about 45kN in order to observe the speed limit and this condition continues until the rising gradient of one in fifty is encountered at 20 km from the start (at about 450 s) and power is then increased again to the maximum. At that point the tractive force shows a step increase and then continues to increase with time until the 25km point is reached (about 550 s) when the coasting phase starts. It is interesting to note the reduction in speed which occurs at the start of the rising gradient. When coasting starts the ,applied tractive force falls to zero and at 28km, the braking phase begins, with a constant thrust of -200kN applied. The train comes to a halt 680 s from the start, at about 29 km. The braking phase involves a constant acceleration of -0.55m/s^2 (approximately 5% g), which represents a modest brake application.

Figure 12: A Virgin Pendolino set, as used in the illustrative example of conventional and inverse simulation methods applied to train performance investigation. {Photograph D.Murray-Smith)

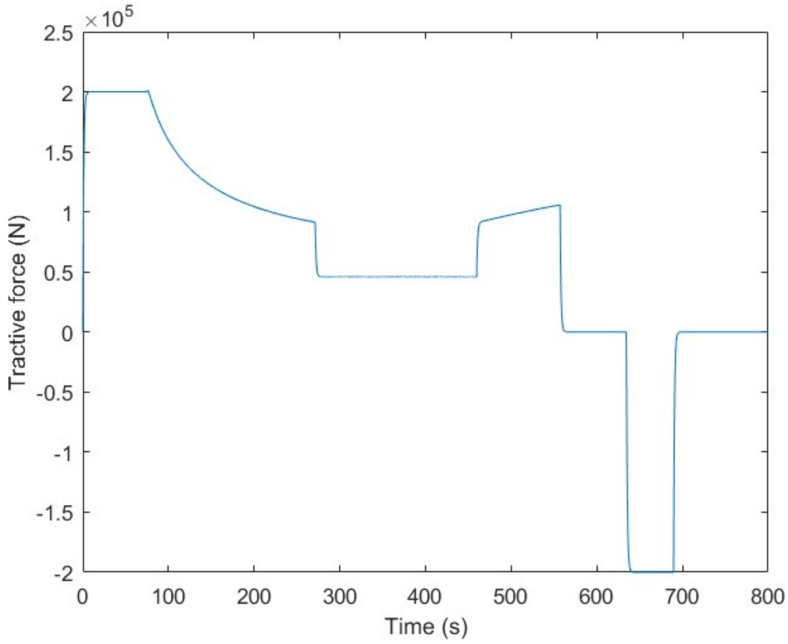

Figure 13(a): Plot of applied tractive force (N) versus time (s) used in the conventional forward simulation of the 9-car Pendolino set, as described above.

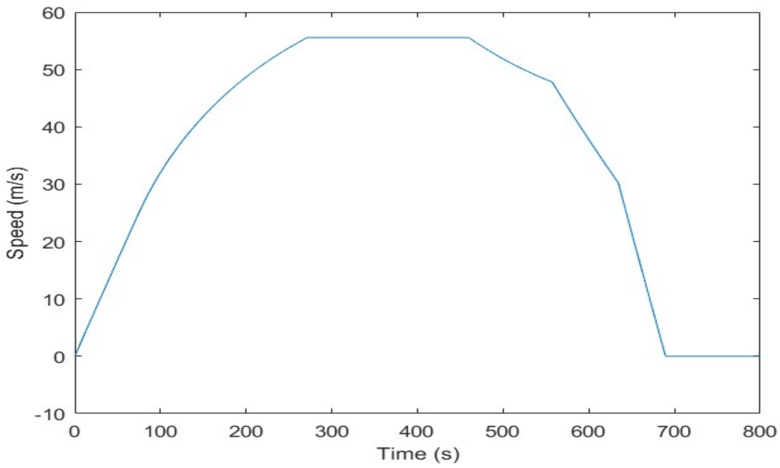

Figure 13(b): Plot of speed (m/s) versus time (s) for the Pendolino simulation.

