A review of literature on roadmapping to reduce freight transport CO2 emissions by 2050

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Executive summary

Introduction

This report provides a review of progress towards the decarbonisation of freight transport by 2050 and is intended to inform freight transport policy and practice. All modes are considered but greatest attention is given to road freight operations by truck. Far less research has been carried out into the decarbonisation of other aspects of logistics and supply chain activities including handling and storage, energy consumed by logistics buildings and computing, packaging and waste arising.

The research has consisted of a systematic review of freight transport decarbonisation roadmapping publications, together with a wider, narrative review of freight transport decarbonisation literature. A summary of decarbonisation legislation and targets in the UK since 2008, together with a review of carbon emissions from freight transport operations since that date has also been carried out. The prospects for, and the challenges and barriers to, net zero carbon emissions from freight transport operations by 2050 have also been considered.

The primary focus of this report is the UK. However, the review of freight transport decarbonisation roadmaps and measures included in the work draws on research from the EU and the rest of the world, and therefore should contain material of general use and relevance to all those interested in the subject.

Progress to date towards freight transport decarbonisation

The UK was the first country to introduce legally binding long-term greenhouse gas (GHG) emissions reduction targets through the Climate Change Act in 2008. In 2019, the UK became the first major economy to enact a legally binding target of ‘net zero’ GHG emissions by 2050. Freight transport will have to play its part in achieving this target. The UK Government will publish its Transport Decarbonisation Plan during 2021, which will provide further details about freight transport’s role.

The most recent analysis by the UK Government shows that domestic transport (passenger and freight) was the largest emitting sector of UK greenhouse gas (GHG) emissions in 2018 (28% of UK total), followed by energy supply (23%), business (18%), residential (15%), agriculture (10%), waste management (55%) and other (2%) (BEIS, 2020). When international aviation and shipping to and from the UK are added to domestic transport GHG emissions, this increases emissions from the transport sector to approximately 32% of total GHG emissions in the UK in 2018 (Committee on Climate Change, 2020). The importance of the various modes in the UK’s total transport GHG emissions are as follows: road accounts for 67%, aviation 24%, shipping 8% and rail 1%) (BEIS, 2020).

ITF has produced modelling estimates of global CO_2 emissions from transport that subdivide these into freight and passenger transport. These indicate that freight transport was responsible for 36% of total transport CO_2 emissions in 2015, with both domestic and international freight transport responsible for 18% of this total (ITF, 2019).

Road is the dominant mode in terms of UK freight transport activity and GHG emissions for UK freight transport. In terms of goods moved domestically in the UK in 2018, road accounted for 79% of tonne-kilometres, compared with 9% by rail and 13% by water (Department for Transport, 2020o). Road freight accounted for 33% of GHG emissions from all domestic transport (i.e. passenger and freight) in the UK in 2018. Heavy goods vehicles (HGVs – those above 3.5 tonnes gross weight, also referred to as trucks) and light goods vehicles (LGVs – those up to and including 3.5 tonnes gross weight) accounted for 17% and 16% of GHG emissions from UK domestic transport in 2018, respectively (BEIS, 2020a).

A review of official emissions data from UK freight transport operations over the last decade indicates that GHG emissions were higher for trucks and LGVs in 2018 than they were in 2008. The relative importance of road (compared to rail and inland water) continued to grow over this period. The average length of haul for HGV road freight operations increased over this period, there was little change in the operational efficiency of these vehicles as reflected by empty running and loading factor metrics, and the average size and weight of HGVs increased, as lighter, smaller vehicles were replaced with heavier ones. The average age of HGVs and LGVs increased over the decade and few lower- or zero carbon road freight vehicles were in use in the UK in 2018. Gains in the energy efficiency of road freight vehicles as a result of technological improvements over the last decade in the UK have been offset by growth in vehicle activity, vehicle size and weight, and a lack of improvement in the efficiency of freight transport operations.

Systematic review of freight decarbonisation roadmapping publications

A systematic review of roadmapping publications in the last five years that focus on freight transport decarbonisation identified 53 relevant publications that provide an assessment of various freight decarbonisation technologies and measures, and a set of milestones necessary to reduce or eliminate carbon emissions. Publications were not limited to those that considered the situation in the UK, 21 one focus on the UK, 17 of have an EU/Europe coverage (including the UK), while 15 have an international or worldwide coverage

Two-thirds of the publications included in this detailed review focus specifically on freight transport CO_2 emissions only, while the other third of the publications comprise a consideration of wider sources of CO_2 emissions. Almost half (25) of these publications consider road transport only, while 17 of them consider all transport modes (sometimes without much modal detail included). Four of the publications consider only maritime shipping, three focus only on aviation, and two only on rail transport, with two on both road and rail transport.

Generally, the literature reviewed has been framed in terms of technologies and operational measures required to decarbonise freight transport, but they do not tend to address the transition towards zero carbon over time. In other words, the actions required, timings and CO_2 emission reductions that will occur en-route to 2050 are often not well discussed. Nor do many of these publications address the timings and costs that might be incurred to establish the infrastructure necessary to support the carbon saving measures, or the costs the logistics sector would incur for using the technologies and measures. Only three publications have provided what could be described as full roadmaps to 2050 with quantification of the likely role that a wide range of freight decarbonisation measures can play over a given timescale, while other publications contain roadmaps that focus on a far narrower consideration of freight decarbonisation.

These 53 publications were analysed in order to identify a suitable framework used and categories of action that can lead to freight transport decarbonisation. Eight categories were identified each consisting of a number of freight decarbonising measures as shown in the table overleaf.

Categories	Specific measures	
Reducing the level of freight transport demand	• Consumer behaviour • On/re shoring of supply • More local sourcing	• Dematerialisation • 3D printing • Circular economy
Shifting freight to lower-carbon transport modes	• Rail • Short sea shipping • Inland waterways	• Cargo bikes • Synchromodality • Intermodal equipment
Improving asset utilisation	• Collaboration • Retiming of deliveries • Delivery frequency	• Vehicle loading • Higher capacity vehicles • Double deck trailers
Organisation of physical logistics systems	• Supply chain networks • Regional & urban distribution hubs • Platooning	• Autonomous vehicles • Modular packaging • The physical internet
Digitalisation	• Artificial intelligence • Internet of things • Predictive analytics • Big and broad data	• Telematics • Route planning • Intelligent transport systems • Airspace management
Increasing energy efficiency	• Engine technology • Aerodynamics • Tyres selection • Idling reducing technologies • Lightweighting of vehicles • Fuel additives and lubricants • Vehicle maintenance	• Automatic tyre inflation • Driver assistance systems • Driver training • Fuel management programme • Reduced aircraft taxiing • Using air/sea port (not vehicle) energy
Switching to lower-carbon energy	• Electric vehicles • Electric road systems • Hydrogen • Gas	• Synthetic biofuels • Sustainable air fuels • Hybrid vehicles
Energy systems	• Battery technology • Renewables • Hydrogen production • Ammonia production	• Smart grid technology • Energy storage • Synthetic fuels

Of the 53 roadmapping publications included in the systematic review, only seven of them contain a comprehensive discussion across a wide range of freight transport measures in the various decarbonisation categories. The category most commonly addressed by the reviewed publications (50) is ‘switching to lower carbon energy’. This is followed in frequency by ‘energy systems’ (with these two categories being highly related to one another and both discussed in 40 of the publications). These are followed in terms of the frequency with which they are considered by: ‘increasing energy efficiency’ (28 publications), ‘physical logistics systems’ (18 publications) and ‘improving asset utilisation’ (16 publications), ‘shifting to lower-carbon transport modes’ (14 publications, ‘digitalisation’ (14 publications). ‘Reducing the level of freight transport demand’ is the least commonly addressed category, addressed in 8 publications.

Only 10 of the 53 publications reviewed provide quantified forecasts of the expected effects of any of the freight transport measures/categories, and only a few provide such forecasts of CO_2 emissions reductions across a wide range of freight decarbonisation categories and measures. These publications suggest that truck CO_2 emissions could be cut by between 30-60% by 2050 through vehicle energy efficiency and logistics operation measures without taking account of zero carbon fuels.

Research that has taken account of worldwide freight transport indicates that progress towards decarbonisation at a global scale by 2050 will be far less than when just taking developed countries into account as change will be far slower in developing than developed countries. This work indicates that, taking into account the predicted growth in demand for freight transport, even the implementation of yet to be announced freight decarbonisation measures in conjunction with existing measures will be insufficient to prevent total worldwide freight CO_2 emissions in 2050 being greater than in 2015 (ITF, 2019).

Wider, narrative review of freight transport decarbonisation

A wider, narrative review of freight decarbonisation in relation to each of the eight categories has also been carried out using these 53 roadmapping publications, together with more extensive literature.

Much of the literature views electricity as the key potential power source for achieving zero emissions truck operations by 2050 (either via an Electric Road System or electric batteries), but other fuel sources including hydrogen and advanced biofuels such as synthetic methane, synthetic methanol, and synthetic liquid hydrocarbons playing a role. It is clear from the many publications examined that electrification of freight transport offers an extremely important potential for road freight carbon reduction, but there are challenges to be overcome for both vehicles and the storage of electricity. Although electric vehicles are seen by many as the way forward, for zero carbon truck operations to be possible requires the decarbonisation of the electricity sector in the next 10 to 15 years. It has been suggested that without government intervention to prohibit the use of fossil fuelled road vehicles, it would take approximately 20 years for these vehicle fleets to be phased out and replaced with electrified vehicles. Using electricity as the key fuel source to power trucks would require either the development of an Electric Road System on major roads, or major developments in battery technology that reduce their weight and cost in order to commercialise their application for long-distance truck operations. Some truck manufacturers and fuel suppliers view hydrogen as offering the best opportunity for truck decarbonisation and are aiming to put in place trials to further develop and demonstrate the required technology, prior to larger-scale commercial uptake.

Electric batteries are already being deployed in light goods vehicles (LGVs – i.e. vans) in the UK, especially for those operating in urban areas where increasingly stringent vehicle emissions are already being implemented. Electric batteries are likely to be best means by which to decarbonise these commercial vehicles.

For other freight modes, the future availability of zero carbon fuel sources also remains unclear and much debated. Conventional diesel rail freight locomotives in the UK cannot currently be replaced by electric ones due to the lack of electrification of some of the rail network including private sidings that they operate on. Research indicates that CO_2 emissions reduction will be much more difficult to achieve in aviation and shipping than in road freight due to the fuel source requirements of the vehicles and operations. Predicted growth in the demand for freight transport by all modes is expected to add to the difficulty of achieving decarbonisation.

In aviation, there is no expectation of zero carbon fuels for long-haul flights by 2050, only more sustainable fuels with lower-carbon content. Similarly, the provision of zero carbon fuels for shipping currently presents a technological challenge and may not materialise at commercial scale by 2050.

In addition, the replacement cycle for deep-sea ships, rail locomotives and aircraft is far longer than for trucks. Therefore, even if technological and commercial developments provide new zero carbon fuel sources for trucks and these other freight transport modes in the not too distant future, the CO_2 emission reduction benefits they would provide may well not occur quickly enough to achieve net zero freight operations by 2050 due to the time it will take to replace these vehicle fleets.

This emphasises the importance of implementing freight transport measures that increase the energy efficiency of freight transport vehicle and operations, together with the use of existing lower-carbon fuels and other decarbonisation measures including reducing the demand for freight transport and modal shift in reducing CO_2 emissions from freight transport. In the case of air and shipping, efforts to make use of ground-based zero carbon fuels for vehicles stationary in air- and sea-ports will also have a role to play.

Challenges and barriers to freight decarbonisation

There are a range of challenges and barriers that need to be overcome in relation to the implementation and adoption of these measures by freight operators if freight decarbonisation is to be achieved. These include technological readiness, demonstrations, trials and pilots, infrastructure implementation and support, investment and funding requirements, regulations and legislation, fiscal policy, information and publicity campaigns. Most national and international governmental decarbonisation action to date has been focused on establishing targets for carbon emission reductions by given dates. Little regulatory action has been taken by governments to assist in achieving such targets in freight transport or other sectors.

The review of roadmapping publications focussing on freight transport decarbonisation carried out as part of this report has indicated that these studies have not been carried out by freight operators. Many have been produced by governmental bodies, academics, consultants and third sector organisations. A few have been produced by trade associations and professional bodies. When these roadmaps identify innovations that are required or provide recommendations and measures that should be researched and/or adopted, they typically fail to take freight operators and freight users sufficiently into account and include these operators in their thinking. Instead, these recommendations tend to be directed at governmental bodies, infrastructure providers and those engaged in the provision of future zero carbon fuels for freight vehicles. However, freight operators and users have a key role to play in freight decarbonisation. These companies will choose the decarbonisation measures available that are most cost effective. There is a need for greater consideration and inclusion of freight transport operators and users in roadmaps because they will define the direction in which net zero CO_2 emissions can be achieved.

Many issues need immediate attention if total or even partial decarbonisation is to be achieved for trucks, rail, air freight and shipping in the UK and more widely by 2050. Very importantly, a choice needs to be made at a national government level about the zero carbon fuel source to be developed for long-distance truck operations. Many of the roadmaps reviewed are unquestioning about the future availability of zero carbon trucks. However, unless such a decision is made very soon, and the necessary levels of funding made available to support fuel technology, trials and pilot schemes, and transport and energy infrastructure, there is little prospect of the widespread deployment of zero carbon trucks in the UK by 2050. Even with such a decision and public funding, little time remains given the time needed for developing this technology and the related transport and energy supply infrastructure, its testing, the town planning hurdles that need to be addressed, and the time it will take for substantial uptake of such vehicles, given existing fleet replacement cycles.

Given the technological, commercial and other challenges that exist in the development, roll-out and uptake of zero carbon fuels, it is important that other freight decarbonisation measures that are already available, namely vehicle energy efficiency and logistics operation measures, receive greater attention in the short-term from policy makers, the freight and logistics industry, and their users and customers.

