THE TRANSPORT HIERARCHY: A CROSS-MODAL STRATEGY TO DELIVER A SUSTAINABLE TRANSPORT SYSTEM.

Institution of MECHANICAL ENGINEERS

Improving the world through engineering

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Empowering new technologies and renewable fuels are key contributors to achieve sustainable transport solutions that will not only meet net-zero emission targets but will also provide significant social benefits.

Amol Gulve M.E. CEng FIMechE
IMechE COP26 Clean Transport Lead

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The urgent need to provide environmentally clean transportation of all types presents a number of very substantial and complex technological challenges. The engineering approach to this is to identify the barriers, deal with them as a number of more manageable problems – and then provide the solutions.

Dr. Ken Hart CEng MIMechE
Visiting Fellow – Aerospace Engineering
University of Hertfordshire, UK

This report has been produced by the Institution of Mechanical Engineers as part of our COP26 activities and the findings of this report were presented in the Clean Transport section of our COP26 conference on 29th October 2021.

Lead authors:

Amol Gulve M.E. CEng FIMechE
IMechE COP26 Clean Transport Lead

Ken Hart
Visiting Fellow – Aerospace Engineering
University of Hertfordshire

Iain Flynn
Fellow IMechE, Rail Manager & Engineer

Prof. Reza Ziarati, PhD
Chairman, Center for Factories of the Future

Thomas Moore
Principal Systems Engineer, TE Connectivity

Published October 2021
Design: Karoshi

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Executive summary

This report addresses the engineering challenges which must be overcome to reduce the transport sector's greenhouse gas emissions (GHG) and identifies practical solutions in a UK context.

The objective is to support the public, government agencies and private sector bodies in their ambition to meet the target of net-zero emissions. To achieve this, the top three priorities of the Transport Hierarchy are considered as a framework.

The Transport Hierarchy prioritises maximising demand reduction, system efficiency/modal shift, and energy efficiency/renewable resources as critical priorities which can be applied to various transport modes. The policy statement discusses the three priorities and focuses more in depth on priority three for improved transport efficiency using renewable resources. Priority three is discussed in detail for each transport sector and various alternative solutions are recommended.

The road to net-zero emissions by 2050 is a clear mandate. However, any cost-effective and proven technology advancements and operational changes that can significantly reduce emissions from the transport sector, as opposed to eliminating them completely, should still be pursued and implemented, especially if they can be achieved in shorter timescales. The policy statement provides recommendations and identifies technology skills/gap requirements that would need to be addressed to introduce technically and economically feasible solutions to reduce greenhouse gas emissions to near zero.

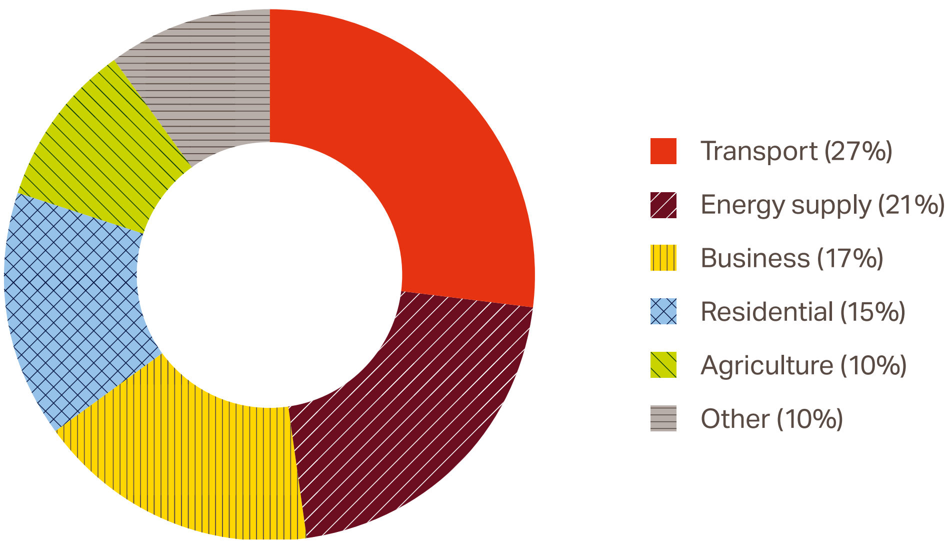
Introduction

In 2019, 454.8 million tonnes (CO_2) of greenhouse gas emissions (GHG) were emitted in the UK, a 7% decline from 485.5 million tonnes in 2016. **Figure 1** shows the breakdown of the GHG emissions for each sector. Transport became the largest contributor in 2016, and in 2019 its increased emissions were responsible for 27% of the UK GHG emissions. In 2019 91% of transport emissions were from road vehicles[1].

There have been improvements in road vehicle fuel efficiencies over the last 30 years, but these have been more than offset by the growth in mileage to 356.5 billion in 2019, while cars have continued to get bigger and heavier due to the popularity of sports utility vehicles.[2]

The National Travel Survey indicates that in 2019 (**Figure 2**), the modal share of car use for UK land travel amounted to 77% in distance travelled. The equivalent figures for bus and rail transport are 4% and 10% respectively. Van and HGV freight traffic in the UK has also grown steadily such that, in 2019, 79% of all domestic freight was moved by road and only 8% by rail.[3]

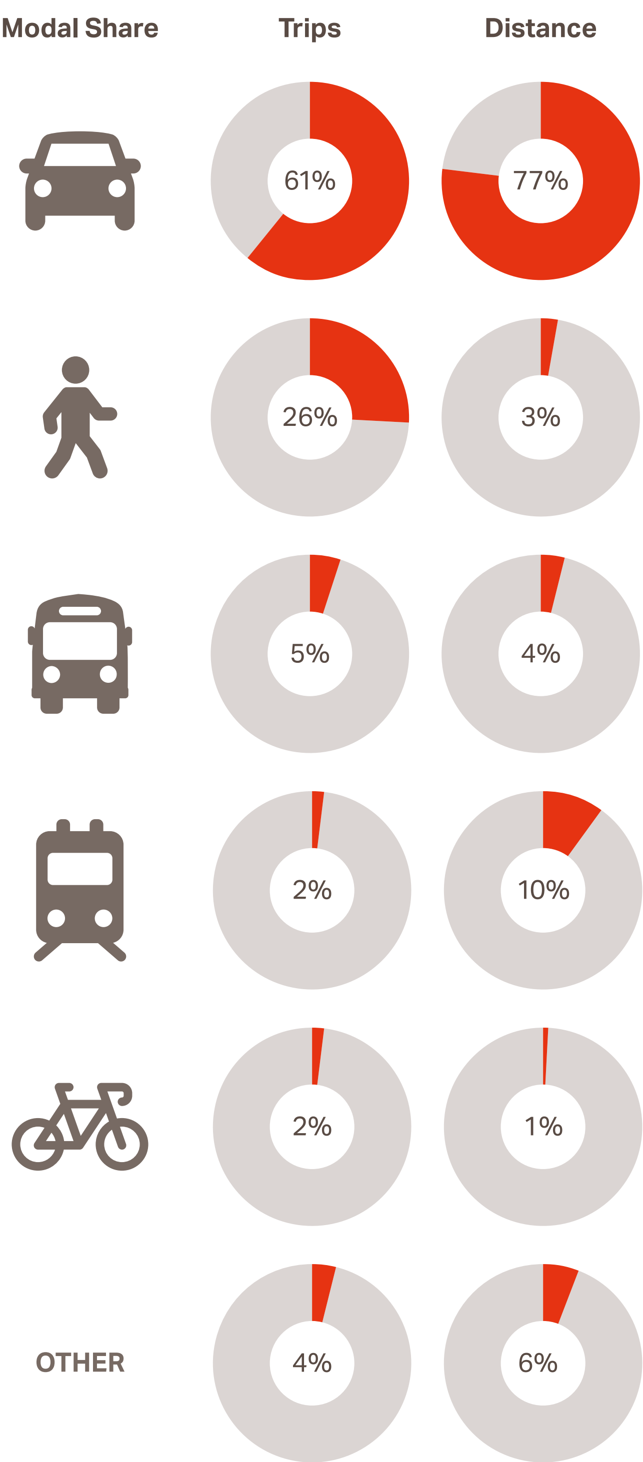
Figure 1: Territorial UK greenhouse gas emissions by sector, 2019 (%)



The UK is in a comparatively fortunate position compared to other countries. Its size, high population density, and dense legacy Victorian (but modernised and expanded) rail infrastructure coupled with its rapidly decarbonising electrical power supply system provide it with an ideal existing, under-utilised, carbon-free transport infrastructure. This paper develops the theme of modal shift from road and aviation to electrified rail as a key solution to reducing UK GHG transport emissions. As the government observes in its May 2021 report on the future of railways in Great Britain, rail is 'the only form of transport currently capable of moving both people and heavy goods in a zero-carbon way', and can form the 'backbone of a cleaner, greener, public transport network'.[4] The Institution agrees and strongly supports this vision. It is time to turn it, through engineering and policy measures, into reality. In addition, the significant modal shift to rail is only possible if there is significant increase in rail capacity, hence the need for HS2 and its extensions.

A modal shift of 4% of passengers and freight to rail would save more GHG emissions than the rail sector's current total, but this would require a 35% increase in rail capacity[5]. However, HS2 (if its planned extensions are built), Northern Powerhouse Rail and Crossrail significantly increase rail capacity, and much of the network, for most hours in the week, in most parts of the country have surplus capacity, particularly in the aftermath of the Covid-19 pandemic.

Figure 2: National travel survey



In 2018, a consultation on the Future of UK Aviation emphasised the importance of aviation to the success of the UK economy through its contribution of at least £22 billion and more than 230,000 jobs[6]. In that same year aviation was responsible for 7% of the UK's GHG emissions[7]. According to data provided by the Global Aviation Carbon Assessment (GACA) model, it is estimated that in 2019, global commercial passenger and freight air transport contributed 920 million tonnes of CO_2 emissions; 85% of this was from passenger flights[8]. 80% of aviation emissions are from flights over 1,500km where there are no practical transport alternatives[9].