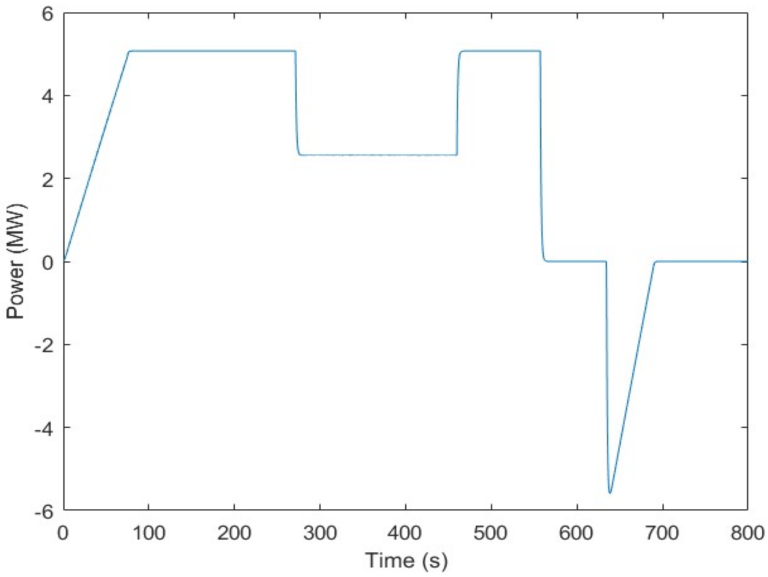

Figure 13(c): Plot of power (MW) versus time (s) for the Pendolino simulation.

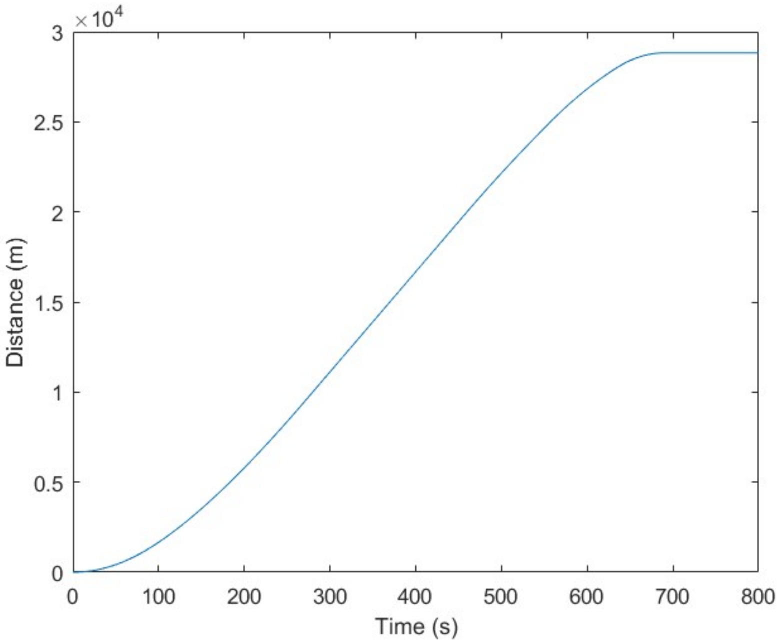

Figure 13(d): Plot of distance travelled (m) versus time (s) for the Pendolino simulation.

The use of simulation methods, as exemplified by the results in Figures 13 (a) –(d), allows the effects of factors such as train weight, available power, adhesion limits, speed restrictions and driving strategy to be investigated in a systematic fashion for any given route. The results shown are typical of what can be achieved in train performance modelling using a low-cost laptop computer and readily available computational tools such as Matlab® and Simulink®.

In recent years there has been a growth of interest in inverse simulation methods which allow chosen model input variables to be found that will generate specified model outputs. Although these techniques have been applied mainly to aeronautical and marine engineering problems one specific method of inverse simulation has also been applied to train performance simulation [126] and allows a continuous system simulation model of the kind discussed above to be used to investigate directly the variations of tractive force or power required if the journey time is increased or reduced. This is done through adjustment of the shape of the curve defining distance travelled versus journey time and this curve then becomes an input variable for the inverse simulation. This contrasts with the conventional forward simulation process where the distance time curve was obtained as an output and power or tractive force variables were used as inputs.