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1 Introduction

Over the last six years the Centre for Sustainable Road Freight (SRF) has identified over 30 different vehicle technologies and logistics measures that would contribute to decarbonisation of road freight transport. Both qualitative and quantitative roadmaps have been developed by SRF to examine the opportunities for decarbonisation using these technologies and measures. An Excel based software model has been developed and used within SRF and as part of a project for the Committee on Climate Change, with the results contributing to the 5th carbon budget 2027-2032 (Greening, Piecyk, Palmer, & McKinnon, An assessment of the potential for demand-side fuel savings in the HGV sector, 2015). Reports have also been produced for the Office for Science and DfT based on the results from this roadmapping work (Greening, Piecyk, Palmer, & Dadhich, Decarbonising road freight, Future of Mobility: Evidence Review, 2019).

This report contains a review of documents published since the SRF roadmapping was initially carried out, including journal articles and reports by other organisations which have also studied and suggested ways of reducing CO_2 emissions in freight transport in the coming years in order to meet emissions reduction commitments established by the UK and other national governments. These documents, which have been reviewed, are referred to as 'roadmaps' in this report due to the fact that they provide approaches and plans as to how CO_2 targets could be met. They cover a wide range of technologies and solutions from various industry sectors and geographical regions.

The global logistics and delivery sector makes up about 15% of the world's GDP (Wible, Mervis, & Wigginton, 2014). On average, about 7-8% of a product's cost reflects its delivery costs, and transport constitutes about 40% of these costs, although there is wide variation in this percentage according to the product distributed (International Energy Association, 2017). Regional differences in vehicle attributes, payloads, policy frameworks and activity, as well as the average age profiles of the truck fleet, mean that the average specific fuel consumption by road freight vehicle category can be markedly different across various countries.

It is difficult to obtain a consistent measure of CO_2 emissions for freight transport and, in particular, road freight transport. However, in a document by the EEA (2017), greenhouse gas emissions by IPCC source sector for EU-28, states that transport, including international aviation, accounts for 24.6% of all greenhouse gas (GHG) emissions. Trucks account for less than 2% of the vehicles on the road but 22% of CO_2 emissions from road transport (Transport & Environment, 2020). The EC-DC R&I (2018) states that, in Europe, freight transport accounts for about 30% of all transport CO_2 emissions and around 6% of total CO_2 emissions. Since 1990, all the IPCC source sectors have reduced GHG emissions, but transport has consistently increased with a rise of over 30% (EEA, 2017a). Sources may differ slightly in their interpretations of the statistics but, whichever source is used, it is clear that there are significant challenges to make freight transport almost fully decarbonised by 2050.

The demand for freight movements by trucks will steadily increase with the growth of population and trade. Fuel consumption of trucks are a large component of the operating costs for road haulage companies. In the United Kingdom and the United States, fuel represents 20-30% of operating costs (ATRI, 2016). In the EU road freight transport currently uses approximately 50% of all diesel fuel with projections to 2050 suggesting that road freight activity may increase by up to 100%, although this growth wouldn't be consistent across all regions (European Commission, 2016) (ITF, 2018). In Europe the highest growth is expected to occur in EU13 where a strong correlation between GDP and freight growth has been observed (European Commission, 2016).

Achieving net zero CO_2 emissions by 2050 (the target set by the UK Government) involves identifying technologies and measures that can make this happen and setting out the steps by which this could be done, referred to for the purposes of this report as 'roadmapping.' However, the literature examined shows that it is difficult to obtain the data to produce accurate estimates of the impacts of all the measures and their interactions, but nonetheless these estimates are important to set up the pathways towards decarbonising.

The term roadmap is defined as "a strategic plan that defines a goal or desired outcome and includes the major steps or milestones needed to reach it." In the context of this report, the aim is to examine a wide range of literature to assess the various technologies and measures necessary to reach zero carbon emissions by 2050, and to understand what needs to be done when to achieve that goal, including the costs and CO_2 savings achieved, plus the likely take up of the various technologies and measures.

Roadmaps are needed to clearly define the steps necessary to reduce CO_2 emissions from freight transport and to understand the actions that need to be taken by individual companies, public and private sectors, governments, and society. Several publications have suggested that there will be considerable growth in technology innovation over the coming years (EASAC, 2019) (EC-DC R&I, 2018) (ERTRAC, 2019) (ITF, 2019). This uncertainty on possibly key aspects such as enabling conditions and technology options available makes it difficult to identify a clear roadmap to 2050. It is a case of the unknown unknowns.

Although the focus of this study is the UK, worldwide, and in particular EU research, is still relevant and has therefore been included in the review and has been put in the context of UK requirements where appropriate. Much of the report focuses on road freight, but some consideration of other modes (rail, water and air) is also included. Drawing on the documents that have been reviewed, this report presents a summary of technologies and solutions that are likely to have a significant impact on the ability to reduce CO_2 emissions from freight transport, the likely importance of their contribution where such forecasts are available, and the likely timescale for their adoption and implementation.

Crucially, one of the major issues in a roadmap is understanding the likely take up of any decarbonising component. The theory put forward by Everett Rogers in 2003 is relevant in this context. He states that the rate of adoption of a product or idea differs among five distinct categories of consumers: Innovators, Early Adopters, Early Majority, Late Majority, and Laggards. Innovators are more willing to try innovations and take risks. Early Adopters embrace change opportunities but need support materials to adopt the product. Early Majority. adopt innovations before the average person, but they require evidence that the innovation works. Late Majority are sceptics who adopt innovations after many others have tried them. Laggards are conservatives who adopt innovations after seeing statistics or experiencing pressure from other adopters. These categories typically have a percentage make up of 2.5%, 13.5%, 34%, 34%, and 16% of the target market respectively (Rogers, 2003). On an accumulative basis these create an S curve and it is this principle of the take up of technologies and measures that has been used in the SRF roadmapping model.

Truck operators work in a competitive environment with the aim of minimising costs and maximising profits. When there is an economic case for more efficient trucks then it is likely an investment will be made, but this is dependent on the accounting practices of companies. In the United States, for example, companies with fleets of up to 20 vehicles tend to only consider technologies with paybacks ranging from 6 to 36 months, with an average of one year, while those companies operating the largest fleets of 501 or more vehicles consider a payback period of between 18 and 48 months, with an average of two years (Schoettle, Sivak, & Tunnell, 2016). A number of interlinked factors have been identified why there is a failure to invest in new decarbonising features (International Energy Association, 2017):

- the *payback gap* - the time it takes for the investment to be fully amortised by fuel cost savings
- *imperfect information* - lack of access to accurate information about the investment
- *split incentives* - when different people in the same company disagree about implementing efficiency measure
- *liquidity and scale constraints* - smaller firms or firms from poorer countries may not have the capital for investing in more efficient technology
- *trade-offs* - there may be other priorities within the business

The first two are often cited as barriers to investing in new or emerging technologies.

This introduction has discussed the broad situation and issues around decarbonisation of road freight from a perspective of estimating the current CO_2 emissions and take up of carbon saving initiatives. Chapter 2 provides an explanation of the methodological approach to analysing the literature. Chapter 3 provides context with respect to decarbonisation legislation and targets in the UK since 2008, together with a review of carbon emissions from road freight as well as other freight modes since that date. Chapter 4 contains the results of the systematic review of freight decarbonisation roadmapping publications. Chapter 5 provides a more detailed, narrative review of the contents of these publications together with the use of additional literature in relation to the various categories of freight decarbonisation measures. Chapter 6 considers progress towards freight decarbonisation, taking into account the challenges and barriers that need to be addressed, together with the likelihood of freight transport achieving net zero carbon emissions by 2050. Chapter 7 provides the conclusions.

Road freight transport decarbonisation is the main focus of this report, especially in relation to trucks. However, non-road freight modes (rail freight, air freight and maritime shipping) are also considered, albeit more briefly than road freight. This is intended to assist in providing insight into the relative situation for road freight compared to these other modes, and to outline progress and challenges in freight decarbonisation as a whole.

2 Methodology

The techniques used for this report consist of systematic or structured literature review methodology, together with a narrative review of literature. Using both of these techniques was considered to be the best way of providing evidence to inform freight transport policy and practice.

The literature search involved selecting a set of key words and then combining them in different ways to form search strings. Specific databases were selected to test these search strings. The search strings were then modified to try and produce a better set of results.

There are a huge number of search results produced for the various key words related to the topic of this report. Simply typing "roadmap" into Google produces 73.4 million results and "roadmapping" 991 thousand results. These can gradually be reduced however by refining the search words to be more specific. Thus, the string "road freight emissions" and roadmap produces 1,680 results. Because this topic is so fast moving new articles are being added daily, and Google is therefore likely to produce better results than academic journals.

There is a plethora of academic databases and it is important to be pragmatic in selecting them. Although academic papers, because of the peer review process, are more rigourous and less biased, they do tend to take longer to publish and so can be quickly out of date. Despite this, a number of academic databases have been searched including ABI/INFORM, Scobus, EBSCO, Science Direct as well as Google Scholar.

The following key words were used in various combinations in the electronic literature search:

- Roadmap
- Roadmapping
- Freight
- Transport
- Mega trucks
- Electric trucks
- Long haul
- HGV's
- Transport modes
- CO_2 emissions
- Decarbonisation
- Sustainability
- GHG
- Greenhouse gas emissions
- 2050
- Energy systems
- Road electrification

In many instances the same publications were shown in the searches. Table 1 provides an example of the type of responses to the various search strings.

Table 1: Example of responses to search strings

Key words	Google	Science Direct	Proquest ABI/Inform
Roadmapping freight transport	2,520,000	15	
Roadmapping long haul trucks	5,060,000	10	
Roadmapping electric trucks	904,000		
roadmapping "energy systems" "freight transport"	98,700	2	
roadmapping "energy systems" "long haul"	147,000		
roadmapping "decarbonisation" "freight transport"	22,000	1	
roadmapping "decarbonisation" "long haul"	8,120		
roadmapping "sustainability" "freight transport"	209,000	5	63
roadmapping "sustainability" "long haul"	461,000	3	
freight road electrification	4,470,000	1349	16
freight road electrification 2050	252,000	503	
Freight decarbonisation			15
road freight emissions roadmap		299	
Freight sustainability			106

Clearly Google provided the majority of responses, but these are from more commercial sources rather than academic. As previously mentioned, the publications identified via the Google searches are more up to date in this fast-changing area, although, possibly, not as rigorous as academic papers. In addition to the online literature search, publications produced as part of the SRF work were included, as were publications known to the author. The references in these publications proved a useful further source of material.

Because of the rapidly evolving technologies and business models to enable freight operations with zero carbon emissions, the screening process excluded any publications that were more than 5 years old from the 'most relevant' category and detailed analysis (i.e. published prior to the SRF 2015 publication - Greening et al., 2015), though some were included as 'relevant' in the wider review.

Publications identified during the literature search were classified according to not relevant, and therefore discarded, or relevant in which case they were examined in more detail. Reading the titles enabled most of the filtering, with the abstract or executive summary read in cases where there was any uncertainty.

These searches identified a potential 118 publications for the systematic literature review that were downloaded and examined. 53 of these sources were found to contain the level of detail expected from a roadmapping type discussion. These publications were included in the systematic review. The other publications were informative, and some of them were used in the wider review contained in chapter 5 but were excluded from the content analysis presented in chapter 4 as they were either too general in their transport coverage or did not contain a forward-looking roadmapping focus.

Inevitably, because of the size of the literature, plus the time and resources available, although care has been taken to include as many relevant publications as possible, it is likely that some will have been missed, and more will certainly have been published since the production of this report. In addition, the selection and analysis of literature is a highly subjective and gap-prone process. The views expressed in this report are those of the authors and, although this report has been peer reviewed, it is likely that others will see different views from the same body of literature.

There is also a regular, on-going flows of new publications in newspapers, periodicals and the outputs of logistics/transport associations about freight decarbonisation techniques and new technologies. Whilst these have not been included in the systematic literature review (see chapter 4) they have been made use use of been cited in the wider, narrative review where relevant (see chapter 5).

3 Setting in context freight transport and GHG emissions in the UK

3.1 GHG emissions reduction legislation in the UK

The UK was the first country to introduce legally binding long-term greenhouse gas (GHG) emissions reduction targets through the Climate Change Act in 2008. This committed the UK to an 80% reduction in GHG emissions relative to the levels in 1990. In 2019, the UK became the first major economy to enact a legally binding target of 'net zero' GHG emissions by 2050 (ITF, 2019). This requires that the UK reduce GHG emissions by at least 100% relative to 1990 levels by 2050 (Priestly, 2019). 'Net zero' refers to achieving at least a balance between the amount of GHG emitted and the amount of GHG removed from the atmosphere. This net zero target can be achieved by reducing GHG emissions as well as removing GHG from the atmosphere.

The UK Government has already announced that sales of new light goods (LGVs – with a gross weight up to and including 3.5 tonnes – also commonly referred to as vans) powered by diesel or petrol will be banned by 2030, with hybrid LGVs banned from 2035, after which date all LGVs will have to be zero carbon emission vehicles (Department for Transport, 2020d). Specified types of alternatively-fuelled LGVs are currently permitted to operate up to a maximum weight of 4.25 tonnes (rather than 3.5 tonnes) with those holding car driving licences permitted to drive them (Department for Transport, 2020c). In the case of trucks (also known as heavy goods vehicles (HGVs) with a gross weight over 3.5 tonnes), the UK Government has implemented EU CO_2 emission standards regulations for new trucks by 2025 and 2030 (see section 5.7 for further details), and has also has established an industry-wide voluntary target for reducing GHG emissions by 15% by 2025, from 2015 levels (Department for Transport, 2020c).