This global air transport contribution to CO_2 emissions amounted to 2.6% of the ~36 Gigatonnes of CO_2 emitted globally from all sources in 2019. However, there is widespread recognition that worldwide demand for air transport will increase significantly over the next 30 years as passenger and cargo traffic is directly related to economic prosperity, which is growing rapidly, especially in China, India and other Asian economies[10]. This increase in air transport will lead to increased GHG emissions unless more radical, additional technology innovations and operational changes are implemented.

The overall contribution by aviation to climate change must also take into consideration factors beyond just CO_2 emissions. NOx emissions affect the amount of ozone in the atmosphere and water emissions, at certain altitudes and atmospheric conditions, form contrails that can stimulate the formation of cirrus clouds. These clouds reduce the amount of thermal radiation released into space by the atmosphere and thereby upset the equilibrium with the radiative energy received from the sun, resulting in atmospheric warming. This radiative forcing raises the overall effect of aviation emissions on climate change significantly above that based on CO_2 emissions alone.

In 2018, worldwide GHG emissions from fishing and domestic/international shipping amounted to 1,076 million tonnes, 2.9% of the global total. This is expected to rise to 1,278 million tonnes by 2030. Maritime freight accounted for a further 8% in 2019 (14 MTCO2e). The share of shipping emissions in global anthropogenic emissions has increased from 2.8% in 2012 to 2.9% in 2018.[11]


3

Transport hierarchy

The Institution of Mechanical Engineers (IMechE) proposed in 2013 a hierarchy of measures as shown in **Figure 3** which can be used to achieve coherent planning and engineering of transport systems to reduce emissions[12].

Figure 3: Transport hierarchy[12]

MORE SUSTAINABLE

Priority 1	Reduction in demand for transportation	Manage the reasons why transport is needed and the context in which transport demand is derived, to deliver the same access to services and activities with less powered/ motorised transport.	Minimising demand is the first priority, in ways that maintain or improve quality of life and access to essential goods, services and activities such as: • remote working • reduced travel distances • reduced freight demand • reduced freight transport distances
Priority 2	System efficiency – modal shift	Enable the choice of transport modes with the lowest environmental impacts, and enable easier changes between modes.	Focusing on making energy transformation more efficient. Less fuel and focussing on least CO_2 emission followed by reducing other harmful emissions such as NOx, SOx and so forth which includes: • shifting mode from cars to walking and cycling • increased use of public transport – buses, trams and trains • increased system efficiency by switching to battery for electric car, vans, buses and trucks
Priority 3	Improved transport vehicle energy efficiency and use of renewable fuels	Increase all efficiency measures of transport modes and their use, particularly in terms of gCO_2/km for passengers and gCO_2/tkm for freight.	Identify the opportunities for the development and application of new technologies which produce efficiency improvements to reduce the energy required for transport. It also examines the scope and feasibility of using an increased quantity of renewable sustainable resources to provide this energy rather than continuing to rely on the burning of fossil fuels which generates large quantities of carbon emissions.

LESS SUSTAINABLE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JUMP
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MARATHON
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Priority 1: Reduction in demand for transportation

Maximising demand reduction is the first priority, in ways that maintain or improve quality of life and access to essential goods, services and activities, by eliminating waste – cutting journeys that serve no real purpose and shortening journey distances while achieving the same objective.

Opportunities for demand reduction includes:

Reducing the need for travel: A new study conducted by Carbon Trust on behalf of the Vodafone Institute for Society and Communication provides recommendations in which businesses and governments can plan and incentivise hybrid working to accelerate decarbonisation, while also addressing the challenges changes may pose to cities, transport, local economies, and infrastructure suppliers.[13]

Reducing demand for vehicle usage: Passenger car journeys currently account for 77% of vehicle miles travelled and 61% of emissions in the UK. Reducing demand for car travel offers significant potential for reducing emissions, with associated benefits for congestion, air quality and health.

Societal and Technological changes: This includes factors such as increased home-working, increased use of IT and technology and continuing trends towards greater use of internet shopping. There is a potential for a 1–4% reduction in total car mileage by 2030, and between 4% and 12% by 2050, from societal behaviour change and technology. These are based on the latest academic evidence and CCC analysis of travel data.[14]

Increase in car occupancy: Shared mobility (eg shared cars and shared trips) can also reduce car travel demand. There is scope for average car occupancy to increase from 1.6 today to up to 1.7 by 2030 and up to 1.9 by 2050. High-occupancy vehicle lanes are one example of local interventions that can encourage car-sharing. Studies have shown these to reduce vehicle trips by between 4% and 30% in certain cases

Modal shift to active travel: Walking trips have increased in recent years, cycling has been relatively flat, while trips taken by bus have declined. There is a potential for 5–7% of car journeys to be shifted to walking and cycling (including e-bikes) by 2030, rising to 9–14% by 2050. In 2019, 7% of car journeys were less than 1 mile, while a further 17% were between 1 and 2 miles.[13] A recent study based in Cardiff concluded that walking or cycling could realistically displace around 41% of car journeys of less than 3 miles. E-bikes offer considerably greater range, so if they become widespread then there may be potential to shift a greater number of journeys away from cars. It is possible that this could enable e-bikes to displace car journeys of up to 9 miles (in contrast to a maximum of 4 miles assumed for conventional bicycles).[14]

Priority 2: System efficiency – modal shift

Across the UK, 68% of workers typically travelled to work by car as shown in **Figure 4**, though this varied by region with London having a substantially lower proportion (27%). Rail offers a significant environmental benefit over other transport modes and can be a key contributor to low carbon economic growth.

Modal shift: public transport

There is scope to switch car journeys onto appropriate public transport such as buses and rails that account for 5% and 4% of all journeys. A recent study found that public transport usage within major cities could rise to 6% by 2030. The UK Climate Assembly recommended a reduction in the amount we use cars by 2–5% per decade, relative to today's levels. Increased provision of bus lanes and high-occupancy vehicle lanes can incentivise switching to public transport and shared mobility by making these easier and quicker than individual transport[14]. In addition to reducing CO_2 emissions, the modal shift from cars to public transport will also result in less congestion, noise level and pollution in urban areas.

Modal shift: road to rail

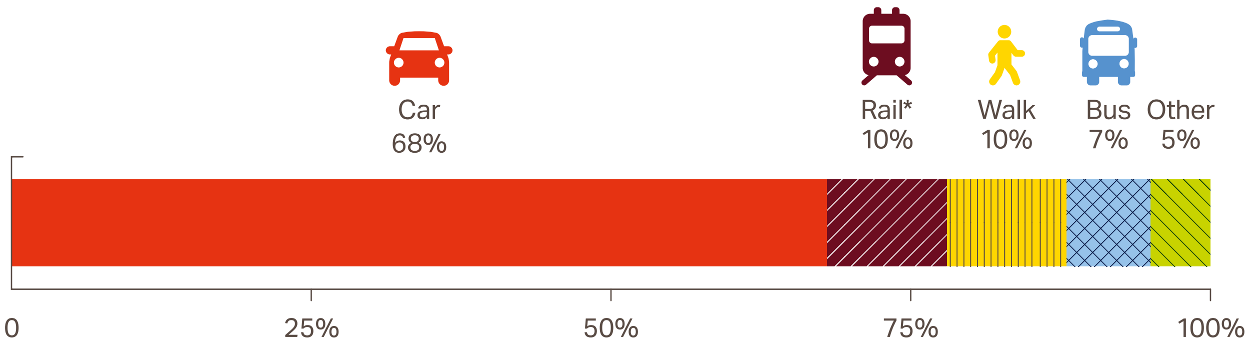
Electric trains, when powered directly from a renewable source, provide the only form of zero emission transport society has, or is likely to have in the foreseeable future, capable of:

- heavy haul, long-distance freight
- high-speed, long-distance passenger
- mass transit in cities

This is because of the unique characteristic of electric trains: they do not depend on on-board energy storage and instead can use power generated remotely. Train braking energy can be returned to the distribution system for reuse. In most transport modes this is wasted as friction (although road vehicles with batteries can also capture some for reuse). Directly powered electric trains are freed from the intrinsic constraints of cost, safety, weight, volume, and energy inefficiency introduced by on-board energy storage. These arise from the underlying physics of transport and energy storage rather than a lack of technology. Energy storage, in the form of better batteries and perhaps hydrogen or other fuels produced using renewable energy, will improve over time but the Institution does not believe that improvements will occur quickly enough, if ever, to supplant the fundamental usefulness of electric trains as an emission-free form of transport.

Figure 4: Usual method of travel to work, UK, 2018[15]

*Rail includes travel by National Rail, underground, light railway systems and trams



Even if non-electric traction is used, or the electricity used is generated using fossil fuels, rail has an energy advantage over all other transport modes, because of the low rolling-resistance of steel wheel on steel rail. The UIC have calculated that, globally, rail carries around 9% of freight and passenger traffic by any transport mode, while using only 2.2% of the energy consumed by the transport sector. This balance is even more favourable in the UK's case. Railways made up 1.4% of the UK's transport CO_2 emissions in 2018 but provided 10% of all passenger miles. Rail accounts for 0.5% of the UK's total CO_2 emissions[1]. This would drop to zero if the rail system were fully electrified and the electric power generation system fully decarbonised – goals that, while ambitious, are economically realisable using current technologies.

Although only 38% of UK's mainline railways are electrified by route km, the proportion of rail passenger kms (including London Underground) using electric traction is around 80% because electric trains are overwhelmingly used on busier routes. Electrifying the rest of the network is the key to decarbonising UK rail, and through modal shift to reducing GHG emissions from the entire transport sector.