For example, if we consider the results obtained from the example of the 9-car Pendolino set discussed above and increase the journey time by 5% we obtain the required time history of tractive force versus time shown in Figure 14. This shows the expected increase in overall journey times for each part of the record and an overall increase in journey time from 680s to 714s. It also shows that the initial tractive force has fallen from 200×10^5 N to a value of about 180×10^5 N and it may be seen that tractive force values used in some other sections have also been reduced. It is interesting to note that there is one part of the record where the tractive force required to maintain the modified schedule is larger than it was previously. This is in the period of coasting in Figure 13(a) where the applied tractive force was zero and the speed was reduced by the effect of rising gradient and the train resistance. In Figure 14 the tractive force needed to maintain the schedule over this part of the route was no longer zero due to the initial conditions applying at the start of that section. Although a uniform increase of journey time was applied in this example, the same approach could be used more selectively to examine the effects on the tractive force or power of an increase or reduction of the time required for a specific section of the route. Similarly, the effects of changing any parameter of the train model or a constraint such as a speed restriction could be investigated very easily using this methodology.

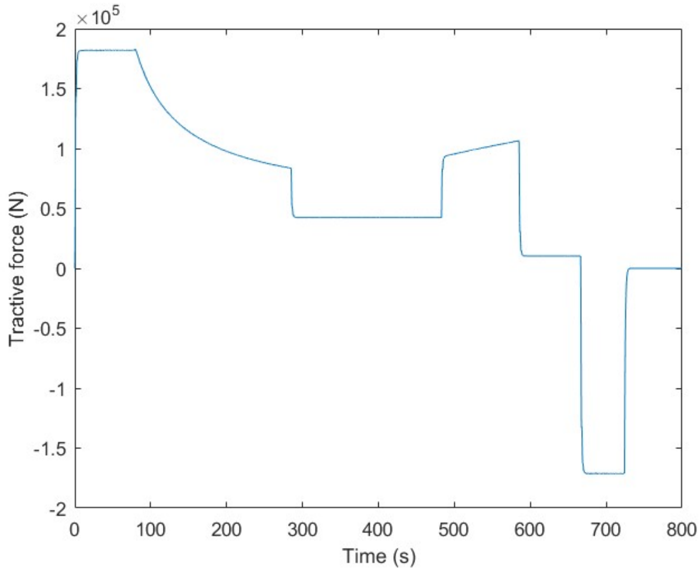

Figure 14: Plot of tractive force (N) versus time (s) found from inverse simulation with distance/time record of Figure 13(d) applied as input but with all time values increased by 5 %.

Inverse simulation methods may also be helpful in assessing the potential benefits of energy recovery from regenerative braking or energy storage, but this approach does not appear to have been used yet for such applications. However, conventional modelling and simulation studies have already proved useful in considering some of the design issues in supercapacitor-based systems with the aim of determining the optimal characteristics of a storage device in terms of overall energy efficiency and minimisation of voltage reduction at the pantograph. Although it has not yet been attempted, it is also possible that application of the inverse simulation approach could provide further insight in that type of application.

7. Tramways and light rapid transit systems

It is recognised that tramways and LRT systems involving street running and sections of reserved track are much more energy-efficient and much less polluting for mass urban transportation than buses. It has been estimated that trams use about 1/3 of the energy required for an equivalent vehicle with rubber-tyres for a similar journey.