The UK Government is currently drawing up a Transport Decarbonisation Plan (TDP) which is due to be published during 2021. However, its existing decarbonisation planning has already identified that, in relation to freight this will include (Department for Transport, 2020c):

- The decarbonisation of domestic road freight and rail freight vehicles
- Improving the efficiency of road freight and logistics operations (including through the use of innovative digitally enabled solutions, data sharing and collaborative platforms)
- Participating in international efforts to reduce air freight and seaborne freight emissions

The UK's Climate Change Act currently excludes emissions from international maritime shipping and international aviation. Air pollution from international shipping is regulated by the IMO (International Maritime Organisation) through the 'International Convention for the Prevention of Pollution from Ships' (also known as 'MARPOL'). In 2018, the IMO adopted an initial strategy which sets a target to reduce GHG emissions from international shipping by at least 50% by 2050 compared to 2008, and to "reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008" (IMO, 2018). These targets are not currently legally binding on member countries until it has been made mandatory in an IMO convention.

In 2008, IATA, the trade association of the world's airlines, adopted targets to reduce CO_2 emissions from air transport. These included annual improvements in fuel efficiency of 1.5%

per year from 2009 to 2020, a cap on net CO_2 emissions from aviation from 2020, and a reduction in net CO_2 emissions from aviation of 50% by 2050, relative to 2005 levels. These are not legally binding. In 2019, ICAO (International Civil Aviation Organization – an agency of the United Nations) adopted a resolution which reiterated two existing ICAO aspirational goals for international aviation (ICAO, 2019). These are that international aviation should aim to achieve 2% annual fuel efficiency improvement until 2050, and for carbon neutral growth from 2020 onwards (these had originally been established by ICAO in 2010). Again, these are not legally binding. Linked to its goal of carbon neutral growth, in 2016 ICAO adopted a global CO_2 offsetting mechanism called CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) which commences in 2021 (ICAO, 2021). In addition, CO_2 emissions from aviation have been included in the EU emissions trading system (EU ETS) since 2012, with airlines required to monitor and report their CO_2 emissions for flights wholly within the European Economic Area (EEA) (European Union, 2011).

3.2 The importance of transport in GHG emissions in the UK

Transport, including freight transport, is currently one of the high GHG-emitting sectors that will need to change radically in this regard (other high-emitting sectors include energy generation and supply, housing and domestic heat, industry and agriculture). The most recent analysis by the UK Government shows that transport was the largest emitting sector of UK GHG emissions in 2018 (28% of UK total), followed by energy supply (23%), business (18%), residential (15%), agriculture (10%), waste management (55%) and other (2%) (BEIS, 2020a).

The transport sector comprises passenger and freight transport GHG emissions from road, rail, aviation and maritime transport. In the UK, road travel is the most significant source of domestic GHG emissions in the transport sector, accounting for 91% of domestic GHG emissions from transport in the UK in 2018. This is followed by domestic maritime transport, which accounted for 4.8% of GHG transport emissions in the UK in 2018, and domestic rail and air travel, which accounted 1.4% and 1.2% of GHG transport emissions in the UK in 2018, respectively (BEIS, 2020a). Renewable energy sources accounted for 9% of UK transport energy consumption in 2019 (excluding aviation), while accounting for 37% of UK electricity generation (BEIS, 2020).

ITF has produced modelling estimates of global CO_2 emissions from transport that subdivide these into freight and passenger transport. These indicate that freight transport was responsible for 36% of total transport CO_2 emissions in 2015, with both domestic and international freight transport responsible for 18% of this total. (ITF, 2019). Such estimates of the comparative contribution of CO_2 emissions from domestic and international freight transport in the UK, as the freight component of aviation and maritime shipping has not been calculated by Government.

However, freight operations are responsible for the majority of UK domestic and international maritime activity and GHG emissions. In 2019, freight vessels (including tankers, container ships, Ro-Ro vessels, and dry cargo ships) were responsible for 98% of all ship arrivals at UK ports, while passenger vessels only accounted for 2% (Department for Transport, 2020g). Based on refuelling at UK ports, international shipping to and from the UK was responsible for more GHG emissions than domestic shipping in the UK in 2018 (equivalent to 5% and 4% of UK total domestic and international GHG emissions from transport, respectively). Therefore, in total, shipping to, from and within the UK accounted for approximately 3% of the UK's total GHG emissions and 11% of the UK's transport GHG emissions (BEIS, 2020a). It has been estimated that international shipping accounted for 2.5% of global CO_2 emissions in 2020 (IMO, 2020).

International aviation to and from the UK accounted for 93% of all GHG emissions from UK aviation in 2018. Based on refuelling at UK airports, international aviation to and from the UK was responsible for far more GHG emissions than domestic aviation in the UK in 2018 (equivalent to 22% and 1% of UK total domestic and international GHG emissions from transport, respectively). In total, all UK aviation (flights to, from and within the UK) accounted for approximately 7% of the UK's total GHG emissions in 2018 (BEIS, 2020a). Meanwhile, GHG emissions from all international aviation accounts for approximately 2% of total global GHG emissions (European Commission, 2017).

Freight and mail are carried on both dedicated freighter aircraft as well as in the bellyhold of passenger aircraft, with the latter being far more common. In 2019, dedicated freighter aircraft only accounted for 3% of all flights to, from and within the UK and carried 31% by weight of all UK air freight and mail. By weight, 76% of air freight and mail is moved on longer international flights outside the EU, 18% is moved on flights to and from the EU, and 6% on UK domestic flights. By weight, dedicated freighter aircraft move 13% of air freight and mail on longer international flights outside the EU, 88% of EU air freight and mail, and 98% of UK domestic air freight and mail (CAA, 2020).

When international aviation and shipping to and from the UK are added to domestic transport GHG emissions, this increases emissions from the transport sector to approximately 32% of total GHG emissions in the UK in 2018 (with road accounting for 21%, aviation 7%, shipping 3% and rail 1%) (Committee on Climate Change, 2020).Table 2 shows the absolute and relative GHG emissions of UK domestic and international transport modes in 2018.

As is the case for domestic passenger transport activity, road is the dominant mode for domestic freight transport in the UK. Road freight accounted for 90% of tonnes lifted domestically in Britain in 2018, compared with 4% by rail, 6% by water, and 0.009% by air. In terms of goods moved domestically in 2018, road accounted for 79% of tonne-kilometres, compared with 9% by rail and 13% by water (Department for Transport, 2020o).

Road freight accounted for 33% of GHG emissions from all domestic transport (i.e. passenger and freight) in the UK in 2018, and 36% of GHG emissions from UK road transport. This is equivalent to 9% of UK total GHG emissions in 2018. HGVs (also referred to as trucks) and LGVs accounted for 17% and 16% of GHG emissions from domestic transport, respectively (BEIS, 2020a). HGVs performed 87% of their traffic activity on motorways and rural roads in the country in 2018 compared with 13% on urban roads, while for LGVs this split was 65% and 35%, respectively (Department for Transport, 2020q).

Table 2: Transport GHG emissions for UK domestic and international transport, 2018

Transport mode	GHG emissions (million tonnes)	% of GHG emissions from all UK transport
Cars and taxis	68.5	40.5%
Heavy goods vehicles	20.7	12.3%
Light goods vehicles	19.4	11.5%
Buses and coaches	3.2	1.9%
Motorcycles & mopeds	0.5	0.3%
Other road transport emissions*	0.6	0.4%
Rail	1.8	1.1%
Domestic aviation	1.5	0.9%
International aviation	36.7	21.7%
Domestic shipping	5.9	3.5%
International shipping	7.9	4.7%
Other transport*	2.2	1.3%
Total	168.9	100.0%

Notes:
* - emissions from road vehicles running on liquified petroleum gas (propane and butane), emissions from the evaporation of engine lubricants and urea as well as urea use, and biofuel use.
** - 'military aircraft and shipping and 'aircraft support vehicles'.

Source: (BEIS, 2020a).

It should be noted that road transport GHG emissions are calculated from UK road traffic data. Therefore, the international (i.e. non-UK) parts of the road freight journeys to and from the UK made by UK-registered or foreign-registered goods vehicles are not included in these domestic road freight transport GHG emissions calculations. Neither are the foreign road journeys of goods that arrive in the UK by ship or aircraft. In 2018, goods moved by UK-registered and foreign-registered goods vehicles making international journeys to and from the UK accounted for 2.6% and 18.9% of total (i.e. domestic and international) goods moved by road to/from the UK, respectively. In terms of goods lifted, UK-registered and foreign-registered goods vehicles making international journeys to and from the UK accounted for 0.6% and 2.5% of total goods lifted by road to/from the UK, respectively (Department for Transport, 2020i). No data is available for road journeys made in foreign countries that transport goods to seaports and airports for despatch to the UK.

Rail freight was only responsible for 16% of the total GHG emissions from rail transport in 2018/19 (Office of Rail and Road, 2020), which equates to 0.2% of domestic GHG transport emissions in the UK in 2018.

Although this report is concerned with the GHG emissions that arise during freight transport, it is important to note that in addition to the transportation of goods, many other aspects of logistics operations also result in GHG emissions. These include the handling and storage activities involved in the supply of goods from point of production to consumption. At the various locations in supply chains which goods are transported between (including factories, assembly plants, warehouses, distribution centres, transhipment centres and local transport depots) the goods are moved to and from transport vehicles and to and from these buildings using materials handling equipment (such as forklift trucks, pallet trucks, conveyor systems and gantry cranes).

Whilst goods are in storage in such buildings, energy is consumed in the provision of heating and lighting. Estimates suggest that warehousing accounts for approximately 10% of carbon emissions in the UK (two estimates put it at 11% while another put it at 13% - (AEA, 2012) (Baker & Marchant, 2015) (World Economic Forum and Accenture, 2009). Lighting is the major source of energy consumption within an ambient warehouse, accounting for 65%-95% of total energy consumed (Carbon Trust, 2019).

Logistics packaging is also required to maintain the quality of goods, prevent damage and achieve efficient space utilisation during freight transportation and storage activities. Various freight transport and other logistics activities are supported my many computing devices, which provide logistical support services including vehicle monitoring, inventory management, stock control and order picking. These computing devices and the servers on which data is stored are powered by electricity.

As is the case for freight transport activities, all of these aspects of logistics operations result in energy consumption and therefore have implications for GHG emissions. However, estimates of the GHG emissions associated with all of them are not currently available.

It should be noted that while this report is primarily focused on freight transport decarbonisation in the UK, freight transport operations take place in all countries of the world as well as between many of them. The UK is only responsible for a small proportion of global freight transport activity. It is the intention of the authors that, whilst not specifically referring to GHG emissions from freight transport and efforts to reduce them in countries outside of the UK, the contents of this report should be of general use and interest to those engaged in the consideration of freight transport decarbonisation across the world.

3.3 Trends in UK freight transport activity and GHG emissions since 2008

Since 2008, when the UK Government first introduced GHG emissions reduction targets, policymakers have emphasised that the freight transport and logistics sector must play its part in GHG reduction. Public sector publications making this point have been backed up by research, technology development and trials, funded by public and private sector organisations as well as by private foundations and charities. Freight transport and logistics companies have taken part in these trials and long-term implementations. Joint public-private sector working groups and consultations have been formed to work on the development and communication of freight transport GHG reduction targets and approaches.

There are several main approaches by which the decarbonisation of freight transport can be achieved. These include approaches that reduce the total distance that freight vehicles have to travel: for instance through reducing the demand for freight transport activity by reorganising supply chain organisation and altering the location of facilities between which goods are moved; by shifting goods transport to less carbon-intensive freight modes (especially from road to rail); improving the efficiency of existing freight transport operations (by increasing the quantity of goods carried in each vehicle movement, and reducing empty vehicle journeys). In addition, freight GHG emissions can also be reduced by using the most energy efficient conventionally fuelled freight vehicles that make use of recent advances in engine technology and vehicle design, as well as using vehicles that run on less carbon-intensive fuel sources. Progress in achieving GHG reductions in freight transport via some of these approaches over the last decade can be monitored through the assessment of data collected by the UK Government, especially data that provides insight into HGV usage and operations.

3.3.1 Freight modal split for surface transport

Freight transport by means of rail and water is able to take advantage of the far greater carrying capacities of these modes compared to road vehicles. Thereby, if the greater carrying capacity of these modes is utilised, they typically result in less GHG emissions per unit carried than the use of road transport.

There was little change in the proportion of goods lifted by road, rail and water in Britain between the 2008 and 2019 (with road accounting for 88% of all goods lifted in 2008 and 90% in 2019). In terms of goods moved, the proportion of tonne-kilometres performed by road, the most carbon intensive surface transport mode, increased from 67% of all goods in 2008 to 79% in 2019, an 18% increase in the relative importance of road freight (Department for Transport, 2020o) (see Figure 1).

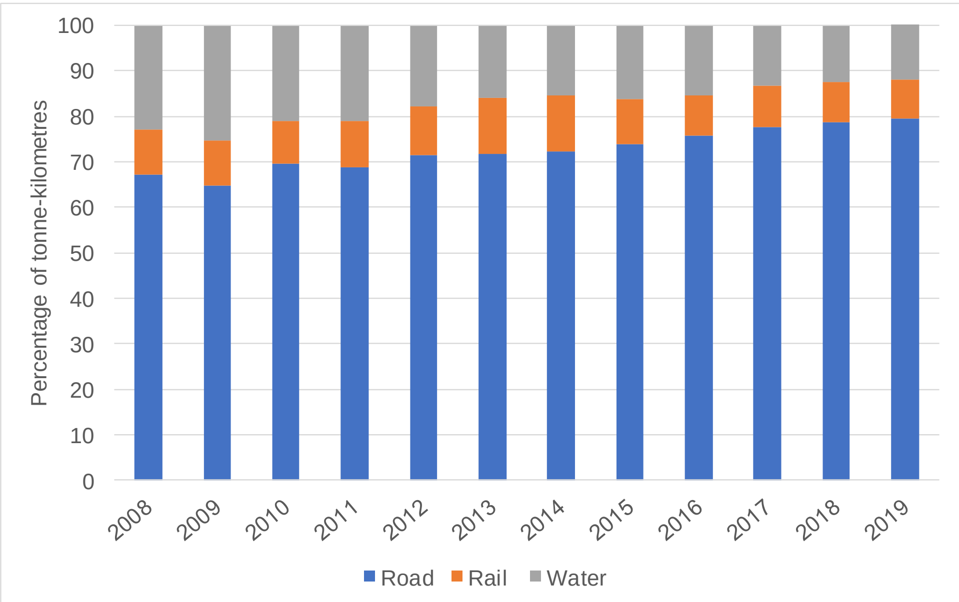

Figure 1: Goods moved in Britain by mode, 2008-19 (Department for Transport, 2020o)

The importance of domestic freight transport activity by mode varies significantly from that for all freight transported globally. It has been estimated that in 2015 maritime shipping accounted for 70% of total tonne-kilometres performed worldwide, road for 18%, rail for 9%, inland waterways for 2% and air for 0.25% (ITF, 2019).