Rail excels economically and environmentally when its high capacity is fully utilised. While some parts of the network have reached full capacity in recent years, this has generally only been in and around London and some other cities at peak hours. HS2 (if its extensions are built) and Crossrail, and the digitisation of train control systems, as well as many capacity upgrades schemes all around the country, are already underway to address key national capacity constraints. On routes such as Thameslink, and soon on Crossrail, the combination of existing electrification and train control technologies will enable 24 trains per hour (tph) in each direction, with each train capable of carrying over 1000 passengers. Much of London Underground can deliver over 30 tph and the Victoria Line 36tph. Surplus rail capacity exists across much of the country, for much of the time.

This has been exacerbated by Covid 19. Once HS2 is open, and providing its planned extensions are built, the existing East, West and Midland Main Lines will provide additional north-south freight capacity. All are fully electrified already except for a northern section of the Midland Main Line.

Objections to (for example) HS2 and its extensions have been raised around the 'embedded CO_2' involved in its construction compared to benefits in operation. This needs to be kept in perspective. The official appraisals have been legally obliged to assume the 'reasonable worst foreseeable' case, for example that rail fares continue to rise while air and road costs fall, and other analyses taking into account greater modal shift and better construction techniques reach different conclusions[16]. Moreover the latest construction CO_2 equivalent emission estimates for HS2 Phase 1 (5.7–6.1m tonnes)[17] and Phase 2a (1.5m tonnes)[18], or around 7.5m tonnes in total, should be compared with 11.3m tonnes for the construction of the proposed Heathrow Third Runway[19]. The construction of these 175 route miles, which will provide a carbon emission benefit for hundreds of years, especially when electricity supply is fully decarbonised, has a carbon footprint only 50% greater than the effect of freezing fuel duties since 2010, and for each year of construction would have a climate impact of less than 1% of UK aviation emissions or 0.5% of road emissions[16].

Virtually all of London's rail services are electric, and TfL has committed to decarbonise its bus system (all new buses will now be zero-emission[20]). London's already rich rail and extensive bus system, and increasingly good walking and cycling environment, will be further enhanced by Crossrail, which add about 10% to rail capacity in the city in 2022. On 25 October 2021 the city's Ultra Low Emission Zone covering a population of 3.8m came into effect. London is moving towards zero-carbon transport.

The Channel Tunnel has always operated far beneath its design capacity. It is capable of carrying 24 tph (30tph would be possible with a new signalling system) and was designed to carry around 10m tonnes of rail freight annually, whereas immediately pre Covid it was running at around 15 trains per hour, of which many were car and freight shuttles which limit capacity. In 2017 it carried HGVs amounting to 20m tonnes of freight per year whereas only 1m tonnes of rail freight was carried[21,22].

A fundamental economic characteristic of rail is its extremely high fixed but low marginal costs. If seats are being filled on otherwise half-full trains, or container trains are fully rather than partially loaded, the marginal cost of the additional traffic is extremely low. Furthermore, running more trains on existing infrastructure has a low additional cost if capacity exists. Assuming the country is committed under all circumstances to maintaining the existing rail network, with the associated fixed costs, there therefore exists a great deal of additional low emission transport capacity already available at a low cost. This surplus rail capacity may not always exist at times of traditional high demand, though travel patterns are changing due to Covid. A future low-emission transport strategy for Britain should focus on making the most of this additional very low-cost unused rail capacity.

Rail (pre-Covid) accounted for only around 10% of UK passenger km (and 8% of tonne km for freight) with most traffic being carried by cars and HGVs powered by fossil-fuel internal combustion engines. This is despite rail passenger demand having doubled over the last twenty years. A radical short-medium term programme of shifting road (and domestic aviation) passenger and freight traffic onto rail would give immediate emission reductions. There would be further benefits such as reduced congestion and cleaner cities with fewer road traffic accidents. As has been shown in London some combination of efficient high-frequency service provision, easy modern ticketing, reasonable fares, and road pricing could accomplish modal shift from road (and domestic aviation) to rail quickly and at minimal cost. If this programme were successful, longer term plans would be based on existing schemes to remove rail capacity bottlenecks and rolling electrification of non-electrified tracks. More rail and less road traffic in the long-term would also leave more zero-carbon electricity for non-transport purposes such as space heating, since per passenger km or tonne km rail uses less energy than battery powered road vehicles.

Modal shift from road to rail will also demand more integrated planning at the network level to accommodate freight and passenger trains (whose differing speeds can reduce overall network capacity) on the same infrastructure, and to balance the growing demand for weekend leisure travel with infrastructure maintenance requirements. This was difficult under the previous disaggregated industry structure but is much more likely to happen under the government's recently announced plan for Great British Railways[4].

Modal shift: air to rail

GB city-centre to city-centre journey times by rail and air travel are sufficiently comparable to be competitive up to ~350 miles (or even longer with the faster speeds afforded when HS2 is part of the route between city-pairs). There could also be a greater public interest in shifting from air to rail for journeys to major European cities if the Channel Tunnel is used more effectively with sleeper and regional trains introduced as was originally intended. Better integration of rail and air travel through improved airport rail links and combined ticketing would also be of benefit to emission reduction.

The prime current barrier to a modal shift from air (or road) to rail is user rejection of expensive long-distance rail fares or freight rates. This could be addressed by revisions to government financing of the air and rail transport sectors which consider emissions taxation and hidden subsidies. The capacity of Britain's long-distance mainlines, almost all of which are electrified, have been progressively increased over recent decades, and HS2 will add substantially to north-south capacity. ERTMS ('digital railway') signalling will further add to network capacity. To make rail an even more attractive choice than air, passengers need to have a wider range of walk-up prices and have a greater chance of getting a seat, with demand spread more evenly throughout the day. A new fares system enabling better products would make this achievable rather than aspirational.

Priority 3: Improved transport vehicle energy efficiency and use of renewable fuels

Road transport

In addition to its large contribution to carbon emissions and climate change, road transport emissions in towns and cities are the biggest contributor to localised pollution and health issues.

Road transport is a major source of air pollutants as shown in **Figure 5**, with major contributions coming from passenger cars (55%) and HGVs and Vans around 16%[23].

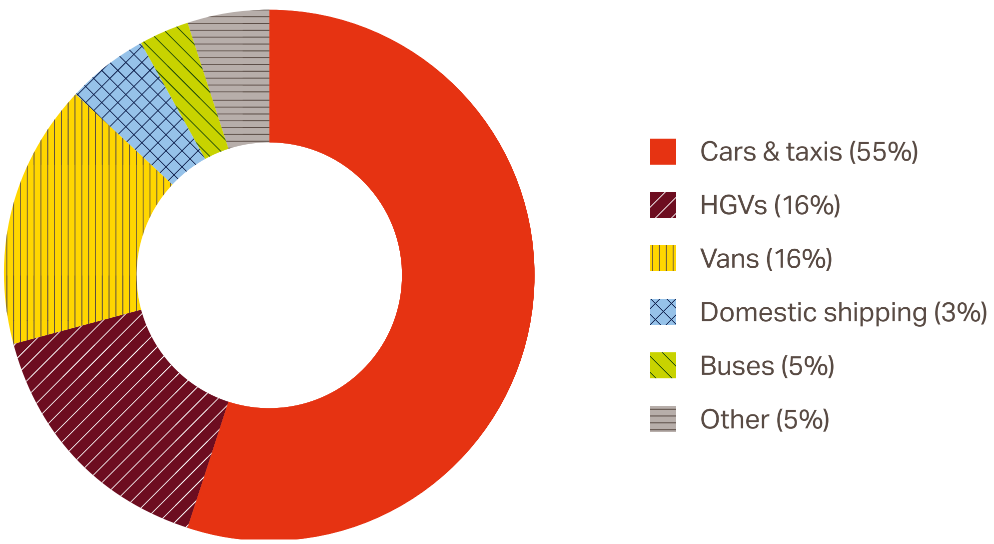
Electromobility in urban public transport is developing very fast, becoming a promising pro-ecological way to make cities more sustainable[24]. More established technology is the use of electrification either by charging a battery from a shore supply or an overhead-line. Trolley buses are able operate under an over-headline within urbanised areas and can make shorter journeys using batteries recharged in motion while powered by an overhead line.

An emerging technology is hydrogen fuel cell buses[25], there are numerous examples of their trial and use across the world. Aberdeen hydrogen bus pilot concluded that electrolyser plants are a mature, scalable, and reliable technology (99.9% over 5 years); prices will continue to decrease and offer grid balancing opportunities[26].

Large, long-haul HGVs are particularly challenging to decarbonise. Vehicles are in use for long periods of the day and require high levels of power and energy for their operations. Larger articulated vehicles are driven significantly further than rigid vehicles. The average articulated HGV travels more than 400km per day, mostly at high speed[23].

The key near-term options for fully decarbonising HGVs are battery electric vehicles (BEVs) and hydrogen fuel cell (FCVs). BEVs are highly energy efficient and have zero tailpipe emissions. They also have substantially lower greenhouse gas emissions than conventional petrol and diesel vehicles, even when taking into account the electricity source and the electricity used for battery production.

Figure 5: Domestic UK GHG emissions by mode, 2019



Assuming the current UK energy mix, battery electric vehicles produce the lowest greenhouse gas emissions of all the energy sources and fuels assessed, irrespective of vehicle type and operation. For example, a battery electric vehicle is estimated to have greenhouse gas emissions around 66% lower than a petrol car and 60% lower than a diesel car.[23]

Hydrogen fuel cell HGVs are fitted with an electric powertrain as show in **Figure 6**. Energy is stored on board the vehicles as hydrogen, which is converted to electricity in fuel cells. There are no tail pipe emissions – the only by-products are warm air and water vapour. The vehicle will also have a battery to produce additional power when needed, and to recuperate electrical energy from braking. Vehicles will need to refuel at hydrogen refuelling stations.[23]

Apart from the rapid development of battery technology, hydrogen is a good complementary option as an alternative fuel for long-distance transport. MAN Trucks for Long Haul transport is testing both the use of a fuel cell and an H2 combustion engine.