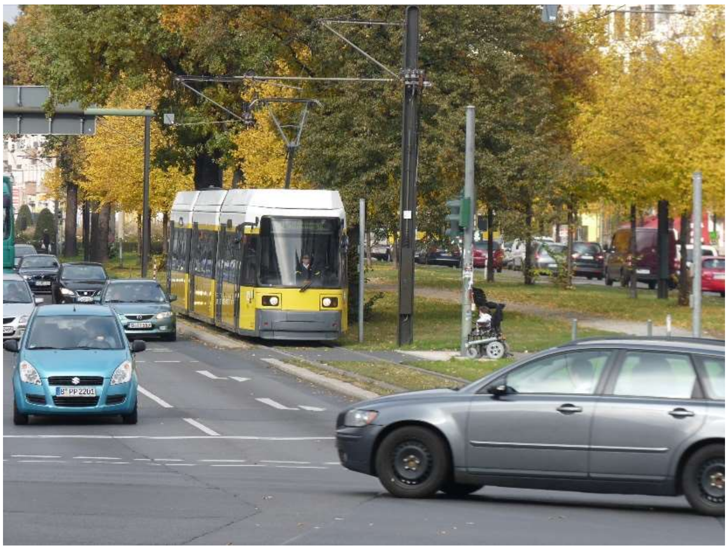

Figure 15: Modern Berlin tram near Hauptbahnhof, Berlin (Photograph: D. Murray-Smith)

The recent approval of the extension of the Edinburgh tram system to Leith and Newhaven is encouraging and it is important to note that the recently published report by the Glasgow Connectivity Commission [127] recommends substantial investment in a metro system for Glasgow and the surrounding areas. This could involve some routes having automated trains such as those in Copenhagen, with other routes based on a hybrid segregated/street-running light-rail type of solution. However, experience in other parts of Europe and in North America suggest that tramway and light-rail transport investment need not be limited to large conurbations such as Edinburgh and Glasgow. Other Scottish towns and cities could well benefit from developments of this kind and it is interesting to note that planners in North America are reporting significant growth in private investment close to new tramway and light-rail routes in several towns and cities. Also, as mentioned in Section 3.2, some modern tramway and light rapid transit systems in the USA (e.g. Oklahoma City and Milwaukee) and in some European cities, involve a mix of conventional catenary and battery power. This is highly relevant in places where there are concerns about the use of catenary in historic areas. It is also interesting to note that recent passenger surveys in the UK suggest that tramway and light rail systems are more highly rated by their users than other forms of public transport for similar journeys.

8. Discussion

As mentioned in Section 1, transport policy decisions in Scotland are influenced by geographical, historical, economic and political issues that are different in some ways from those in the remainder of the United Kingdom and other European countries. The National Transport Strategy [128] and the Strategic Transport Projects Review [129] and reports such as those produced by the Glasgow Connectivity Commission [127] and the Rail Delivery Group [46] provide useful background information, along with the annual Scottish Transport Statistics reports (e.g. [41]) and a recently announced transport review [130].

There is clearly scope for significant additional rail infrastructure improvements and further electrification in Scotland which could contribute significantly to reduced CO_2 and other emissions, as well as providing shorter journey times (see, e.g., [39], [46], [131].) Where traffic densities would not justify conventional electrification over a complete route, new possibilities are appearing through developments in hybrid rail vehicles using a combination of conventional electrical traction and batteries or hydrogen fuel cells., as discussed in Sections 3.2 and 3.3.

Geographical factors make regenerative braking highly relevant in Scotland for several reasons. Firstly, we have many routes that have significant gradients that require use of the brakes during prolonged descents. Secondly, we have many routes with local speed restrictions which again require braking effort as they are approached. In addition, suburban routes, especially in the Glasgow area, involve many intermediate stations that are often closely spaced. The acceleration phase as the train leaves one station is followed, after a relatively short time interval, by application of the brakes for the next station. As discussed in Section 3.4, regenerative braking systems are a possibility not only for conventional electric trains but also for trains that use batteries or hybrid systems involving the use of batteries together with hydrogen fuel-cells as the main power source. Developments taking place in Scotland in hydraulic systems for energy storage are also relevant, both for regenerative braking [95] and efficient provision of ancillary power in diesel trains [96].

One important point in terms of the electrical power systems and renewable energy issues is that Scotland is fortunate to have universities with engineering research groups that have proven track records in these fields. For example, the work at the Institute of Energy Systems at the University of Edinburgh includes research on adaptation and resilience in energy systems and on electro-mechanical modelling of tidal turbines. Important research is also taking place within Department of Electronic and Electrical Engineering the University of Strathclyde in the area of future power networks and smart grids and also on wind and marine energy systems. Multidisciplinary research activities are also under way within the Research Division for Systems, Power and Energy within the James Watt School of Engineering at the University of Glasgow, with work on power electronics, high-efficiency renewables, decarbonised fossil fuels and the use of system integration and computer-based simulation in the design of renewable and sustainable power systems.