3.3.2 Strategic location of freight-related activities (average length of haul by HGVs)

The Department for Transport's 'Continuing Survey of Goods Transport' provides average length of haul data for HGV operations. The length of haul indicates the average distance over which goods are transported on each HGV journey. A reducing average length of haul over time would potentially indicate the relocation of facilities between which goods are transported, and thereby reduced GHG emissions, all other things being equal.

The average length of haul for HGV road freight operations in Britain was 22% greater in 2019 than in 2008 (see Figure 2) (Department for Transport, 2020l).

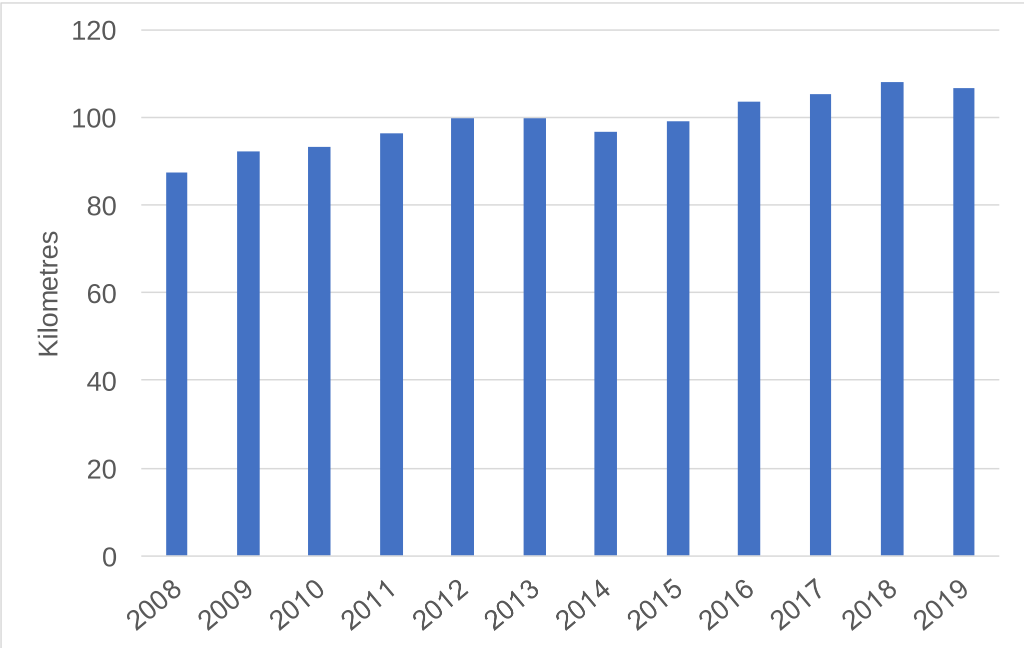

Figure 2: Average length of haul by HGVs in Britain, 2008-2019 (Department for Transport, 2020l)

3.3.3 Efficiency of road freight transport operations

The loading factor (the extent to which the vehicle's weight capacity is used over the distance it travels when loaded) and the empty running (the proportion of its distance travelled over which it runs unloaded) indicate the efficiency of road freight transport operations. An increasing loading factor and a reducing proportion of empty running are both indications of greater efficiency.

Based on all rigid and articulated vehicles , the loading factor of HGV operations in Britain was just over 5% higher in 2019 than in 2008 (see Figure 3) (Department for Transport, 2020m). The biggest improvement (12%) came from vehicles between 3.5 and 7.5 tonnes, with larger rigids showing a slightly worse fill rate. Articulated vehicles generally had an improved fill rate of just over 3%.

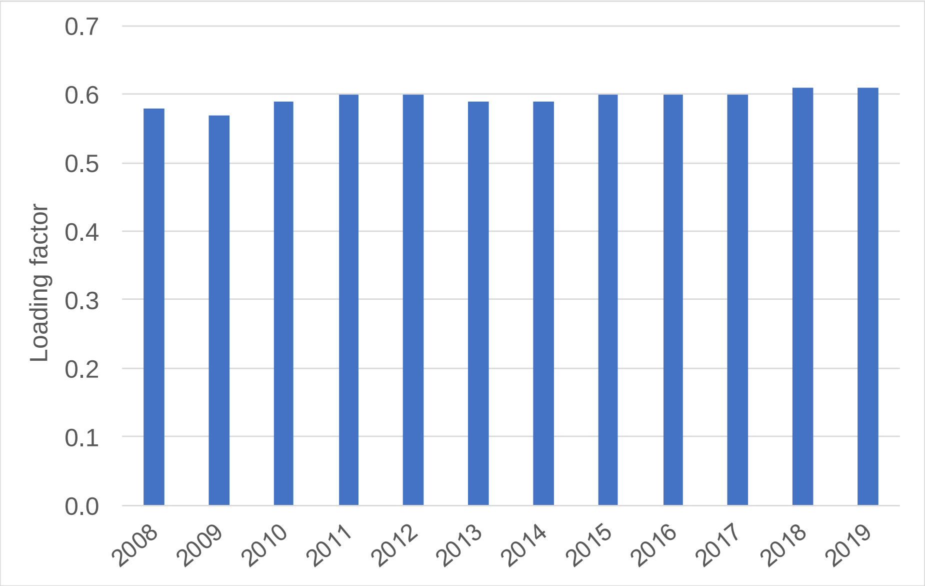

Figure 3: Loading factor of HGVs in Britain, 2008-2019 (Department for Transport, 2020)

For all rigid and articulated vehicles, empty running by HGVs in Britain was 1.1% higher in 2019 at 30% than in 2008 (see Figure 4) (Department for Transport, 2020m). This varies from 22.6% for articulated vehicles of 33 tonnes or less to 37.1% for rigid vehicles more than 25 tonnes.

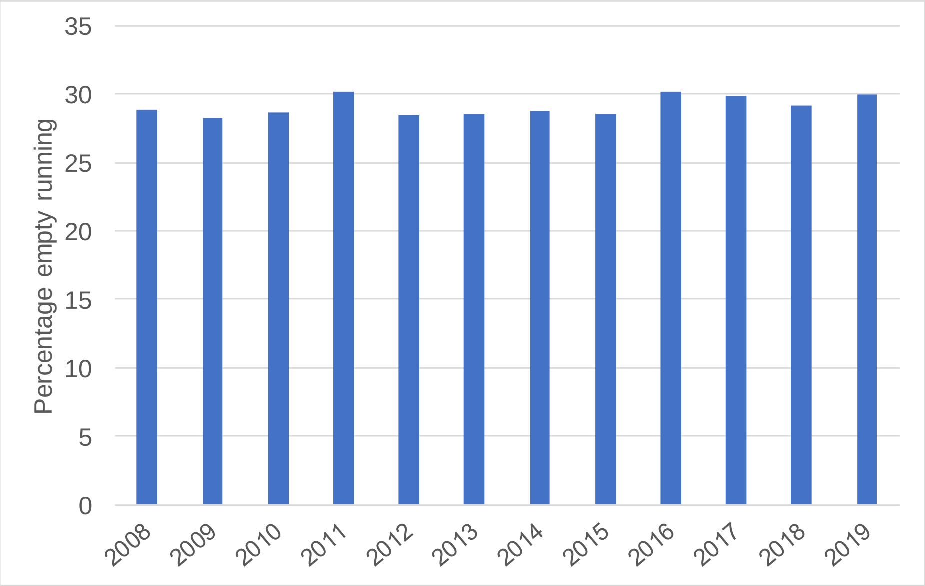

Figure 4: Empty running by HGVs in Britain, 2008-2019 (Department for Transport, 2020).

3.3.4 Road freight vehicle replacement

The frequency with which operators replace their freight vehicles has implications for the speed of implementation of improvements in vehicle design, engine efficiency or new fuel sources, all of which can reduce GHG emissions. Therefore, lower the average age of freight vehicles, the faster the rate of implementation of such decarbonisation features.

The average age of HGVs in Britain increased from 6.7 years in 2008 to 7.4 years in 2019, an increase of 11%, while the average age of LGVs increased from 6.8 years in 2008 to 8.3 years in 2019, an increase of 23% (see Figure 5) (Department for Transport, 2020r) (Department for Transport, 2020s).

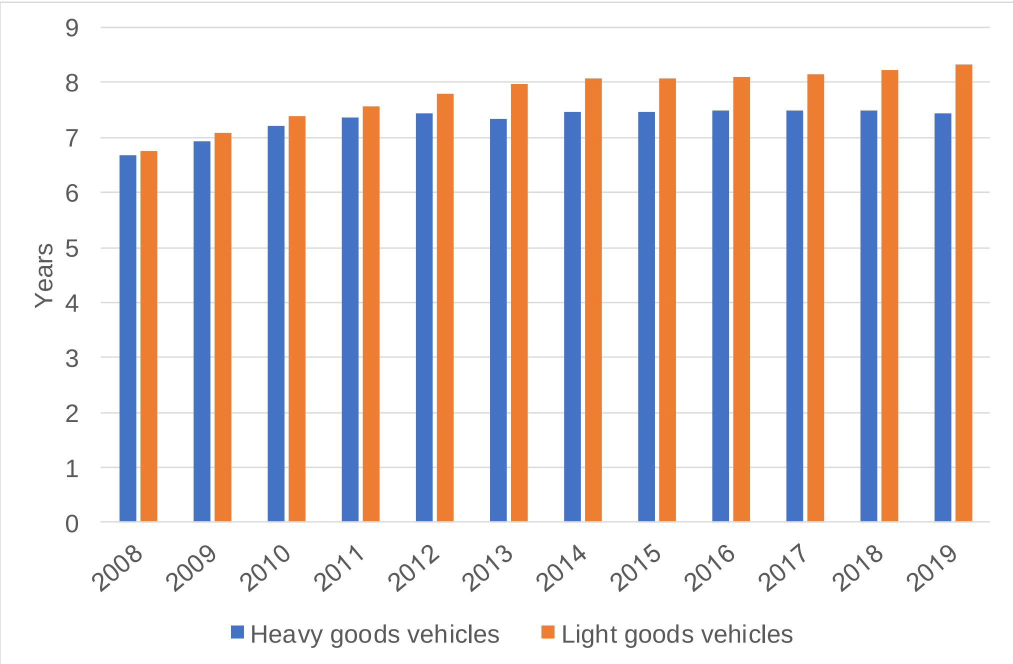

Figure 5: Average age of light and heavy goods vehicles in Britain, 2008-2019 (Department for Transport, 2020).

In 2019, 29% of HGVs were at least 10 years old, compared with 24% in 2009. For LGVs, 34% were at least 10 years old in 2019, compared with 29% in 2009 (Department for Transport, 2020r) (Department for Transport, 2020s).

3.3.5 Use of alternatively-fuelled road freight vehicles

The acquisition and use of goods vehicles powered by fuels with lower carbon content than conventional fossil fuels reduce the GHG emissions of the goods vehicle fleet. Vehicles powered by gas (biogas or gas-diesel hybrid) or electric batteries (in the case of lighter HGVs) rather than diesel have been available for a considerable period of time. However, the variety and range of such vehicles was, until recently, rather limited.

In 2019, there were a total of 600 gas and 400 battery electric HGVs licensed in Britain, equivalent to 0.2% of the total HGV fleet in 2019. This represented a 47% reduction in the total number of these vehicles compared with 2008 (Department for Transport, 2020t).

Meanwhile in 2019, there were a total of 10,400 battery electric and 5,300 gas-powered LGVs licensed in Britain, which represented 0.4% of the total LGV fleet. This was a 146% increase in the number of electric LGVs and a 57% reduction in the number of gas LGVs compared with 2008. Overall, there was a 121% increase in the total number of electric and gas powered LGVs between 2008 and 2019, albeit from a very small base (Department for Transport, 2020v). In 2019, 3500 electric LGVs were registered for the first time compared with 1000-1500 such vehicles registered each year between 2015-2018 which indicates an increase in uptake from a small base (Department for Transport, 2020u).

3.3.6 GHG emissions by type of road goods vehicle

UK Government modelling has calculated that between 2008 and 2018, the GHG emissions by HGVs and LGVs operated in Britain increased by 6% and 22% respectively. In the case of HGVs, the total distance travelled declined by 2% over this period but the proportion of articulated HGVs over 41 tonnes gross weight increased from 16% of the fleet in 2008 to 23% in 2018 (Department for Transport, 2020o). In the case of LGVs, this was due to an increase in the total LGV fleet (from 3.2 million to 4.1 million vehicles) and its activity (from 67 to 88 billion vehicle kilometres) (Department for Transport, 2020o).

3.3.7 Summary of recent UK trends in road freight operations and GHG emissions

Road is by far the most important mode of freight transport in the UK, accounting for approximately 90% of all goods lifted and the majority of freight transport GHG emissions.

Chapter 3 has reviewed available official national data to consider the extent to which relevant aspects of road freight transport vehicle use and operations have become more or less GHG-intensive since the first GHG reduction targets were enshrined in law in the UK in 2008.

Table 3 summarises the direction and extent of change in the aspects of road freight transport reviewed using UK Government data. As indicated by

Table 3, despite the introduction of legally binding GHG reduction targets in the UK, all but one of these aspects of road freight transport have become more GHG intensive since 2008. This indicates a lack of progress to date in the uptake and implementation of freight transport decarbonisation in the UK.