When in use, fuel cells do not cause any climate-damaging emissions, as they only emit water vapor. In addition, it provides a range of approximately 800 km for long-distance truck transport with a high payload capability.[27]

Diesel-powered vehicles like dump trucks and load, haul, dump (LHD) loaders emit massive amounts of harmful gasses, including carbon dioxide, nitrogen dioxide, carbon monoxide, and others. Miners are exposed to such emissions for a long time because of long shifts, and therefore, experience several adverse health effects, including an effect on sensory perceptions, severe respiratory irritation, emphysema, and chronic bronchitis. The emissions also increase the heat generated in underground mines; according to the International Council on Mining and Metals (ICMM), 40% of an underground mine's energy outlay is spent on operating ventilation systems to remove pollutants and heat from mining tunnels. Such factors increase the overall operational cost of the mine while decreasing their production efficiency.

Figure 6: Hydrogen fuel cell vehicle powertrain

The deployment of electric mining vehicles, including electric dump trucks and electric LHD loaders, offers enhanced energy efficiency, reduced harmful emissions and heat dissipation, lower maintenance time, decreased ventilation requirements, reduced operating costs, improved working environment (air quality), mitigated the environmental impact, and improved mining profit. According to Mobile Equipment Design and Automation Technology, the replacement of diesel-powered vehicles with electric mining vehicles can reduce approximately 7,500 tons of CO_2 and save 3 million litres of diesel fuel and 1 million litres of propane every year.

Growing demand for freight transport will make measures to improve lorry efficiency insufficient to achieve the climate targets. In order to meet the objective of decarbonising HGVs by 2050, it is recommended that the sales of new urban and regional delivery diesel lorries will need to be phased out by 2035 at the latest – a target that can be achieved through BEVs and Hydrogen FCVs. For long-haul trucks, sales of new diesel lorries will need to be phased out before 2040.[28]

In the meantime, because vehicles with internal combustion engines will still be on the road for many decades, we should take a holistic approach to road transport decarbonisation by supporting the development and deployment of low carbon, sustainable biofuels and synthetic fuels.

Rail transport

Directly powered electric trains

Key UK rail industry bodies, such as the Rail Industry Association (RIA) and Network Rail, have published many papers on rail decarbonisation in recent years, and the Institution and its members have supported this effort directly and by running seminars and providing underpinning research. The most recent, and most thorough, is Network Rail's Traction Decarbonisation Network Strategy[29]. The Institution supports Network Rail's analysis but can go further in emphasising the engineering truth: direct use of electricity in trains is the only feasible zero-emission form of transport we have, or are likely to have by 2050, capable of providing long-distance, high-speed passenger services; long-distance, bulk freight; or mass transit in cities. Hydrogen, sustainable fuels, and batteries can each play a role in some transport applications (including rail) but each has significant drawbacks and none can match the utility of this existing, well established form of transport.

There is broad consensus in the rail industry, supported by the Institution, borne of a deep understanding of the underlying engineering and economics of rail. This briefing considers a more radical approach, and the consensus is that:

- Electric trains directly powered by renewable electricity are emission-free and are always the preferred solution
- Because of the low rolling resistance of steel wheel on steel rail, and because electric trains can recover energy on braking, rail is energy-efficient compared to other mass or bulk transport modes, provided trains are well loaded
- A strategic programme of rolling electrification would sharply reduce the costs of electrifying the remainder of the network (most main lines and many others are already electrified)
- Batteries have a role when combined with direct electrification (battery/electric bi-modes) or added to primarily diesel-powered trains to recapture braking energy (hybrids)
- Hydrogen is the only net zero option for high powered transport that cannot be directly powered by electricity. However, in rail it has many drawbacks though could be used for lightly loaded services
- Hydrogen, batteries, or sustainable fuels may provide transitional solutions but should not be regarded as an alternative to full network electrification

Diesel/battery bi-mode trains, as with the recent Intercity Express Trains, are not a supported solution. The power of electric trains is limited only by the current they can draw from the overhead wires. By contrast, self-powered trains must store energy and generate their own on-board power. This takes a great deal of space, which is limited on a train, and has a significant weight penalty. In all forms of transport weight translates directly into lower energy efficiency. Self-powered trains, whether diesel, battery, or hydrogen, cannot match an electric train's power. For example, a 9-coach bi-mode train delivers 4.5 MW in electric mode compared with 3.5 MW in diesel mode. This gives faster journey times and better network utilisation.

Electric trains are thus the only zero-carbon form of transport suitable for high-volume, high-speed commuter services which require high acceleration and capacity. They are lighter, have lower maintenance costs and are extremely energy efficient since there is no on-board energy storage or conversion, and braking is regenerative. Electric trains are also cheaper than any rail alternative once electrification is in place. Trains powered in other ways also require energy storage and conversion systems. The same logic also applies to other transport applications requiring high power outputs over long periods of time: heavy, long-haul freight and high speed, long-distance passenger services.

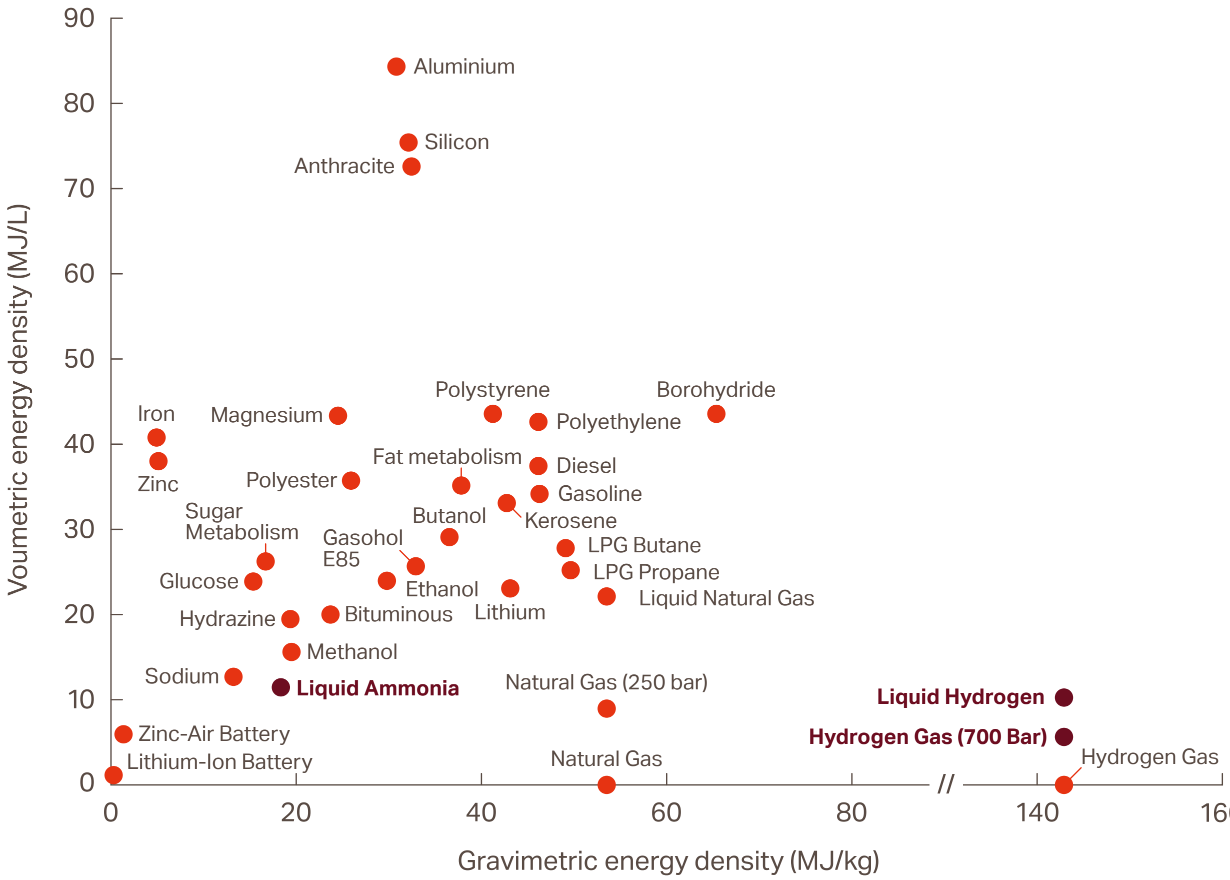
Alternatives to directly powered electric trains

On lightly used non-electrified lines there is a transitional role for battery and hydrogen passenger trains. Network Rail have estimated that this might be 8% for hydrogen and 5% for battery on the currently unelectrified network[29]. However, each has significant limitations. For the same volume, a diesel tank can store 36 times the energy of a traction battery pack or 8 times the energy of hydrogen in a heavy pressure vessel at around 350 times atmospheric pressure.

Furthermore, hydrogen trains are intrinsically inefficient, requiring 2½ times more electricity than conventional electric trains for the same amount of traction as explained in the IMechE's January 2019 report 'The Future for Hydrogen Trains in the UK'.[30]. The volumetric energy density of hydrogen (**Figure 7**), even when liquefied and stored at very high pressures and low temperatures, is extremely low, and only a quarter that of diesel. This makes its use on rail intrinsically problematic since space is at a premium. Directly-powered electric trains are unique amongst mainstream public transport modes in not needing to carry stored energy.

The energy density of even the best batteries is many times less even than hydrogen, limiting battery use to low-power applications and thus ruling them out for most rail applications. The role batteries can play is to extend the reach of electric trains onto non-electrified sections of the network.