Scotland has also seen some interesting trials in terms of unconventional power sources for bus, rail and ferry services. For example, battery-electric and hydrogen-powered buses are starting to appear on the streets, as discussed in Sections 3.2 and 3.3. As mentioned in Section 3.3 there has also been much recent publicity concerning the use of surplus wind and tidal energy in Orkney to produce hydrogen. A 500kW electrolysis machine has been installed on the island of Eday, with hydrogen being transhipped to Kirkwall where it is used to supply the port's hydrogen fuel cell which produces electricity for shore-to-ship power. The process is claimed to reduce pollution and is also seen as a basis for hydrogen bunkering facilities in the future. However, the technology is still expensive and the cost of electricity from a fuel cell is currently more than double that from a diesel generator. The transhipment of hydrogen by sea or land also introduces problems compared with other fuels.

As pointed out in Section 1, whenever comparisons are being made with transport developments elsewhere in the United Kingdom, the devolved administration in Scotland is an important factor. Although there are many high-profile road projects being undertaken in Scotland it must be recognised that, in contrast to the situation in England and Wales, the Scottish government has had a consistent policy and programme of rail electrification since it took over the responsibility for Scotland's railways from the U.K. Department for Transport (DfT) in 2005. The Scottish government (through Transport Scotland) remains sympathetic to further railway electrification provided it can be delivered at an affordable cost. The policy in Scotland is thus significantly different from the stop-go approach to rail electrification adopted by the UK Government and the DfT. For example, in 2007, the UK Government published its white paper "Delivering a sustainable railway" which concluded that the case for network-wide electrification had yet to be made [50]. Nevertheless, by 2009, the Government had announced the Great Western main line and North West electrification programmes and then proposals for the Midland mainline. We have, of course, seen a significant cut-back to the Midland mainline programme since then and also important changes to the Great Western electrification programme in the light of increasing costs (now likely to reach £4 million per single track km.) and delays in completion.

In contrast with the situation in England, Scotland has seen a significant increase in electrified routes in the years since 2009 (see, e.g., [130]). Projects such as the Airdrie-Bathgate-Edinburgh electrification (completed in December 2010), the Paisley Canal line (completed November 2012 the Springburn-Cumbernauld section (completed in May 2014), the Rutherglen to Whifflet line (completed in June 2014). the Edinburgh to Falkirk High and Glasgow Queen Street mainline (completed in December 2017), the group of lines involving Cumbernuld, Greenhill, Dunblane, Alloa and Polmont (completed in December 2018) and the Holytown to Midcalder via Shotts line (completed in May 2019). The total distance involved in these projects is 526 single track kilometres. Additional rail electrification in Scotland, building on these achievements, and aimed at reducing journey times to ensure that inter-city travel by train is always significantly faster than by road could be an important development. Such a policy would help increase levels of rail usage while also reducing carbon dioxide and other emissions.

Although the costs of conventional electrification in the UK appear high, the Railway Industry Association (RIA), has stated that the industry can deliver electrification at a lower cost and Its "Electrification Cost Challenge" initiative led by RIA technical director David Clarke is intended to demonstrate that electrification need not be so expensive [43]. Although the results from this investigation are not yet publicly available, it is believed that initial findings include the identification of cost saving opportunities as well as benchmarking to compare UK costs with those elsewhere. For example, RIA's benchmarks include the electrification of 1,362 single-track kilometres in Denmark and the electrification of 225 single-track kilometres between Ulm and Lindau in Germany. Costs for these are approximately £1 million per single-track kilometre. These relatively low costs appear to be a result of steady rolling programmes of electrification in both countries. Scotland has also benefitted over the past ten years in having a rolling programme of electrification and, although costs here (e.g. Cumbernauld to Springburn at £1.2 million/single-track kilometre in 2014) are slightly higher than in Germany and Denmark the costs are less than one third of those (on a basis of the figure per single track kilometre) of the Great Western electrification project. It is likely that, with the experience gained and lessons learned in recent and current electrification projects in Scotland, further cost reductions might even be possible in future projects. This depends on the skills and expertise presently available being retained and further cost reductions might even be possible in future projects, provided the momentum is maintained ([43], [45]).