Table 3: Changes in factors influencing GHG emissions in road freight transport in Britain, 2008-2019

Factor	Heavy goods vehicles (HGVs)	Light goods vehicles (LGVs)
Modal split (goods moved by road rather than less-carbon intensive modes)	18% worsening (based on tonne-kilometres	Not available
Tonne-kms	6% increase	
Average length of haul	22% worsening	Not available
Loading factor	5% improvement	Not available
Empty running	5% worsening	Not available
Vehicle kilometres travelled by national fleet	2% improvement	34% worsening
Proportion of alternatively fuelled vehicles	47% worsening (from very small base)	121% improvement (from very small base)
Total GHG emissions*	6% worsening	22% worsening

Notes:
* - 2008-2018 rather than 2008-2019 due to data availability.

Key:

Worsening
Improvement

It may seem somewhat surprising that UK Government estimates indicate that the total GHG emissions from the total British HGV fleet worsened over the period despite the fact that the total distance they travelled reduced. This is due, at least in part, to the fact that there has been a shift towards the use of the heaviest articulated HGVs, which have poorer fuel economy and therefore greater GHG emissions per vehicle kilometre travelled. Over the period 2008-2019, articulated HGVs over 33 tonnes gross weight increased their relative share of all goods lifted by HGVs from 53% to 61%, and their share of total HGV vehicle kilometres from 47% to 54%.

3.4 Recent trends in operations and GHG emissions of non-road freight transport modes

Although road is the dominant mode of freight transport in the UK it is important to put this in the context of what trends are happening to other modes of transport in terms of reducing GHG emissions.

3.4.1 Rail freight

Rail is considered to be a more efficient form of transport than conventional road vehicles, maritime and aviation in terms of energy consumption and GHG emissions per passenger-kilometre or tonne-kilometre performed. Passenger rail services are far more numerous in the UK than rail freight services, with passenger services responsible for 84% of the total GHG emissions from rail transport in the country in 2018/19 (Office of Rail and Road, 2020).

There are approximately 630 locomotives in operational use by rail freight operating companies in the UK (Rail Industry Decarbonisation Taskforce, 2019). Rail is most energy and GHG efficient when powered by electricity. The majority of rail freight trains in the UK are powered by diesel locomotives.

In 2019/20, diesel freight trains were responsible for 96% of all GHG emissions from rail freight in the UK. GHG emissions from UK rail freight operations fell by 16% between 2008/9 and 2019/20 (Office of Rail and Road, 2020). However, over this period, freight moved by rail (measured in tonne-kilometres) fell by 31% (Department for Transport, 2020o). This represents a 15% increase in GHG emissions per tonne-km of rail freight performed between 2008/9 and 2019/20.

3.4.2 Maritime shipping

The average carbon intensity of international maritime transport (freight and passenger) improved 20-30% between 2008 and 2018. However, these improvements in carbon intensity have not been linear over this period, and more than half of them were achieved between 2008 and 2012. Since 2015, the rate of carbon intensity reduction has fallen with, on average, annual improvements of 1-2%. This improvement in carbon intensity is the result of an increase in average ship size and a reduction in operating speeds (often referred to as 'slow steaming') (IMO, 2020). However, despite these improvements in carbon intensity, GHG emissions from international maritime transport increased by approximately 10% between 2012 and 2018. This was due to the growth in total shipping activity (IMO, 2020).

UK total maritime transport GHG emissions decreased by 25% between 2008 and 2018, with the greatest fall in emissions occurring after the global financial crisis of 2008. Over this period, international maritime freight tonnages to and from UK ports fell by 8% and ship arrivals by 15% (Department for Transport, 2020g). As well as reductions in ship arrivals and tonnages carried, GHG emissions reductions were also due to improvements in energy efficiency, and where international vessels serving the UK choose to refuel, which is affected by relative fuel prices, and which determines the allocation of international shipping emissions. The reduction in GHG emissions of UK international shipping is likely to be due to reductions in maritime freight traffic including dry and liquid bulk such as coal and oil to and from the UK and increased use of the Channel Tunnel by goods vehicles (Committee on Climate Change , 2020).

Shipping is projected to continue to grow over the coming decades and, without actions, global GHG emissions are forecast to increase by up to 50% by 2050 (European Parliament, 2020).

3.4.3 Air freight transport

Freight is carried on both dedicated freighter aircraft as well as in the bellyhold of passenger aircraft, with the former being far less common and only accounting for 3% of all flights to, from and within the UK (CAA, 2020).

Global GHG emissions from aviation have grown at approximately twice the rate of total global GHG emissions since 1990 (Sustainable Aviation, 2020). In the UK, international and domestic aviation GHG emissions were 124% higher in 2018 than in 1990 (BEIS, 2020a). This is due to the substantial increase in air traffic over the period.

Despite this growth in activity, the aviation industry has increased operational efficiency with the use of larger aircraft with greater carrying capacities, and by achieving higher load factors (i.e. more passengers and cargo per flight). In addition, demand for short haul flights to EU countries has outstripped the demand for longer haul destinations. Military and domestic aviation activity in the UK have diminished while international traffic has grown. The implementation of new aircraft with enhanced engine technology, improved maintenance practices and greater use of airport infrastructure rather than auxiliary power units on aircraft, together with improved airspace management have also contributed to more GHG efficient operations. Carbon offsetting schemes have also led to reductions in net GHG emissions (Sustainable Aviation, 2020) (Committee on Climate Change, 2020a). There has also been some limited use of sustainable aviation fuels.

As a result, between 2005 and 2016, major UK airlines carried 26% more passengers and freight, but CO_2 emissions only increased by 9% (Sustainable Aviation, 2020). Similarly, between 2010 and 2016, international air transport movements within the UK grew by 20%, but international GHG emissions increased by only 7% (Department for Transport, 2018). GHG emissions from total aviation to., from and within the UK in 2018 were only 3% higher than in 2008 despite UK passengers increasing by 24% (Committee on Climate Change, 2020a) (BEIS, 2020a)

Between 2008 and 2018, dedicated freight flights to, from and within the UK fell by 8% and passenger flights (which carry freight in their bellyhold) fell by 3%, while the weight of freight and air cargo carried rose by 8% (CAA, 2020). Over this period, GHG emissions from all UK aviation (domestic and international) rose by 3% (BEIS, 2020a).

However, much remains to be done to reduce GHG emissions in aviation given the predicted strong growth in demand for air services. It has been estimated that due to continued demand growth, global GHG emissions could result in aviation accounting for 4-8% of total global GHG emissions compared with the 2% for which it currently accounts (Department for Transport, 2018) (European Commission, 2017).

3.4.4 Summary of UK GHG emissions from non-road transport modes

Table 4 provides a summary of the changes in UK domestic and international GHG emissions from non-road transport modes (namely, rail, maritime shipping, and aviation) over the period 208-2018.

Table 4: Change in UK GHG emissions by non-road transport modes, 2008-2018

Transport mode and geographical coverage	Change in total GHG emissions, 2008-2018
All UK rail	11% improvement
UK domestic shipping	*20% improvement*
UK international shipping	*29% improvement*
All UK shipping	25% improvement
UK domestic aviation	*34% improvement*
UK international aviation	*6% worsening*
All UK aviation	3% worsening

Note: the data refers to all rail, shipping and aviation operations (i.e. including passenger and freight)

Source: calculated from data in (BEIS, 2020a).

4 Systematic review of roadmapping literature

4.1 Publication date, author and funder, and geographic coverage

The 53 publications included in the detailed systematic review of freight transport decarbonisation roadmapping literature were analysed in terms of their year of publication, the type of author/s and funder/s of the research, and the geographic area covered by the research in the publication. A listing of these 53 publications together with a summary of some of their key characteristics is provided in Appendix A.

Figure 6 shows the year of publication of the literature reviewed. As previously mentioned, all publications prior to 2015 and most publications released more than three years ago were omitted from this content analysis due to the rapid evolution in the freight decarbonisation debate. As can be seen, the relevant literature identified and included in this analysis increased year-on-year between 2017 and 2019. There are fewer 2020 publications included than for 2019 (15 compared with 18 publications), but rather than indicating a reduction in interest in the subject, this is likely to be a reflection of the impact of the Covid-19 pandemic on research and publication activities.

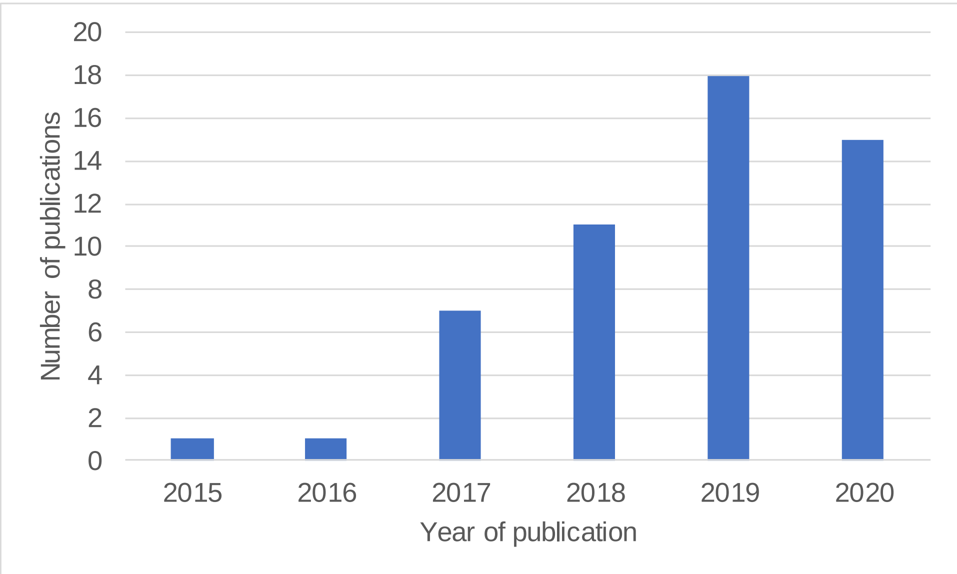

Figure 6: Publication year of the literature reviewed

The organisation of the author/s responsible for the writing and analysis contained in each of the publications reviewed were allocated to several categories to reflect their status. Figure 7 shows that public sector organisations (i.e. national and international governmental organisations, executive agencies, independent public bodies, national and international research centres and other publicly-funded bodies) were responsible for the production of more of the publications than any other type of author (15 publications). This is unsurprising given that it is governments that have been responsible for setting national decarbonisation targets. Thirteen of the publications were produced collaboratively, between two or more of the organisational types listed in Figure 7. Academics, consultancies, the private sector (including trade associations and organisations representing industry), and the third sector (i.e. not-for-profit advocate and non-governmental organisations, charities and professional bodies) were each responsible for between six to seven of the publications.

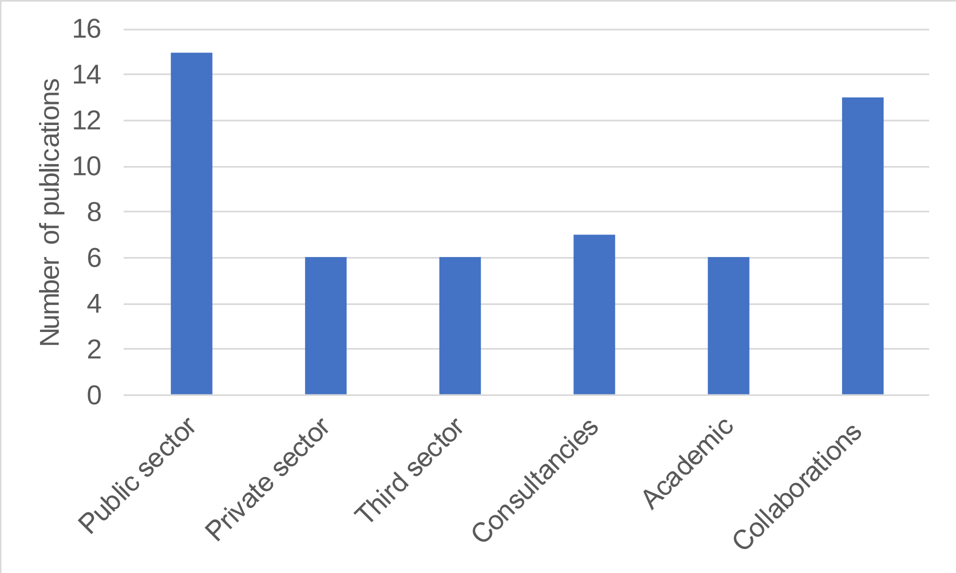

Figure 7: Organisation category of the author/s of the publications reviewed

Figure 8 shows the categories of funding source of the work carried out in the publications reviewed. In the case of the few publications by academics that provide no acknowledgement of the funding source for the work, it was assumed that the funder was the author's own institution.

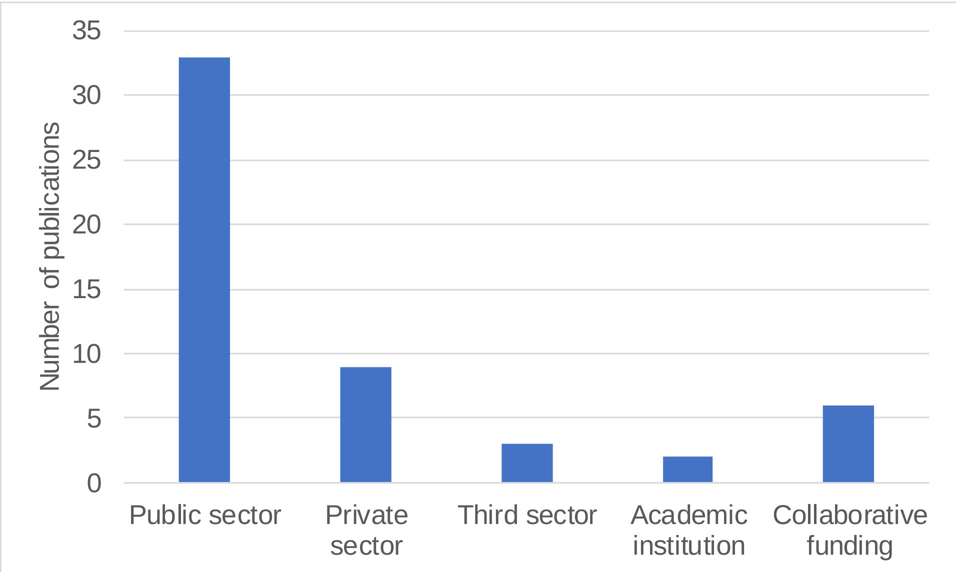

Figure 8: Category of funding source of the work for the publications reviewed

The public sector is by far the most common source of funding for the publications reviewed, responsible for funding 6 out of 10 of them. Public funding sources include national and international governmental bodies, executive agencies, independent public bodies, and national and international sources of research funding such as the European Union).