Figure 7: Energy density of fuels[31]



The rail industry is able usefully to 'piggy-back' off hydrogen (and battery) developments in other transport modes and there is a limited value in more trials and demonstrators. As better batteries and sources of green hydrogen become available the industry will be able to utilise them.

Bi-mode (electric and diesel) trains offer through journeys to destinations beyond the electrified network. However, when in diesel mode they have high GHG emissions and even in electric mode are burdened with the extra energy cost of carrying around engines and fuel. They are thus not an industry-preferred solution. In high-power applications, for space and weight reasons, it is not feasible to replace diesel power packs with hydrogen or battery traction, although it is accepted that these technologies will improve. Even if they do, direct electrification would still be more efficient, with less energy lost in conversion processes. The only zero-carbon option for high-speed passenger, high-density urban passenger, and bulk freight: traffic over longer distances is direct electrification, and this is likely always to be the case. Until then bi-mode trains can usefully support a rolling electrification programme. However, these should be Direct Electric/Battery, with trains charging batteries while on electrified routes but able to proceed beyond the electrified network.

Existing diesel trains are energy-efficient compared to HGVs, buses or cars provided they are well loaded. Further technological improvements, for example the limited use of batteries to recapture and store energy on braking, improvements in engines, or the use of sustainable fuels, will continue to reduce diesel carbon emissions per passenger-km or tonne-km for freight. Rail could make full use of sustainable diesel fuel alternatives if and when they become widely available, but even if this happened such fuels would be better utilised in transport modes which are less easy or impossible to electrify. For rail, however, diesel is recognised as being at a strategic dead-end and in future the UK industry will only buy diesel engine products for limited niche applications.

Delivering more electrification

Electrification requires significant capital investment which must be delivered affordably. The rail industry recognises that Government was right to act in response to the unacceptable cost and time overruns of the Great Western Electrification Programme (GWEP) in the 2010s. However, since then, other electrification programmes have run to time and cost and electrification costs (per single track km) have fallen sharply due to better risk assessment and application of engineering standards. Improving technology promises to reduce the costs of new electrification further. For example, there are now new techniques which sharply reduce the need to raise bridges or lower track. RIA's 'Electrification Cost Challenge' report details these improvements and demonstrates how electrification is now being delivered for between 33%–50% of the cost of GWEP.[32]

This report shows that the 'stop-go' nature of electrification projects was an underlying cause of the high cost of the GWEP. Electrification is a specialist activity requiring its own design skills, specific equipment and an experienced supply chain. The UK, unlike countries such as Germany, has historically had an intermittent electrification programme. Each time it halts, expertise is permanently lost and must be re-established. Lessons must be relearnt. Supply chains must be recreated. Transport Scotland have shown what can be achieved through a rolling programme of electrification and is on-target to decarbonise its railways by 2035[33].

There is an overwhelming argument for a strategic rail electrification rolling programme starting with previously halted and small-scale infill electrification schemes. These would give a disproportionate benefit by allowing longer through journeys with electric traction, especially for freight traffic. Following this a thorough review could set medium and long-term priorities and develop plans such as creating a highly capable electric rail network connecting northern cities and conurbations especially in east-west corridors. Transitional technologies would be part of this plan. The industry's priorities are already well-developed, for instance in Network Rail's Traction Decarbonisation Network Strategy[29].

In summary, the key is network electrification. Cost-effective delivery will require a structured rolling programme which begin soon. Major changes to the rolling stock fleets and depots will be needed to make use of the expanded electric network including new electric trains (which are cheaper than any alternative because they are standard and do not need to carry an energy storage system). Battery/electric bi-modes would allow early benefits to be secured while the network programme rolls out. Early starts on both the network and rolling stock programmes are needed and given the urgency of the COP26 global agenda, now is the time to start, with rail demand still suppressed in the aftermath of the pandemic.

More radical solutions to reduce electrification costs should be fully explored. Discontinuous electrification could utilise on-board batteries (rather than diesel engines) to carry trains through sections which are expensive to electrify, in battery/electric bi-modes. For lightly loaded lines, charging could be provided at terminal stations only using any electrification system. Electrification systems which are safer and more efficient than 3rd rail 750V DC (as used in London and the Southeast), but cheaper than the full main-line standard 25kV AC Overhead Line Equipment (OLE), could be explored for intermediate lines. If this was ground-based, as with the obsolete existing 3rd Rail system but using new technologies, for example to enliven conductor rails only in the presence of a train, the disadvantages of both existing systems could be overcome. The safety risk and inefficient current leakage of exposed live conductor rails at ground level could be obviated, while avoiding the need for very expensive rebuilding of road overbridges and other lineside structures that 25kV AC OLE entails.

Air transport

The air transport industry has for many years focused on improving the aircraft energy efficiency, primarily because fuel costs are a dominant factor in the economics of airline operations. Based upon data published by the International Council of Air Transportation, the fuel burn efficiency of new commercial aircraft, as measured by the average block fuel intensity, (fuel used per tonne-km), improved by 41% from 1970 to 2019, a compound annual improvement rate of 1.0%.[36]

Improved fuel burn efficiency leads directly to reduced CO_2 emissions. However, the predicted increase in future demand for air travel could lead to an increase of 19% in the aviation contribution to global CO_2 emissions by 2050, even with an assumed acceleration of improvements in aircraft efficiency to around 2.5% per annum[8]. Hence, as well as the continuation of existing project studies, more radical technology innovations are needed to significantly accelerate the rate of CO_2 emissions reduction from aviation. These include aircraft design changes and new fuel options.

Opportunities for emissions reduction through advances in technology and operational changes

Opportunity	Actions
Reduced aircraft empty weight	• Use of lighter structural materials for aircraft and engines. • Replacement of hydraulic and pneumatic systems by electric systems.
Reduced aircraft drag	• Measures to maintain laminar airflows over greater proportions of wing surfaces – Novel design configuration away from traditional tube and wing. – Blended wing body – Increase aspect ratio wings achieved by incorporating truss-braced wing structure or folding wingtips. – Adaptive wings optimised for each flight segment to improve lift/drag ratio. – Aircraft designed to fly at a lower cruise Mach No. • Distributed propulsion systems (in conjunction with electrically-driven fans)
Reduced gas turbine specific fuel consumption	• **Improved thermal efficiency** – Increased overall pressure ratios – Intercooling between compressor stages – Smaller, hotter cores. Improved high temperature materials and cooling. – Combustion chamber development to reduce carbon and Nox emissions – Cooled and modulated internal air cooling flows • **Improved propulsive efficiency** – Use of very high power gearing to drive higher bypass-ratio fans.

Operational improvement opportunities

- Earlier retirement of older, less fuel-efficient aircraft offers reduced emissions and operating costs.
- Better matching of aircraft design range to operating routes to help maximise load factors
  - Prioritise CO_2 emissions over journey time and passenger preference.
- Replace some long-haul journeys by multi-stage medium-haul to optimise size of aircraft used and its pay-load-fuel efficiency.
- Fly at altitudes where contrail formation is less likely (trade-off with possible fuel burn penalty)
  - 80% of contrail radiative forcing comes from 2% of flights.[33]
  - Focus on particular flight locations and daily variation in prevailing atmospheric conditions.
- Improved en-route air-traffic management to optimise track, climb and descent profiles, cruise fuel-burn efficiency and avoid excessive holding prior to landing.
- Reduce taxi times and use electric tugs for taxing.

Use of sustainable fuels instead of traditional fossil-derived aviation fuel

Fuels under consideration include electricity from batteries, hydrogen and sustainable aviation fuel. Weight is a vital factor in the design and operation of aircraft and comprises the weight of the aircraft structure, the payload carried and the weight of the fuel. The ratio of fuel weight to aircraft gross take-off weight increases with longer operating distance, but reduces substantially during the flight as fuel is consumed, with an associated reduction in drag and fuel burn rate. Comparisons made between aircraft operations using alternative propulsion systems and fuels must consider the weight of all the propulsion system components and any changes made to the aircraft structure, the efficiencies of converting fuel energy into propulsive thrust and the fuel weight variation during flight, as well as the basic weight of the fuel.

Battery-electric propulsion systems

The energy density of the currently preferred lithium-ion batteries has tripled from ~100 to ~300Wh/kg in the last 10 years. By 2025, battery energy density is expected to reach ~400Wh/kg; by comparison, the energy density of aviation fuel is ~30 times this value at ~43.3 MJ/kg (12000 Wh/kg). However, an electric motor-propeller arrangement has a fuel to thrust energy conversion efficiency of ~73%[36] compared to ~23% for a turboprop-propeller system based upon cruise sfc figures and a propeller efficiency of 80%. The equivalent efficiency value for a modern turbofan is ~45%[36]. These differences in efficiency, along with potentially increased power-weight ratios of electric propulsion systems, provide significant moderation to battery fuel weight penalty figures.

The weight penalty due to batteries and any additional structure is closely related to aircraft size, with an increased value for larger-capacity, longer-range aircraft due to their higher fuel weight fractions. In addition, the weight of the batteries remains constant throughout the flight whereas the weight of aviation fuel reduces.

Any extra weight increases the amount of fuel energy required for a given flight. For aircraft designed for longer distance flights the increased landing weight would also require structural changes for the aircraft undercarriage, with further weight penalties.

Battery performance degrades with time and usage. Hence accurate and reliable battery monitoring is essential to ensure that there is always a sufficient store of fuel energy available for the aircraft to reach the planned destination or safe alternative. Thermal management systems ensure that the malfunction of any of the closely packed cells, due to variety of causes, does not lead to excessive temperatures or uncontrolled fire.

The replenishment of an aircraft with aviation fuel is a relatively quick process normally achieved within the timescales required by airlines between flights to unload and load passengers and freight, and service the aircraft. Typically fuel delivery rates of ~1000 litre (800kg) per minute per hose equate to a stored energy replacement of around 34600 MJ per minute.