One of the important features of the approach adopted in Scotland to the planning of large rail projects is that discussions involve close consultation between the ScotRail Alliance (the franchise holder and Network Rail, Scotland) and Transport Scotland, thus helping to strengthen client involvement at all stages. For example, the Scottish High-Level Output Specification (HLOS) for Control Period 6, requires Network Rail to develop "an efficient electrification technical specification optimised for Scotland that, in support of the Investment Strategy, can deliver an efficient and affordable rolling programme of electrification" [132].

The move by the UK Government and DfT in recent years away from further electrification projects has led to the choice of bi-mode electric/diesel trains for services on the Great Western and LNER franchises. Bi-mode trains will therefore be appearing on LNER services in Scotland soon and will be used in diesel mode north of Edinburgh. It is accepted that, in diesel mode, these units have a performance that is inferior to that achievable in electric mode and experience on the Great Western mainline suggests that the diesel performance in practice is inferior to that of the thirty-year old Inter-City 125 diesel units that they are intended to replace. It can also be argued very strongly that the choice of bi-mode electric/diesel trains is not consistent with the published aim of the UK Government to eliminate purely diesel trains by 2050.

Where traffic densities would not justify conventional electrification over a complete route, new possibilities are provided through the developments in hybrid rail vehicles using a combination of conventional electrical traction, hydrogen fuel cells and batteries. The developments in energy storage to recover braking energy using electrical, mechanical or hydraulic techniques are also interesting and appear to have the potential to reduce energy costs significantly on many routes. Some developments of this kind, such as the hydraulic type of energy storage system discussed in Section 3.4 could possibly be applied to existing designs of diesel trains and lead to reductions in energy costs and emissions while these remain in service.
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Trains are designed for an operating life of at least thirty years. Most road vehicles, on the other hand, have a much shorter design life. When looking at emissions with a time horizon of 2025, it is therefore reasonable to assume that trains will be much the same as today but that cars emissions will show some significant movement towards proposed targets. While organisations within the railway sector are actively involved in technical developments that could reduce train energy usage and emissions, it seems unlikely that these will have a significant impact on average values in the next six years.

The comparisons of domestic rail with other transport modes in Section 2 confirms that electric trains are at least as efficient as any other means of transport in terms of the output of CO2 expressed in grams of CO2/passenger-km. In terms of air pollution that is potentially harmful to health, electrified railways also show significant advantages over other transport modes. As electricity supplies are decarbonised further the advantages shown by rail will increase and there is a strong case for transferring passengers from road and air to electric railways to meet future energy and air quality targets. The situation for diesel trains is less clear. Many diesel trains produce more CO2/passenger-km than buses and are also responsible for emissions which can have harmful effects on health, especially in the vicinity of stations.

As the efficiency and emissions performance of cars and buses improves, under the influence of Scottish, UK and EU legislation and political targets, the difference in emissions between cars and high-performance trains will narrow and it will be increasingly difficult to make an environmental case for transferring people onto diesel-powered railways. There is a strong environmental case that further targeted rail electrification should continue to have a place on the industry's agenda as this is one of the best means of reducing CO2 and other emissions. Electric trains on the main London – Manchester and Scotland lines produce far lower CO2 emissions than the aircraft used on competitive routes and there is a good environmental case for encouraging passengers to transfer to the train. Ensuring that existing gaps in the electrified network are eliminated is particularly important to ensure that diesel traction is not required on routes that are already mostly electrified. Further development work is needed on the use of hybrid forms of traction for longer distance services involving some cross-country routes which may not justify electrification over the complete distance.

9. Conclusions

Without information about energy usage and emissions expressed in a way that allow valid comparisons to be made, there cannot be properly informed discussion about modes of transport and, within the railway sector, preferred forms of traction. However, the quantitative information currently available confirms that, at present, electric trains are superior in terms of emissions performance to other forms of transport. On the other hand, some diesel trains produce more CO_2/passenger-km than some types of bus and are also responsible for emissions that are harmful for health, especially in the vicinity of stations.