The publications reviewed vary in terms of their geographic coverage. Twenty one focus on the UK, 17 have an EU/Europe coverage (including the UK), while 15 have an international or worldwide coverage (see Figure 9).

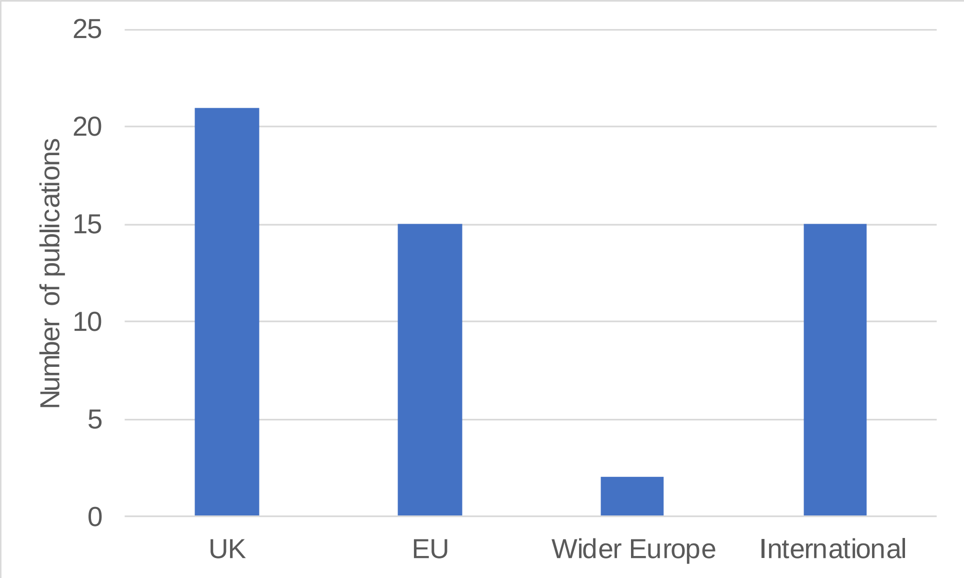

Figure 9: Geographic coverage of the publications reviewed

4.2 Research focus, transport modes included and time horizon

The content and coverage of each of the 53 publications were analysed in terms of whether or not they focus solely on the issue of decarbonisation, whether or not they are solely freight transport focused, the modes of transport included, and the time horizon used by each of the publications.

Forty one of the 53 publications included in this review focus solely on decarbonisation. Only 12 of them contain a broader remit than decarbonisation alone (see Figure 10). The additional transport impacts and issues beyond decarbonisation addressed by these publications include traffic congestion and growth, air pollutants and air quality, transport infrastructure requirements, automated and connected vehicles, and road safety. Some of the publications go beyond transport and decarbonisation considerations and focus on wider environmental sustainability impacts, resource efficiency, energy security, land use and employment issues.

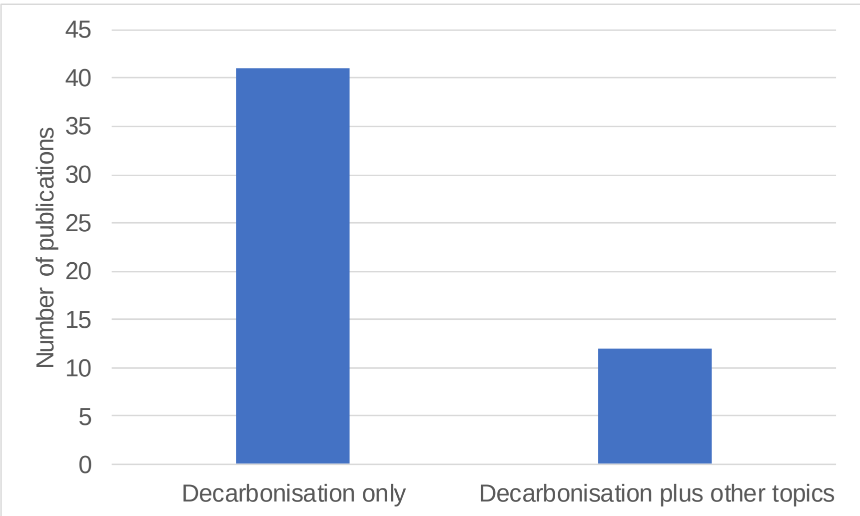

Figure 10: Impacts and issues addressed by the publications reviewed

Two-thirds of the publications included in this detailed review focus specifically on freight transport CO_2 emissions only, while the other third of the publications comprise a consideration of wider sources of CO_2 emissions than freight transport alone (see Figure 11). The latter include consideration of other transport activity that imposes CO_2 emissions including passenger transport (i.e. cars, buses, passenger trains and aviation), as well as other sources (including heat and power provision, manufacturing and other industry, building, agriculture).

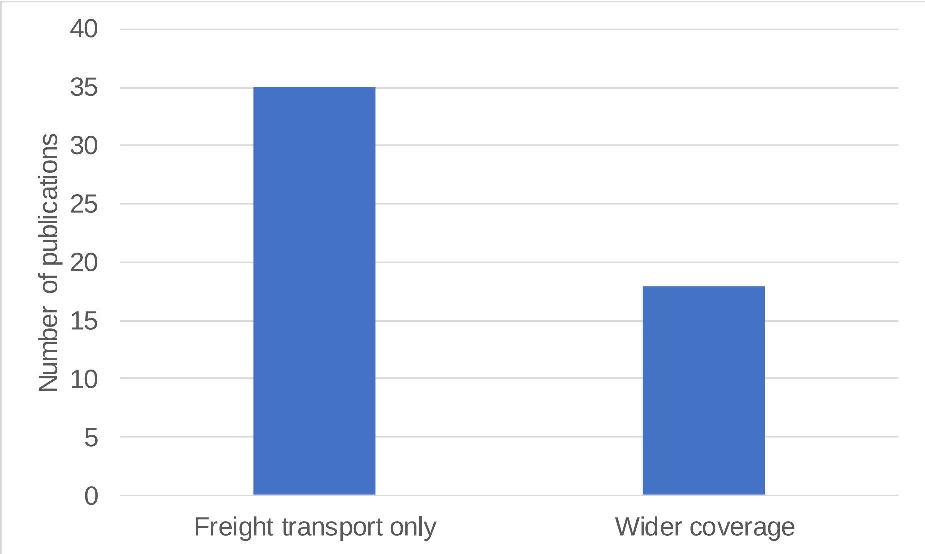

Figure 11: Whether the publications reviewed focused only on freight transport or additional sources of GHG emissions

Figure 12 shows the transport modes considered in the publications reviewed, whether the document considers only freight transport or consists of wider transport coverage. Almost half (25) of these publications consider road transport only, while 17 of them consider all transport modes (sometimes without much modal detail included). Four of the publications consider only maritime shipping, three focus only on aviation, and two only on rail transport, and two on both road and rail transport.

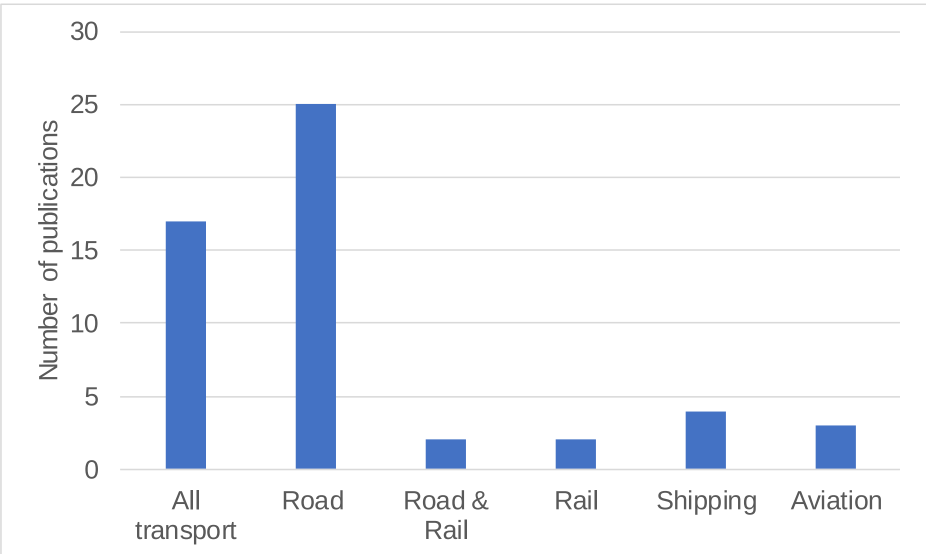

Figure 12: Transport modes considered in the publications reviewed

The publications vary in terms of the time horizon over which they consider and discuss decarbonisation. Figure 13 shows the longest timescale referred to by publication for the 53 publications which refer to a specific timescale. This indicates that 2050 is by far the most frequent timescale considered, presumably due to that being the date for decarbonisation targets being made by many countries.

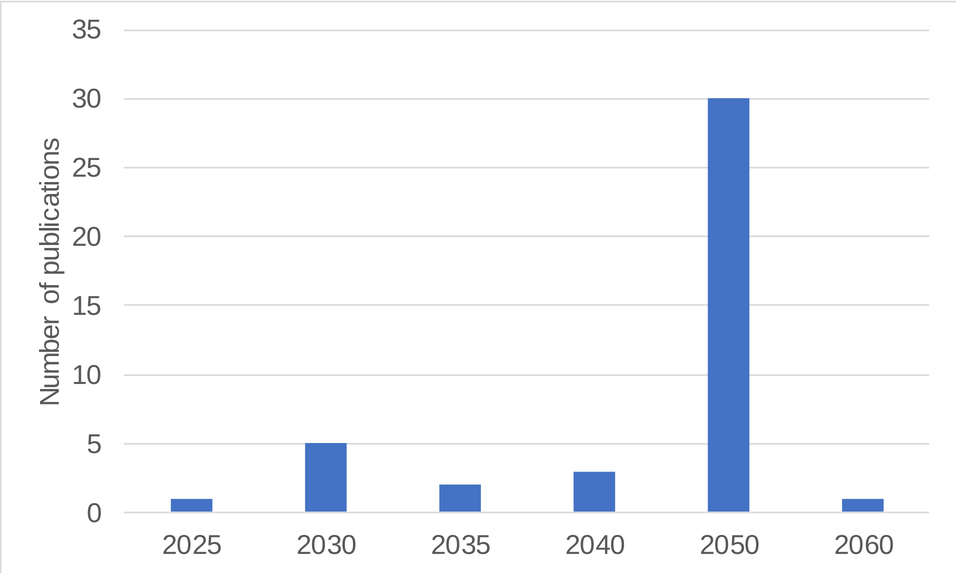

Figure 13: Longest timescale over which decarbonisation is considered in the publications reviewed

Generally, the literature reviewed has been framed in terms of the technology and measures necessary to achieve net zero carbon CO_2 emissions by 2050, but they do not tend to address the transition towards zero carbon over time. In other words, the timings and CO_2 emissions that will occur en-route to 2050 are not well discussed. Nor does the literature address the timings and costs that might be incurred to establish the infrastructure necessary to support the carbon saving measures, or the costs the logistics sector would incur for using the technologies and measures. Only three publications have provided what could be described as full roadmaps to 2050, while other publications contain roadmaps that focus a far narrower consideration of freight decarbonisation. For instance, the Sense project (Sense project, 2020) roadmap focusses only on the physical internet, whilst the ERTRAC roadmaps (ERTRAC, 2019) show a range of strategic road freight carbon reducing measures based on the type of roads used by vehicles. The ITF report (ITF, 2018) presents a different form of road map based on expert opinions of when various measures are likely to be introduced and their likely impact.

4.3 Categories and measures of decarbonisation intervention

For the purposes of this analysis of the content of the publications, the range of freight transport measures that have a bearing on carbon emissions were also considered. In devising a suitable framework that encompasses all of these factors, the publications were analysed in order to identify any framework used and categories of action that can lead to freight transport decarbonisation.

The ALICE report (ALICE-ETP, 2019) which comprises a freight transport roadmap to 2050, makes use of five key solution areas, each containing a list of specific solutions (as shown in Appendix B). Other publications also provide a comprehensive list of freight transport measures that have a bearing on carbon emissions, organised by category (such as Greening et al., 2015; McKinnon, 2018; (International Energy Association, 2017).

The categories presented and discussed in these other publications have been adapted to produce a framework for this report that consists of eight overarching categories. Five of these categories appear in the ALICE report while the other three are based on key factors covered in the other publications. These eight categories are:

- **Reducing the level of freight transport demand** – this refers to reducing the total level of freight transport activity that is required to move and deliver the quantity of goods required, either through changing the nature of production, where production takes place, consumer expectations and service levels, and the quantity of waste arising in supply chains and how it is handled.

- **Shifting freight to lower-carbon transport modes** – this refers to the choice of freight transport mode used to move goods. Mode choice includes: road, rail, sea, waterway and air, and these modes vary in terms of their GHG emissions per unit of freight transport activity. Within the road mode there are several vehicle choices including trucks (HGVs), light goods vehicles (LGVs), motorcycles, and electric cargobikes.

- **Improving asset utilisation in freight transport** – this refers to how efficiently the capacity of freight transport vehicles is used, and thereby, the GHG emissions per unit of goods transported.