Battery charging rates are limited by chemical and thermal effects within the Li-ion cells and charging at high rates can cause degradation and subsequent deterioration in battery capacity and power delivery capability. An alternative to recharging the batteries in situ is to replace discharged batteries with batteries recharged in an airport facility. This presents safety and integrity issues associated with the heavy weight of the batteries and their electrical connections to the aircraft.

Hybrid-electric propulsion systems

These use energy from a battery and from a chemical fuel via a heat engine or fuel cell to deliver power to a thrust-producing propeller or fan. Aircraft flights are continuously optimised, in terms of air speeds, altitudes, engine thrust settings and aircraft attitudes, to achieve the best possible thermal, propulsive and aerodynamic efficiencies and hence lowest fuel burn. Hybrid-electric propulsion systems offer additional optimisation techniques to improve fuel-burn efficiency.

Electric motors, power electronics and electrical transmission systems

Lightweight electric motors with continuous power densities of ~8 kW/kg are being developed for aircraft propulsion systems. The total engine power requirement is typically ~1.5 MW for a conventional 19-seat commuter aircraft, ~3.5–10 MW for a regional 50–100 seat aircraft and ~20 MW for a 100–200 seat, short-haul aircraft. Distributed electric propulsion systems with an increased number of fans driven by smaller, lower-powered motors can ease motor power requirements and provide reduced aerodynamic drag.

The transfer and control of these very large amounts of electrical power from batteries or fuel cells to propulsion motors requires power electronics, circuit breakers and cabling of substantial size and weight operating at high voltages and currents, all with their own challenges when operating in a flight environment.

Hydrogen fuelled propulsion system

Hydrogen has an energy density of ~33 kWh/kg (120 MJ/kg), compared to ~12kWh/kg (43 MJ/kg) for kerosene and ~0.3 kWh/kg for current technology batteries, and can be used to produce propulsive thrust by two methods.

1. **As a combustion engine fuel in a conventional or a hybrid-electric propulsion system.** Many existing reciprocating and gas turbine engines can be operated on hydrogen fuel, albeit with some modifications to ensure safe, reliable and efficient performance throughout the operating envelope, with full release of the hydrogen energy content and minimised NOx emissions. However, the water vapour emissions could contribute to contrails and Aviation Induced Cloudiness (AIC).
2. **In a fuel cell arrangement to generate electricity for a hybrid-electric propulsion system.** Fuel Cells convert hydrogen molecular energy into electricity by electrochemical reaction. The only exhaust product is water vapour, which could contribute to AIC. The process also generates heat which must be managed by a cooling system. The energy efficiency of a fuel cell is ~55%[37]. When combined with a 90% efficient electrical powertrain and 80% propulsive efficiency, this will provide an overall fuel-thrust efficiency of ~40%. The weight of fuel cells and their associated cooling systems could limit their application to smaller regional aircraft.

Hydrogen on-board storage

The volumetric energy density of gaseous hydrogen at sea-level ambient conditions is only ~10.7MJ/m3 compared to 37440 MJ/m3 for kerosene. Hence, for use as an aircraft fuel, hydrogen must be stored as a compressed gas or as a cryogenic liquid to increase its density.

Compressed hydrogen has volumetric energy density values of ~1800, ~3960 and ~5040MJ/m3 at pressures of 200, 500 and 700 bar respectively, whilst that for liquid hydrogen at ~-253ºC is ~8280 MJ/m3. The compression of hydrogen to 700 bar requires an energy input ~21.6 MJ/kg which is around 18% of its energy density. The energy required to liquefy hydrogen is currently twice this value but reductions are expected from new process developments.

Storage of hydrogen at high pressure creates aircraft structural and performance issues associated with the increased overall tank volume and tank weight, which, with current materials, could be as much as 20 times the weight of the hydrogen stored within it. Developments in tanks constructed using composite materials are expected to improve this gravimetric capacity.

For storage in liquefied form, the need to maintain the hydrogen at around -253ºC limits the choice of tank materials and creates steady state and transient thermal issues for the local aircraft structure. Heat insulation is essential to control the evaporation rate of the hydrogen to match the flow rate to the engines and avoid excessive overboard venting. The difference between the volumetric density of liquid hydrogen and that of kerosene would also result in a need for much larger fuel tanks to provide the same aircraft range.

Future aircraft designs that move away from the traditional tube and wing layout could help to mitigate many of these hydrogen storage issues and their associated weight and volume penalties.

The volatility of aviation fuel demands strict, regulated procedures and precautions to ensure its safe usage during re-fuelling, normal flight operation and abnormal situations such as a leakage or fire. Hydrogen is very prone to leakage, which is difficult to detect. It is also highly flammable, with an ignition energy many times smaller than that for aviation jet fuel and burns with a flame that is almost invisible in daylight. Hence, the certification of hydrogen as a commercial aviation fuel would require a number of different and additional regulations to cover its behaviour during all normal and abnormal ground and flight conditions and scenarios.

Hydrogen production and distribution

Large scale use of hydrogen as an aviation fuel would require a very significant increase in its production worldwide. Currently the vast majority of hydrogen is processed, as 'green hydrogen', from natural gas or other hydrocarbons through energy-intensive and CO_2-emitting processes, although some of them do include carbon capture and storage to produce 'blue hydrogen'. Only 4% of hydrogen is currently produced from the electrolysis of water using electricity provided through sustainable processes. Increased demand for this Green hydrogen for use in aviation, and other forms of transport such as road, rail or maritime, could stimulate growth in its production.

Sustainable Aviation Fuel (SAF)

The closed-loop, life-cycle sustainable credentials of biofuels derived from plant-based biomass are that the CO_2 they release during combustion was previously absorbed from the atmosphere during their relatively short growth timescale. However, some plant-based biofuels are derived from crops such as rapeseed, sugarcane, corn, palm oil, and soybean which could also be used as food for human or animal consumption. In addition, some of the large land areas required for growth of biofuel crops are acquired by deforestation. Both of these options are non-sustainable.

Sustainable aviation fuel is an advanced biofuel manufactured primarily from waste animal or plant-based cooking oils, municipal waste and biomass such as agricultural residues as well as dedicated energy crops such as camelina and jatropha.

Non-biological, power to liquid fuels can also be created by synthesising carbon from CO_2 with hydrogen produced using renewably generated electricity. These e-fuels require significant amounts of energy to produce and are much more expensive than conventional fuels.

Production of e-fuel requires significant amounts of energy and hence they are currently much more expensive than conventional fuels. However, they have a very low environmental footprint and could become cheaper if the price of sustainably generated electricity reduces. In various countries, worldwide, biofuels are being blended, in increasing percentages, with fossil-derived fuels for automotive use. However, aviation is a global operation and hence the use of sustainable aviation fuel must comply with international regulations on a 'drop-in' basis such that, through their chemical and physical properties, they are completely interchangeable and compatible with conventional jet fuel, with no requirement for adaptation of the aircraft/engine fuel system or the fuel distribution network.

As part of an on-going certification process, SAF is being introduced gradually into service blended in increasing proportions with conventional aviation fuel. In 2020 the international limit for the blending of SAF was set as a maximum of 50% by volume[38].

In 2020 the international limit for the blending of SAF with conventional aviation fuel was set a maximum of 50% by volume[38].

According to[39] Sustainable Aviation Fuel, can reduce life-cycle carbon dioxide (CO_2) emissions by up to 80% compared to conventional jet fuel. However, SAF accounted for only 0.1% of all jet fuel used in 2019. The biggest barriers to increased SAF adoption are limited supply and high cost around 3–5 times the price of conventional fossil-based jet fuel.

In October 2021, Rolls-Royce officially stated that all of its Trent family of engines will be proven compatible with 100% unblended sustainable aviation fuel by 2023 and urged for a scale-up in its production.

As part of an industry commitment to achieve net-zero carbon emissions by 2050, the USA Departments of Energy, Transportation and Agriculture have launched a government-wide challenge to supply sufficient SAF to meet 100% of the demand for aviation fuel by 2050 and at least 3 billion US gallons of SAF per year by 2030. This is 16% of the 18.27 billion US gallons of aviation fuel consumed by US airlines in 2019.[40]


POWERING
SUSTAINABLE FLIGHT
100%
SAF

Potential alternative fuel option selections for various air transport operations

The issues presented above suggest that there is no single, alternative, more sustainable fuel suitable for all type of air transport operation. However, very significant reductions in emissions can still be achieved by using different fuels for aircraft of different size and duties.

Energy density issues will limit battery-electric propulsion to small commuter aircraft and any emerging urban air mobility vehicles.

Airbus is predicting the use of liquid hydrogen, as a gas turbine fuel or to generate electricity using fuel cells, for regional and 100–200 seater aircraft with operating ranges up to 2,000 nautical miles (nm). The ATI FlyZero project is also proposing liquid hydrogen as a gas turbine fuel for large-capacity, long-range aircraft.

Table 1 shows the contributions[41] to the global aviation fuel usage by various air transport operations. A very substantial reduction in carbon emissions could be achieved by reducing the use of fossil-based aviation fuel for short and mid-range aircraft. Column 6 and 7 shows the most viable alternative fuel options based on current, foreseeable technology development and likely introduction to service.