As the efficiency and emissions performance of cars and buses improves the difference in emissions between cars and trains will inevitably become smaller. Thus, in future, it may be harder to make a strong environmental case for transferring people from cars on to purely diesel-powered or bi-mode trains involving diesel traction. There is, therefore, a strong environmental case for further rail electrification and related infrastructure improvements and, within Scotland, an important additional objective should be to ensure that journey times between major centres of population by rail are less than the equivalent journey times by car. Also, on Anglo-Scottish routes electric trains produce far lower CO_2 emissions than aircraft and a strong case can therefore be made for transfer of passenger traffic to the railways provided the journey time can be made competitive with the journey time between city centres by air. For rail services on routes which may not justify electrification over the complete distance because of low traffic densities, further development work should be encouraged on hybrid forms of traction involving the use of conventional electric traction along with battery and hydrogen fuel cells for the non-electrified sections. These alternative forms of traction are also important for reducing harmful emissions in station areas and could make a significant impact if developments currently under way are successful and the necessary investment is made. The use of energy recovered from braking should also receive further attention as it could provide significant benefits in terms of emissions and energy-costs.

Bus and ferry transport have vitally important roles in many parts of Scotland and, once again, encouragement should be given to the development of battery and hydrogen fuel cell technology for these modes of transport. Encouraging developments in both areas are already taking place elsewhere.

Light rapid transit systems and tramways should be given more consideration than at present for new developments in major urban areas in Scotland as this is a highly effective way of providing public transport that is free from harmful emissions. Glasgow, for example, has an extensive network of closed railway lines and tunnels which could form the basis of a metro system that could transform transport in many areas of the city and surroundings, as proposed in the recent report of the Glasgow Connectivity Commission [127].

The expected increase in the proportion of electric vehicles on Scottish roads in the coming years means that the electrical generating and distribution network capacity needs to be re-assessed and there are still major uncertainties about the extent of the additional investment in electrical generation and distribution required. Those responsible for electrical power systems are already being challenged by the growth of renewable energy and the associated difficulties in continuing to provide a reliable electricity supply. One important factor in making predictions about the growth of electric vehicles is the extent of future government incentives and the possible introduction of new types of tariff for electricity consumers. The timing of infrastructure investment to meet the expected demand from electric vehicles must also take account the rate of change of the proportion of purely electric vehicles compared with plug-in hybrids. However, despite all the uncertainties, the expected increase in home battery charging of cars will require further investment in local distribution networks and in other parts of the supply grid. However, it is possible that, with new forms of tariff that allow both for local generation and supply of stored energy from batteries back into the network, electric vehicles could provide part of the solution by providing energy storage capacity that can help to ensure robustness and stability within the whole network. Clearly, this is a field in which further work is required. Engineering developments and new thinking about tariffs also have important implications for public transport operators considering the future use of battery-powered vehicles.

Developments taking place in autonomous vehicles are potentially very important and could transform our thinking about transport, both private and public. Although there has been much emphasis in the media on applications of autonomous systems to the private car, there is a need for those developments to be looked at carefully by public transport operators. This is potentially important in providing possible solutions to the much talked about "last mile" problem for public transport, where many potential users are deterred by the difficulties faced in going from their starting point to the nearest convenient place where public transport can be accessed and the corresponding problem at the other end of their journey.. In terms of research and development, more interaction between those working on hardware and software systems for autonomous road vehicles and those involved in the automation of rail and tramway systems is also desirable.

Finally, there is a pressing need for increased integration within our public transport systems in Scotland. The Transport Scotland website states that "…the current National Transport Strategy sets out three Key Strategic Outcomes to be used as the guiding principles at national, regional and local level when developing strategy and prioritising resources. These are:

- Improved journey times and connections, to tackle congestion and lack of integration and connections in transport
- Reduced emissions, to tackle climate change, air quality, health improvement
- Improved quality, accessibility and affordability, to give choice of public transport, better quality services and value for money or alternative to car".