- **Organisation of physical logistics systems** – this refers to the way in which logistics facilities and vehicles are organised and operated and how goods are packaged and their impact on GHG emissions.

- **Digitalisation of freight transport and logistics –** this refers to the use of digital technologies in logistics and freight transport to improve efficiency and reduce GHG emissions. This digital technology can be applied to freight vehicle operations, logistics planning and supply chain design.

- **Increasing energy efficiency of freight transport vehicles –** this refers to design and technology features made use of in the production of the freight transport vehicles that are used to transport goods (be they lorries, vans, ships, or aircraft) that influence the energy efficiency of those vehicles per unit of distance travelled.

- **Switching to lower-carbon energy –** this refers to the types of fuel used to power freight transport vehicles. Whereas fossil fuels have conventionally been used to fuel freight vehicles, new fuels are being developed with lower-carbon contents.

- **Energy systems for freight transport** – this refers to the production systems required to generate lower-carbon energy sources for freight transport. It is therefore closely related to the previous category of 'switching to lower-carbon energy'.

Each of these eight freight transport categories that can lead to reductions in CO_2 emissions are associated with a range of specific measures. The publications were reviewed to identify the full range of measures discussed, and these measures were allocated to the eight categories (see Table 5).

Table 5: Freight transport measures identified in the publications allocated to the eight categories in the framework used

Categories	Specific measures	
Reducing the level of freight transport demand	• Consumer behaviour • On/re shoring of supply • More local sourcing	• Dematerialisation • 3D printing • Circular economy
Shifting freight to lower-carbon transport modes	• Rail • Short sea shipping • Inland waterways	• Cargo bikes • Synchromodality • Intermodal equipment
Improving asset utilisation	• Collaboration • Retiming of deliveries • Delivery frequency	• Vehicle loading • Higher capacity vehicles • Double deck trailers
Organisation of physical logistics systems	• Supply chain networks • Regional & urban distribution hubs • Platooning	• Autonomous vehicles • Modular packaging • The physical internet
Digitalisation	• Artificial intelligence • Internet of things • Predictive analytics • Big and broad data	• Telematics • Route planning • Intelligent transport systems • Airspace management
Increasing energy efficiency	• Engine technology • Aerodynamics • Tyres selection • Idling reducing technologies • Lightweighting of vehicles • Fuel additives and lubricants • Vehicle maintenance	• Automatic tyre inflation • Driver assistance systems • Driver training • Fuel management programme • Reduced aircraft taxiing • Using air/sea port (not vehicle) energy
Switching to lower-carbon energy	• Electric vehicles • Electric road systems • Hydrogen • Gas	• Synthetic biofuels • Sustainable air fuels • Hybrid vehicles
Energy systems	• Battery technology • Renewables • Hydrogen production • Ammonia production	• Smart grid technology • Energy storage • Synthetic fuels

Figure 14 shows the extent to which the 53 publications reviewed include consideration of measures within each of these eight categories of freight transport decarbonisation. Each publication reviewed may deal with one or more of these categories. The category most commonly addressed by these publications is 'switching to lower carbon energy', which is addressed by 50 of the publications. This is followed in frequency by 'energy systems' (with these two categories being highly related to one another and both discussed in 40 of the publications). These are followed in terms of the frequency with which they are considered by: 'increasing energy efficiency' (28 publications), 'physical logistics systems' (18 publications) and 'improving asset utilisation' (16 publications), 'shifting to lower-carbon transport modes' (14 publications, 'digitalisation' (14 publications). 'Reducing the level of freight transport demand' is the least commonly addressed category, addressed in 8 publications.

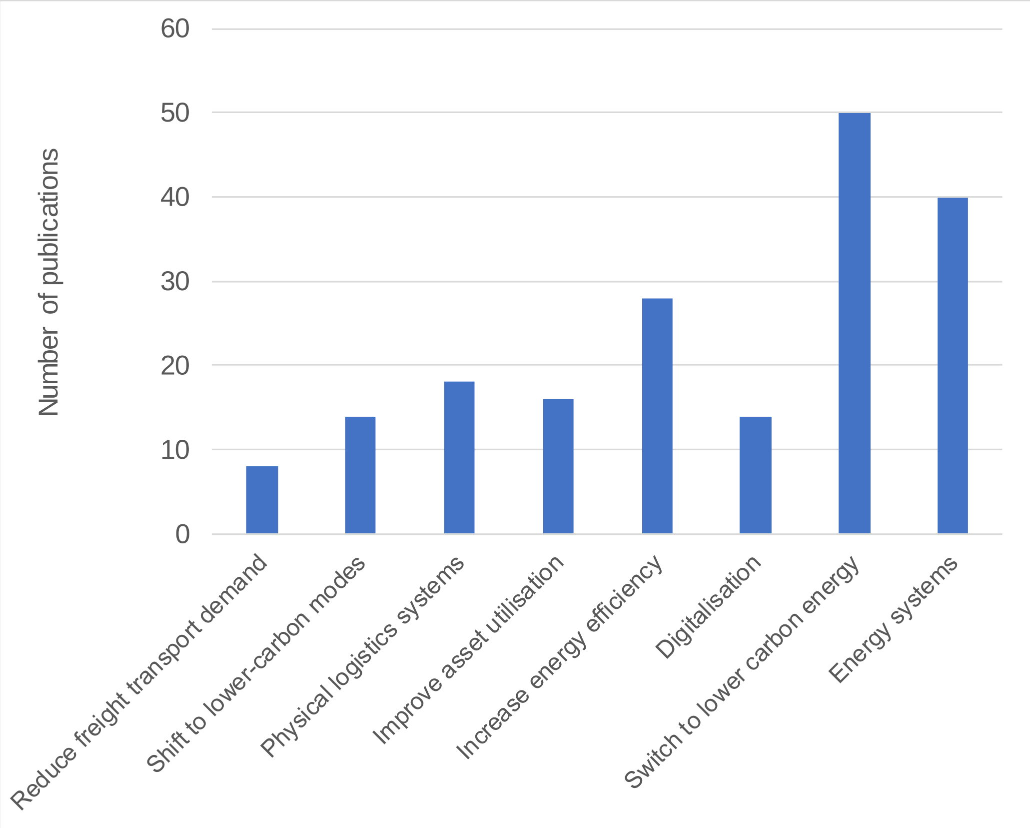

Figure 14: The freight transport decarbonisation categories referred to in the publications reviewed

In addition to the number of publications in which these eight categories of freight decarbonisation are discussed, the depth in which they are discussed also varies. As well as being discussed in more publications than the other six, the categories of 'switching to lower-carbon fuels' and 'energy systems' are also discussed in more detail and depth than the others. In many of the publications, when referred to, the discussion of the other six categories tends to be relatively brief and lacking in detail.

Based on a scale of 1 to 5, the analysis examined the extent to which each of eight categories of freight decarbonisation were covered, the extent to which the sources mentioned policies and research required to support the interventions, whether or not any cost information was provided, the carbon saving potential of the interventions, and the phased timing of the interventions to 2050. The spreadsheet analysis is shown in Appendix C.

Many publications appear to duplicate by cross referencing each other's work. The publications by (ALICE-ETP, 2019) (McKinnon, 2018) (International Energy Association, 2017), (EC-DC R&I, 2018), (Greening, Piecyk, Palmer, & McKinnon, An assessment of the potential for demand-side fuel savings in the HGV sector, 2015) (Greening, Piecyk, Palmer, &

Dadhich, Decarbonising road freight, Future of Mobility: Evidence Review, 2019) all have an excellent depth across a wide range of measures. Of the 53 roadmapping publications included in the systematic review, only seven of them contain a comprehensive discussion across a wide range of freight transport measures in the various decarbonisation categories, and these are highlighted in yellow in Appendix C.

It should also be noted that only one of the publications reviewed mentions the possibility of reducing the absolute level of demand for physical goods. However, it does not proceed to consider the possible options for achieving this, instead noting that this concept would be deemed as viable by few countries and is a political issue that extends beyond the scope of freight transport and logistics research (McKinnon, 2018). In this sense, all the publications reviewed approach the topic of freight decarbonisation within the existing economic paradigm of mass consumption, in which the absolute level of the material flow of goods is accepted and unchallenged.

Figure 15 shows how many of these eight freight transport decarbonisation categories are referred to in each of the 53 publications reviewed. Only three publications refer to all eight categories, with just over two-thirds of the publications referring to four or fewer categories.

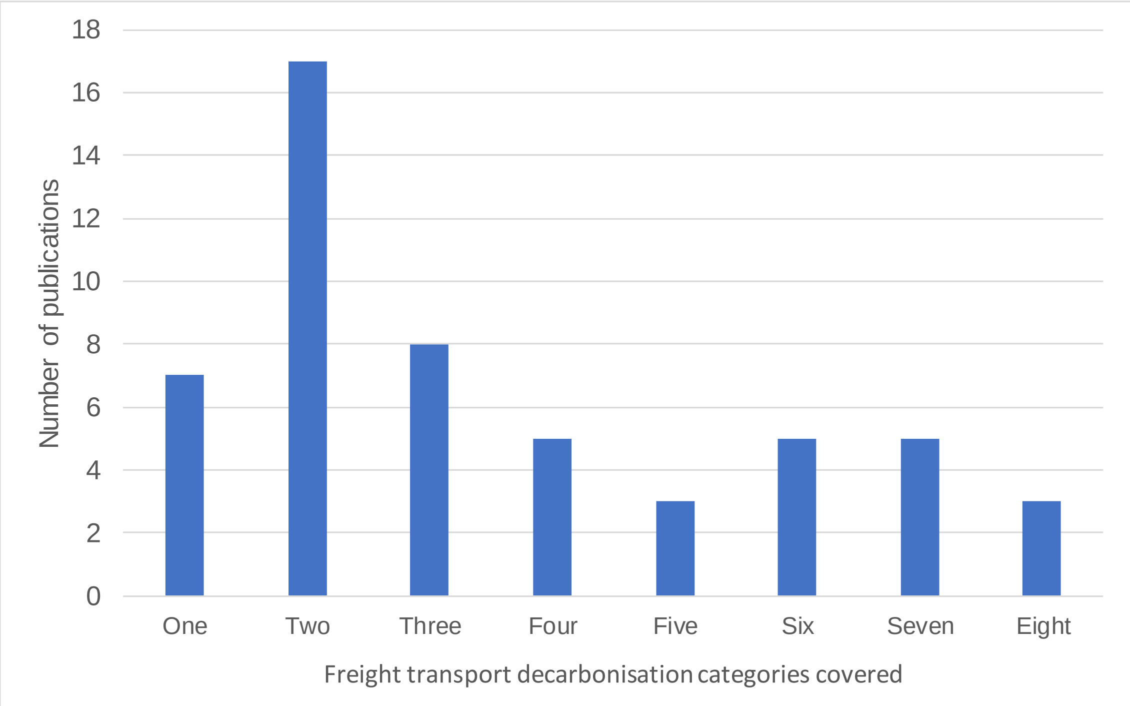

Figure 15: The number of freight decarbonisation categories referred to in the publications reviewed

Carrying out the systematic review has indicated the fuel types deemed in the literature to have the greatest decarbonisation potential for each transport mode in 2030 and 2050 taking into account energy production, infrastructure and other barriers to implementation and uptake (see Table 6).

Table 6: Most promising fuel sources for freight decarbonisation in 2030 and 2050

Transport mode	2030	2050
Road – HGV short distance	Natural gas (CNG and LNG) Biofuels Battery electric	Battery electric Hydrogen fuel cell
Road – HGVs long distance	Natural gas (CNG and LNG) Biofuels	Overhead electric (Electric Road System) Battery electric Hydrogen fuel cell Advanced synthetic biofuels
Road – LGVs	Battery electric	Battery electric
Rail	Overhead electric For locations not economic to electrify track infrastructure: Diesel-electric hybrid Biofuels	Overhead electric For locations not economic to electrify track infrastructure: Bi fuel: overhead electric & hydrogen fuel cell Bi fuel: overhead electric & battery electric
Shipping	Natural gas (LNG) Biofuels	Zero carbon fuels (hydrogen, ammonia, methanol, bio oil, electricity) produced from either renewable energy, bio-energy, or fossil fuels with carbon capture and storage (CCS) (Ammonia and hydrogen produced from natural gas with CCS likely to be most available) Battery electric and hydrogen fuel cells may be viable for coastal and short distance shipping
Aviation	Sustainable Aviation Fuels*	Sustainable Aviation Fuels* Hybrid-electric for short range flights

Note: * Sustainable Aviation Fuels are produced from biomass or recycled carbon wastes and residues such as household waste or waste gases from industrial processes that result in fuel that has at least 60% reduced life-cycle GHG emissions compared with fossil fuels (Sustainable Aviation, 2020a).

Many of the publications view electricity as the major power source for achieving zero emissions for trucks by 2050, but also with other energy types such as hydrogen and advanced fuels such as synthetic methane, synthetic methanol, and synthetic liquid hydrocarbons playing a role. However, this change of power source from fossil fuels to zero emissions sources will not reduce the number of trucks on the road, so it is important to consider the other measures which would reduce the other impacts of road freight transport such as accidents, noise, and congestion by reducing demand, using alternative modes of transport, digitalisation and changing logistics systems. These categories are also particularly important in the transition phase towards vehicles that use zero emission fuels. However, it is inevitable that companies will look at the cost of alternative fuels before embarking on any new technologies. If these energy sources incur higher costs for companies, alternative interventions such as other transport modes, software systems, the physical logistics network, etc. are likely to be further considered.

Also, according to EU targets, in order to achieve net zero by 2050, the amount of CO_2 emissions from trucks should be reduced by at least 55%, from 1990 levels, by 2030 with a target level of renewable electricity of 32%. Given that target, relying solely on electric trucks is not going to achieve the desired level of decarbonisation (EC, 2020). Combined with freight growth, other technologies and measures are going to be needed to achieve the required level of decarbonisation by 2030, to stand any chance of achieving net zero GHG emissions by 2050. In the UK, the target for renewable energy is 50% by 2030, but there is pressure to increase this to 65% (NIC, 2020). As with the EU situation, other energy technologies and freight decarbonisation measures are still going to be needed.