Table 1: Contributions to global aviation fuel usage and likely introduction of alternative fuels

Aircraft type	Seat capacity	Route distances (nm)	Global fleet %	Global aviation fuel usage contribution %	Alternative fuel option	Prediceted deployment date
Commuter	<20	<270	4	<1	All-electric	2025
Regional	<80	270–1,079	13	3	Electric / hybrid / H_2 fuel cells	2030
Short range	81–165	270–2,429	53	24	Gas turbine SAF	Increasing % from now
					Gas turbine H_2 / H_2 fuel cells	2040
Medium range	166–250	540–4,533	18	43	Gas turbine SAF	Increasing % from now
					Gas turbine H_2	2050
Long range large capacity	>250	>3,778	12	30	Gas turbine SAF	Increasing % from now
					Gas turbine H_2	2050

Marine

To reduce CO_2 emissions, shipping industry has started to implement some of the potential areas for energy efficiency that would lead to a substantial reduction both in energy use and in ship emissions as shown in **Figure 8**. These efficiency improvements could lead to some 60% overall reduction of fuel requirements and in ship emissions for a given ship.[42]

Another way of achieving this is to use ammonia and extend the use of Flettner cylinders and sails to assist in propelling the ships. Many ships have started using LNG as a fuel but since this leads to an unacceptable level of methane leakage and slip use of such fuels should be kept to minimum until leakage issues are resolved.

Figure 8: Potential fuel use and CO_2 reduction from various efficiency approaches for shipping vessels

Operational	
Weather routing	1–4%
Autopilot upgrade	1–3%
Speed reduction	10–30%

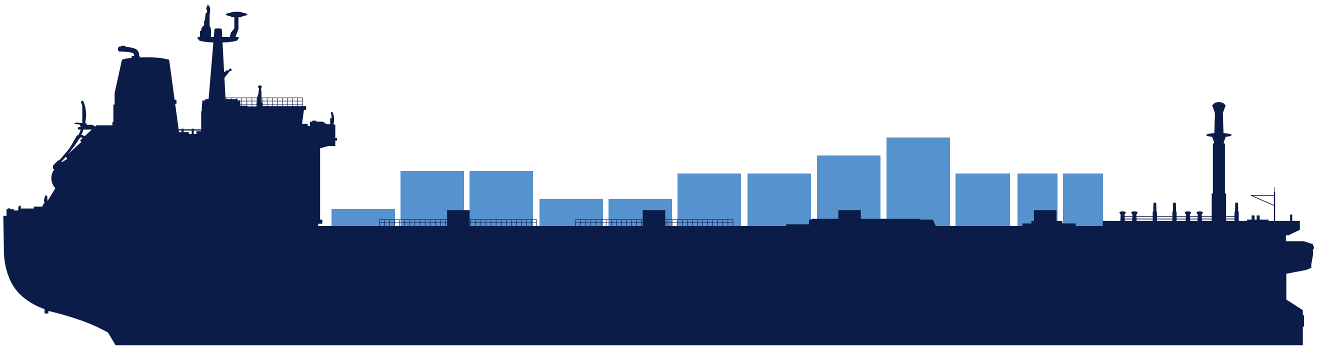
Thrust efficiency	
Propeller polishing	3–8%
Propeller upgrade	1–3%
Prop/rudder retrofit	2–6%

Auxiliary power	
Efficient pumps/fans	0–1%
High efficiency lighting	0–1%
Solar panel	0–3%

Engine efficiency	
Waste heat recovery	6–8%
Engine controls	0–1%
Engine common rail	0–1%
Engine speed de-rating	10–30%

Aerodynamics	
Air lubrication	5–15%
Wind engine	3–12%
Kite	2–10%

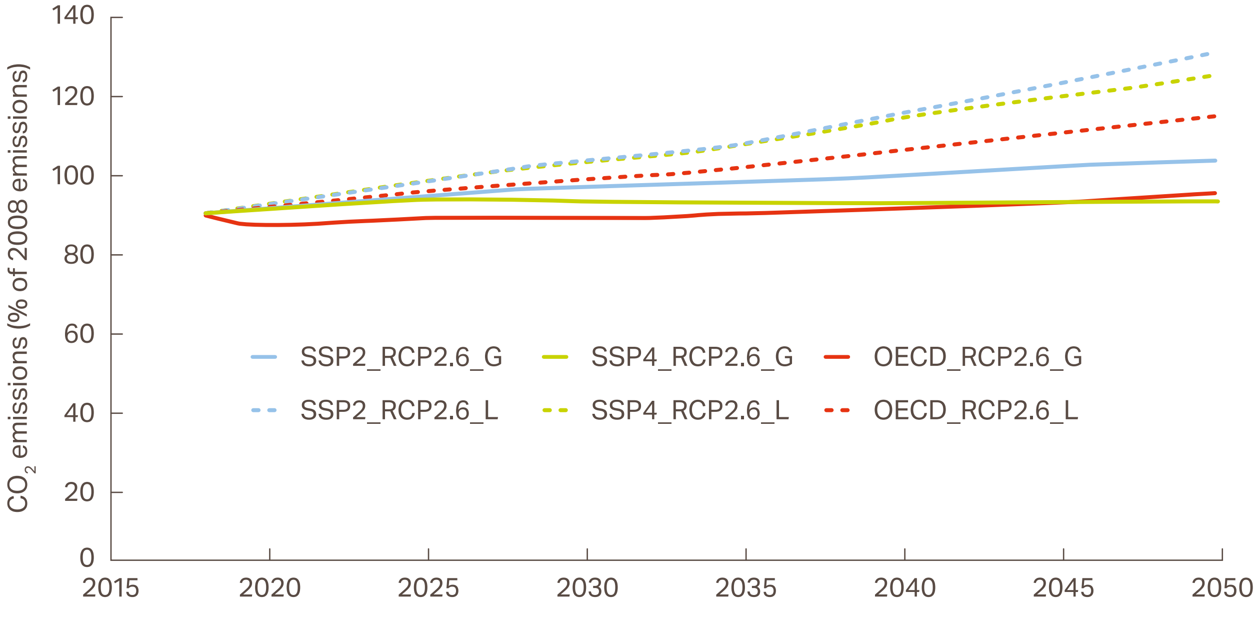
Hydrodynamics	
Hull cleaning	1–10%
Hull coating	1–5%
Water flow optimisation	1–4%



Results have shown that LNG fuels used in Diesel cycle (compression ignition) natural gas engines offer GHG emissions benefits compared to conventional fuels in most cases, although methane leakage and slip can diminish those benefits considerably. In contrast, the results indicate that LNG fuels used in lean burning, Otto cycle (spark ignition) natural gas engines offer little to no benefits compared to conventional fuels. Results from this work will better inform projects and policies aimed at improving the efficiency of fuelling and reducing methane losses and emissions from the use of natural gas in marine transportation systems.[41]

C4FF in their studies have shown that provided the government invests in local supply chains and provide funds for shipping companies to take advantage of energy savings as well as encouraging port electrifications through renewable energy; these could substantially reduce the level of CO_2 emissions by 25% by 2030 to counter the expected increase of possibly by 30% as shown in **Figure 9**.

Figure 9: Projections of maritime ship emissions as a percentage of 2008 emissions




drax
drax
ULTRABULK
HUMPHREYS

To overcome the level of CO_2 emissions shipping industry has started to implement some of the potential areas for energy efficiency by using the mitigation technologies in **Figure 10** below.

Figure 10: Current mitigation technologies in marine industry

Current mitigating technologies

- **Engine modification**
  - EGR
  - BEM/AFR control
  - AEM/3-stage inter-cooling
  - Variable geometry
  - Turbocharging
  - Variable valve/injection timing
  - Water injection
- **Pre & white combustion methods**
  - Water addition
  - HCCI/PCCI/RCCI
  - Duel fuel
  - Dynamisation (quantum physics)
- **Post treatment technologies**
  - SCR
  - Scrubber
  - PACR/Ship-to-port
  - Electric booster
  - Burning NOx oxygen (for more power and less emissions)
- **Energy efficient methods**
  - Speed/slow steaming
  - Weather routing
  - Maintenance
  - Propellor design & coating
  - Air cavity
  - Hull & trim optimisation
  - Ballast water management
- **Alternative source of energy**
  - Low sulphur fuel
  - Hydrogen
  - LNG
  - Bio-fuel
  - Ammonia
- **Alternative fuels**
  - Cold ironing
  - Exhaust extraction
- **Indirect**
  - Fuel cells
  - Solar
  - Wind/e-navigation
  - Wind sails
  - Sea currents

Nomenclature

EGR	Engine Gas Recirculation
BEM	Before Exhaust Method
AEM	After Exhaust Method
ECR	Selective Catalytic Reduction
PACR	Plasma Assisted Catalytic Reduction
LS Fuel	Low Sulphur Fuel

Air cavity
A thin sheet of air is maintained over the flat portions of a ship's bottom with the aid of pumps and hull appendages

Cold ironing
The process of providing shoreside electrical power to a ship at berth while its main and auxiliary engines are turned off

Ship Energy Efficiency Management Plan (SEEMP)

The International Maritime Organisation has also introduced regulations (DNV, 2014) such as the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SSEMP) and Energy Efficiency Operational Index (EEOI) on January 1st, 2013. SEEMP is an operational measure that establishes a cost-effective mechanism in improving the ship's energy efficiency. This measure also assists the shipping companies in providing an approach for managing ship and fleet efficiency performance over time with the help of the EEOI as a monitoring tool. The assistance on the development of the SEEMP operational measure for new and existing ships includes best practices for efficient ship's operation, as well as procedures for deliberate use of the EEOI in new and already existing ships (MEPC.1/Circ.684). SEEMP therefore is a plan to improve the energy efficiency implementation in a ship's operation, reported to provide cost savings of about 5 to 15% and help to bring down GHG emissions.[44]

Each Ship of 400 gross tonnage (GT) and above shall keep on board a ship specific SEEMP. Operational management tool applicable for all ships of 400 GT and above shall include:

- Improved voyage planning (weather routeing/Just in time arrival at port)
- Speed and power optimisation
- Optimised ship handling (ballast/trim/use of rudder and autopilot)
- Improved fleet management
- Improved Cargo handling
- Energy Management
- Monitoring tools (Energy Efficiency Operational Indicator)

In a 2021 report into decarbonising shipping, the IMechE recommended[45]:

1. The UK Governments support the development of a ship demonstrator using retrofitted wind sails. This will allow ship owners and users to understand how renewable wind can be used as primary propulsion on modern ships and could provide a compelling exhibition at COP26.
2. The UK shipping industry and users work with government on creative funding sources to build a '2050 now' ship that demonstrates how a fully autonomous fuel ship, that creates and manages its fuel could operate.
3. The International Maritime Organisation rethinks its recent low ambition announced in November 2020 and seeks to aim for a substantial reduction closer to 70% to meet the requirements of the Paris Agreement.