All three of these Key Strategic Objectives are highly relevant to the topics considered in this report and the lack of integration highlighted in the first of those three principles is particularly important. However, since the current Transport Strategy was established in 2006 (with a refresh document in January 2016) [128], there has been little or no progress of any significance towards the creation of an integrated transport system. As has been pointed out by SAPT and other organisations in Scotland, we need to have a public transport system that provides a convenient and efficient alternative to the use of private cars. The Scottish Government and local authorities appear serious about reducing greenhouse gas emissions and other harmful pollution, but the development of a truly integrated transport system could well achieve more, in the long term, than the introduction of low-emission zones and the ending of sales of cars with internal combustion engines. There are good examples in other countries where integrated systems have reduced the need for access to cities by private cars, reduced pollution and allowed more freedom of movement for pedestrians and cyclists. However, such a change would require a major review of policy at central and local government levels and considerable investment

Freight transport issues are not discussed in detail in this document but many of the reports and papers that are included in the bibliography relate to freight as well as to passenger transport. Further rail electrification provides many potential benefits for freight and improvements in performance of diesel engines could help to reduce emissions on non-electrified routes. A detailed discussion of rail freight appears in a very recent article [133]. It interesting to note that the paper by Zenith, Møller-Holst. and Thomassen, which was presented at FCH 2JU & S2R JU "Hydrogen Train Workshop", Brussels in May 2017 [89], presents a positive view of the potential of hydrogen as an energy source. A study, carried out for one specific route in Norway, involved analysis of the costs and benefits of using conventional diesel, biodiesel, conventional electrification, battery and hydrogen-hybrid energy for freight trains and the results reported in the presentation are also of relevance for other routes.

8. Recommendations

It is recommended that SAPT should:

1.) Continue to press strongly for an integrated transport strategy for Scotland, giving a public transport system that is first choice for most journeys for most people.
2.) Press for rail infrastructure improvements (e.g. further electrification) to make inter-city train journey times in Scotland substantially less than the times by car for the same journeys.
3.) Press for new metro, light rail and tramway systems in Scottish cities.
4.) Press for the adoption of a joined-up approach to future transport and electrical power systems developments.
5.) Support more research and development relating to "smart" electrical grid systems and the effects of renewable generation modes and electric vehicle charging on the capacity and stability of the electrical supply system.
6.) Encourage developments in renewable energy and energy storage for islands and other areas far from main population centres.
7.) Review achievements and encourage research and development activities in new areas of technology (batteries, hydrogen fuel cells etc) for transport applications of all kinds and support evaluations of battery and hydrogen powered trains on appropriate routes in Scotland.
8.) Encourage academic research groups in Scottish universities working in fields such as engineering and computing science, as well as in areas that relate to planning, economics or public policy, to become more actively involved in research that relates specifically to public transport. One example of this could be interdisciplinary research on the potential impact of autonomous systems. This could be started in a small way by organising seminars in collaboration with appropriate academic groups and exploring ways in which SAPT could assist (e.g. through one-to-one discussion with members having relevant interests and experience and, possibly, modest financial support for selected students undertaking project work).
9.) Make every effort to ensure that comparisons of different transport modes are always made on an objective basis (e.g. using appropriate measures of energy and atmospheric pollution).
10.) Encourage all involved in the quantitative analysis of public transport systems to apply robust and reliable methods for system modelling and computer simulation, taking care

to ensure that models are fit-for-purpose and that appropriate steps are taken to subject models to appropriate tests (e.g. by using available real-world test data) before using them for design decisions or policy recommendations.

Footnote. This review forms part of a more extensive study concerned with public transport energy costs and emissions in the specific context of future power sources for transport in Scotland. It provides preliminary results from an ongoing study that was started in May 2018. Links shown in the reference list were successfully accessed during April or May 2019, but the availability of the relevant sources cannot be guaranteed. The author wishes to acknowledge support and assistance from members of the Scottish Association for Public Transport (SAPT) and especially from John McCormick, Tom Hart and Anthony Lennon, who all provided useful information about reports and articles of direct importance for this review. A copy of the slides used for the presentation given at the SAPT meeting in Perth on 5th April 2019 may be obtained as an e-mail attachment in pdf format on request to the author \(david.murray-smith@glasgow.ac.uk).

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