Based on findings[44], it is recommended in this report that the UK Government should actively create funding schemes to invest in technologies that will specifically decarbonise shipping and meet the urgent need to reduce our emissions at sea such as: Slow steaming when admissible; Use of sails and flettner rotors; Weather routing and use of sea currents; Green energy – wind and sun (Flettner rotors/Cylinders; sails & solar panels); Engine efficiency; Hull and trim optimisation and Propeller Polishing; e-navigation; Ballast water management; application of AI , VR and Quantum Physic focusing on Virtual arrival, advanced communications, JIT, predictive requirements and use of quantum physics in fuel molecular restructuring.

Some alternative future fuel options are recommended in **Figure 11**.

Ammonia powered ships

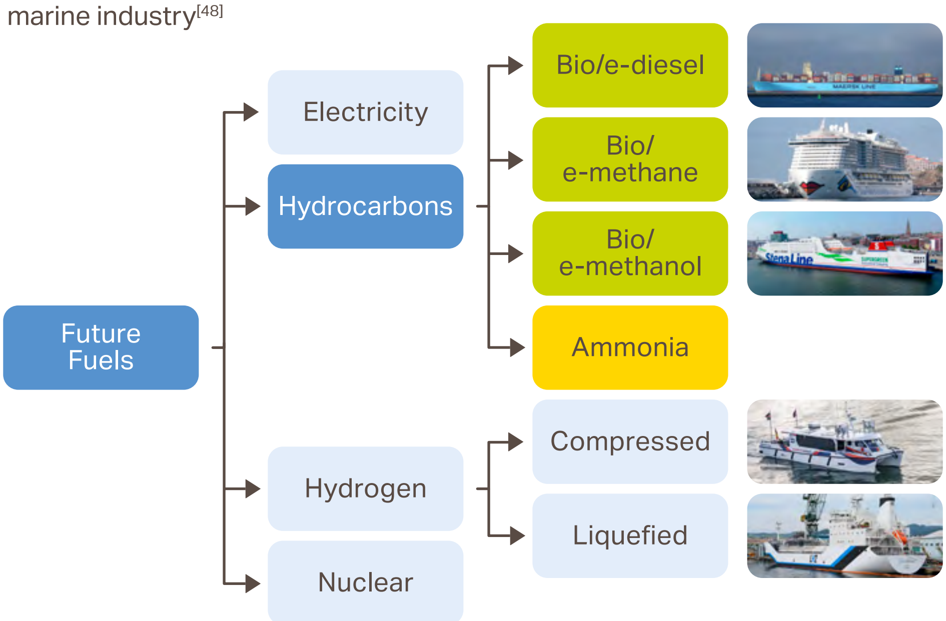
Although poisonous, on ships ammonia (NH3) is a practical way of storing large volumes of hydrogen. Ammonia is liquid below -33 degrees Celsius or at room temperature at 10 bar. Volumetric energy density of liquid ammonia is a third that of diesel and can be burnt directly in diesel engines with a suitable catalyst that provides long term pathway to fuel cells[46].

The worldwide decarbonisation movement has turned ammonia into one of the attractive alternative fuel for power generation. In recent study, it was reported a separate supply was required to deliver hydrogen to enhance ammonia reaction in the spark ignition engine. To achieve satisfactory engine performances with thermal efficiency of around 30%, a hydrogen mass fraction of roughly 10% is required for the ammonia/hydrogen engine. Ammonia elevates heat release rate of full load compression ignition engine by almost 10%. A partial premixed combustion has gained considerable interest in hydrogen/ammonia gas turbine combustion research.

This is mainly due to its ability to operate at equivalence ratio as low as 0.4, and in the slight fuel-rich regime. For operation at equivalence ratio 1.05, the nitric oxide concentration was decreased by a factor of approximately 5.9 when compared with that of stoichiometric condition. In all, ammonia offers a practical opportunity for sustainable power generation via internal combustion engines and gas turbine. Engine parameters optimisation may be needed to increase hydrogen mass fraction further in spark ignition engines and in compression ignition engines a multiple fuel injection optimisation is seemingly a more promising solution for improving ammonia compression ignition engine performances; however, prolonged ignition delay could potentially lead to higher engine noise levels. Ground-breaking combustion technologies are crucial to boost the adoption of ammonia in these engines.[47]

Combustion and emissions performance of ammonia can be improved by innovation in combustion technologies. This combined with advancement of advanced and cost-effective ammonia production technologies based on renewable resources will make ammonia an important component of the future energy demand.

Figure 11: Alternative future fuel options for marine industry[48]




GenH2
TRUCK

Conclusions

The movement of people and goods has brought immense benefit to mankind and continues to do so. The advent and development of motorised transport, in its various forms, has enabled increasingly longer journeys to be achieved in shorter timescales. The fuel for this motorised transport has historically been derived from the carbon in fossil remains extracted from the earth. It is only in relatively recent history that science has shown the by-products from the conversion of this fossil fuel energy into vehicle kinetic and potential energy to be causing extreme damage to the Earth's environment and its climate.

Transport itself is not the fundamental problem, it is the by-products from the propulsion systems of the vehicles used that needs to be tackled.

The role of the engineers to help address this challenge is to:

- Provide informed, independent evidence to industries and government regarding the scope for improvement in the emissions from various transport vehicles, fuels and propulsion systems in order for investment to be focused where real gains can be achieved in realistic timescales.
- Provide clear, science-based, information to enable society to include environmental impact in their decision-making for the types of motorised, or non-motorised transport they use for their journeys.
- Analyse the energy efficiency of all forms of transport vehicle and identify where improvements can be made.
- Assess the feasibility of using various types of alternative, sustainable fuel for road, rail, air and marine transport and the likely timescales for their implementation.
- Raise awareness of the technology challenges related to these developments and the changing skills needed for people to design, develop, and operate such vehicles.

The table on pages 36–37 breaks these aims into more specific objectives.

Summary of recommendations and technology/skills requirements

Transport type	Recommendations	Technology & skill challenges
Rail	Electrify all remaining mainlines and strategic infills as part of a rolling programme	Stop-go supply chain issues greatly increase due to repeated skills loss
	Identify a low-cost way of electrifying lightly used lines	New approach, perhaps based on a modernised discontinuous third rail system
	Battery-electric to replace diesel for short distance services where full electrification is not an option	Rail can 'piggy-back' on hydrogen and battery technology development in other industries, but these have only a niche role given the advantages of direct electrification
	Pricing structure to be competitive with air and road travel to help facilitate modal shift	Strategy for pricing structure
	Battery (and not diesel or hydrogen)/Direct Electric Bi-mode trains should be further developed	Battery and Hydrogen have a transitional role prior to full electrification but are not an alternative to it
Road	Encourage use of public transport	
	Discourage car use for very short journeys	
	Switch freight transport from road to rail	Education on modal shift and system efficiency
	Battery-Electric propulsion for cars	• OEM's to focus more on developing affordable EV based cars and charging-point infrastructure • Development of breadth and depth of workforce skills for maintenance of electric cars •
Air	Encourage train use for appropriate journeys	Competitive rail travel pricing structure
	Continue to develop and implement measures for aircraft drag reduction and engine efficiency improvement	
	Use of electric propulsion systems for small regional aircraft	• Increased battery energy density and airport re-charging infrastructure • Development of technology and certification standards for high power electrical transmission systems • Development of breadth and depth of workforce skills for design and operation of electric aircraft

Transport type	Recommendations	Technology & skill challenges
Air (cont.)	Use of hydrogen as a gas turbine combustion fuel or converted to electricity in fuel cells	• Develop on-board hydrogen storage systems • Certification of hydrogen fuel for aviation • Increased production of green hydrogen • Development of hydrogen distribution and airport refuelling infrastructures. • Fuel cell development • Development of breadth and depth of workforce skills for design and operation of hydrogen-fuelled aircraft
	Increased use of SAF for medium-large capacity, medium-long haul aircraft	Develop capability to produce SAF in quantity in the UK and certificate increased blend %
Marine	Development of new energy efficiency indexes	Indexes focusing on emission reduction
	Training and education programmes	Training the trainers and trainees on ship energy and emissions management
	Process and governance to monitor engine emissions and more effective monitoring of ships to ensure no discharge of waste takes place at sea	Appoint staff to take responsibility for ship energy efficiency, emissions monitoring, and management. Structured organisation specially in the cruise industry to ensure legal and environmental impacts are in acceptable manner
	Development of net-zero marine technologies based on improved hydrogen storage in ammonia	Combustion of ammonia in IC engines and gas turbine optimisation techniques
All	Reduce transport carbon emissions through modal shift	Encourage use of transportation mode that produces lowest carbon footprint • Walk or bicycle if realistic • Public transport rather than petrol/diesel car • Train rather than aircraft
	Increase amount of sustainably produced electricity	
	Increase quantity of green hydrogen production	
	Match future workforce skills to future demands in a changing transport environment	Engineering graduate and technician programmes to include wider variety of technologies
	Focusing on energy usage/demand reduction	Methodologies used in road transport to allow a greater corporation between freight companies to reload wherever feasible rather than returning empty and ideas to make better use of sea currents

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Institution of
Mechanical Engineers

1 Birdcage Walk
Westminster
London SW1H 9JJ

+44 (0)20 7973 1293
media@imeche.org
imeche.org