4.4 Research techniques employed and quantitative forecasts

The publications reviewed make use of a variety of research techniques, the most common of which is a literature review, followed by quantitative analysis or modelling, and focus group, workshop and roundtable discussions with invited experts. Relatively few of the publications made use of surveys or one-to-one interviews (see Figure 16). In addition, some of the publications refer to the use of qualitative assessment and it is likely that many of the publications make use of the qualitative judgement of their authors to some extent, but this is often not explicitly stated. Some of the publications also refer to the input of experts or members in the production of the publication, but without explaining the process by which this was achieved.

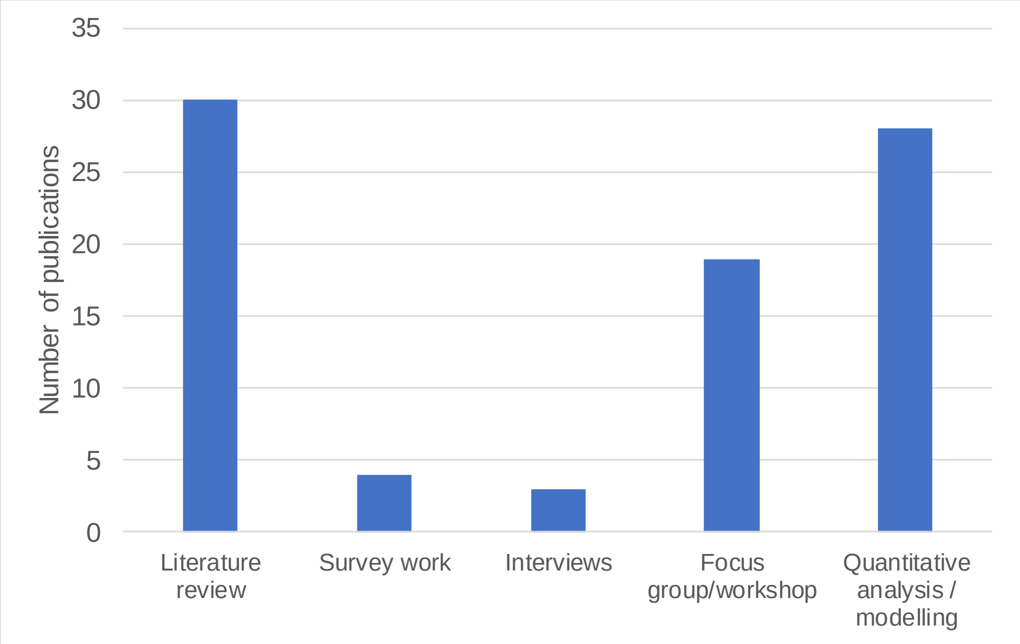

Figure 16: Research techniques used in the publications reviewed

Just under half of the 53 publications reviewed provide detailed explanations of the research techniques that have been used, while a few publications provide no explanation of their methodologies. In the latter cases, it is possible that such information is provided in other documentation or outputs that are not explicitly referred to in the publication.

During a study by APC involving workshops and a literature review aimed at collecting data on the technologies needed to decarbonise road freight (APC, EPC, 2019), they established that it was "challenging" to obtain data from a literature review alone, and neither was it was it easy to obtain data on cost and uptake of technologies from industry sources. This view is supported by the literature review carried out in this report, which has similarly found that there is limited data available.

Another publication by APC (Advanced Propulsion Centre UK, 2018) shows an excellent set of detailed roadmaps to 2050 for the development of electrical powertrain trucks but lacks any CO_2 emission data or financial cost estimates. Some of the work in the publications is based on modelling driven by past trends, with predictions based on assumed policies, pricing and infrastructure. The models used include energy system models, systems dynamics models, simulation, user choice models plus heuristic models using what-if or extrapolation techniques. In those publications reviewed that make use of modelling and other forms of quantitative assessment, the explanation of these models and techniques is typically brief. Presumably, these may be further explained and documented in other publications by these authors.

The majority of publications do not provide quantified forecasts of the expected effects of any of the freight transport measures/categories that they discuss on decarbonisation. Only 10 of the 53 publications reviewed provide such quantified forecasts of the effects of one or more freight transport measure/category, and only three of the publications provide such forecasts of CO_2 emissions reductions across a wide range of freight decarbonisation categories and measure (Transport & Mobility Leuven, 2017) (Greening, Piecyk, Palmer, & McKinnon, An assessment of the potential for demand-side fuel savings in the HGV sector, 2015) (Greening, Piecyk, Palmer, & Dadhich, Decarbonising road freight, Future of Mobility: Evidence Review, 2019).

The first of these publications reference above provides two tables showing forecast CO_2 emissions reductions for long haul and regional truck traffic by 2030 and 2050 (see Table 7 and Table 8). These forecasts indicate that CO_2 emissions from long haul and regional truck traffic could be reduced by 78% and 68% by 2050 compared to 2010, respectively (Transport & Mobility Leuven, 2017). The publication by (Transport & Mobility Leuven, 2017) also specifies a very useful set of decisions and preparations necessary to achieve these reductions. This detailed list of possible actions between 2020 and 2030, 2030 to 2040 and 2040 to 2050 is shown in Appendix D.

Table 7: Potential CO_2 reductions for the long haul cycle (Transport & Mobility Leuven, 2017)

Long haul	**Potential 2030**	**Potential 2050**	**Comment**	**Cumulative reduction 2030**	**Cumulative reduction 2050**
Powertrain efficiency (diesel)	10%	15%	Includes engine, transmission, auxiliaries, …	10.0%	15.0%
Gas vehicles	2%	4%	Methane emissions should be minimised	11.8%	18.4%
Renewable fuels (gas & liquid)	2%	24%	IEA general target, large increase in 2nd generation biofuels needed; includes biogas	13.6%	38.2%
Driver training and ADAS	6%	8%	Includes ACC, PCC, …	18.8%	43.2%
Reduced max. speed	2%	2%	To 80 km/h	20.4%	44.4%
ITS & communications	1%	4%	Platooning	21.2%	46.5%
Aerodynamics	6%	10%	Important contribution expected from trailers and semi-trailers, including solutions developed in the TRANSFORMERS Project	25.9%	51.3%
Tyres	7.5%	12.5%	Includes super singles	31.5%	57.4%
Lightweighting	0%	0%	Compensated by increased weight from other measures	31.5%	57.4%
Pavement	3%	3%	Improved rolling resistance (maintenance or new pavement)	33.5%	58.7%
Logistical efficiency improvements, including digitalisation, collaboration on reducing empty running & improve load factors	2%	10%	Rollout of coordinated system needed	34.8%	62.8%
More flexibility in weights and dimensions (including LHV)	3.5%	7.5%	LHVs permitted to carry out cross border transport within the EU	37.1%	65.6%
Hybridisation (2030)/ electrification (2050)	3%	37%	For 2050, most from full electrification	39.0%	78.2%

Table 8: Potential CO_2 reductions for the regional delivery cycle (Transport & Mobility Leuven, 2017)

Regional delivery	Potential 2030	Potential 2050	Comment	Cumulative reduction 2030	Cumulative reduction 2050
Powertrain efficiency	7%	11%	Includes engine, transmission, auxiliaries,…	7.0%	11.0%
Hybridisation/electric operation	4%	15%	Mostly through improved batteries and on-demand hybrids	10.7%	24.4%
Gas vehicles	2%	4%	Methane emissions should be minimised	12.5%	27.4%
Renewable fuels (gas & liquid)	2%	24%	IEA general target, large increase in 2nd generation biofuels needed	14.3%	44.8%
Driver training and ADAS	8%	10%	Includes ACC, PCC, …	21.1%	50.3%
ITS & communications	2%	5%	Dynamic (eco)routing	23.1%	54.3%
Aerodynamics	3%	5%		25.4%	56.6%
Tyres	3%	7%		27.6%	59.6%
Lightweighting[1]	0%	1%	Higher ratio of vehicle/cargo weight than long haul	27.6%	60.0%
Pavement	2%	2%	Improved rolling resistance (maintenance or new pavement)	29.1%	60.8%
Logistical efficiency improvements	4%	12%	More potential for improvement than in long haul due to lower average load factors; includes digitalisation, collaboration to reduce empty runs & improve load factors	31.9%	65.5%
Reduced max speed	6%	6%	To 80 km/h	36.0%	67.6%
LHV	0.5%	1%	Limited penetration	36.3%	67.9%
Electrification of roads	0%	0%	The business case may not be suitable for regional delivery operations	36.3%	67.9%

These Transport and Mobility Leuven forecasts can be compared with those produced by The Centre for Sustainable Road Freight (SRF) in its truck roadmapping work which uses a similar, but more detailed, range of measures. The SRF modelling work took account of logistics operations measures (including rescheduling delivery times, the use of higher capacity vehicles, reducing empty running through freight exchanges, the Physical Internet and other means, consolidation of loads, restructuring of the supply chain network, relaxation of time constraints, alternative transport modes, platooning, and the use of telematics to optimise vehicle routing), vehicle technology measures (including aerodynamic design, a switch from powered to fixed-deck trailers, vehicle lightweighting, vehicle speed control, rolling resistance tyres and automatic tyre pressure adjustment, use of fuel additives and lubricants with lower viscosity), driver training and driver performance monitoring, and the use of lower-carbon fuels. Using three different scenarios of operational and technological measures, the SRF forecasts indicate that total CO_2 emissions from UK truck operations could be reduced by 60-78% by 2050 compared to 1990 levels (Greening, Piecyk, Palmer, & Dadhich, Decarbonising road freight, Future of Mobility: Evidence Review, 2019).

Modelling of CO_2 emissions from road freight transport (trucks and light goods vehicles) by 2050 carried out by the IEA has taken account of measures to improve asset utilisation, the organisation of physical logistics systems and digitalisation that reduce total vehicle activity and increase average loads carried (these measures include optimised routing, platooning, improved vehicle utilisation, backhauling, last-mile efficiency, re-timing urban deliveries, urban consolidation centres, co-modality, crowd-sourced logistics, co-loading and the Physical Internet). In addition, the modelling has also taken account of the uptake of biofuels, battery electric and overhead catenary electric systems and other fuel types. The forecasts indicate that in the so-called 'Modern Truck Scenario' CO_2 emissions from road freight transport in 2050 will be less than 30% than those in the 'Reference Scenario' (i.e. if these actions had not been taken) and about half their 2015 levels. Approximately 30% of these cumulative GHG emissions reductions are achieved through measures that improve logistics operations (reductions in vehicle activity (18%) and increased vehicle loads (12%)), 30% from vehicle energy efficiency measures (including aerodynamic design and tyres), about a quarter from biofuels, and 16% from the use of electricity generated by low-carbon sources (see Figure 17) (International Energy Association, 2017).

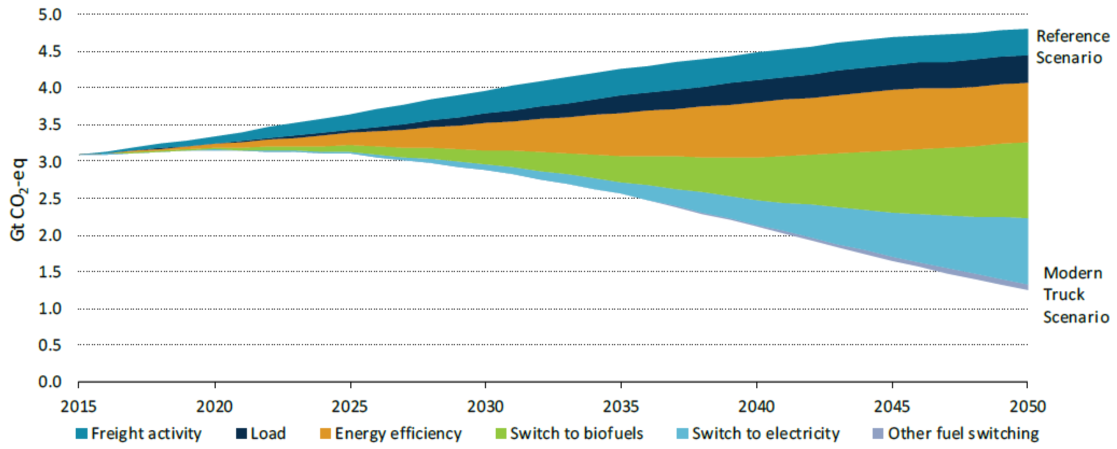

Figure 17: Contribution to CO_2 emissions reductions by measure in the Modern Truck Scenario, relative to the Reference Scenario (International Energy Association, 2017)

Unlike the other studies discussed above, research carried out by the ITF has taken account of freight transport in both developed and developing countries. This is important, given that decarbonisation is likely to be slower in poorer countries, given the investment required. This ITF work forecasts that, taking into account the predicted growth in demand for freight transport and the continuation of decarbonisation measures already announced by the end of 2018 (a so-called 'current ambition' scenario), worldwide freight transport operations will emit 118% more CO_2 emissions in 2050 than in 2015 (a 94% increase for domestic freight transport and a 157% increase for international freight transport). The implementation of additional measures not yet announced to improve the efficiency of freight transport (a so-called 'high ambition' scenario) including revised land-use policies, more stringent carbon pricing, the rapid uptake of renewable electrification, and a substantial reduction in the transport of coal oil and gas is forecast to result in total worldwide freight CO_2 emissions in 2050 being 21% greater than in 2015. This 'high-ambition' scenario results in worldwide freight CO_2 emissions that are 45% lower in 2050 than the 'current ambition' scenario.

Logistics operations efficiency measures and vehicle technology measures (including improvements in vehicle energy efficiency and the uptake of electrification) are forecast to account for total worldwide freight CO_2 emissions being 64% and 22% less than they would have otherwise been in 2050 in the 'current ambition' scenario compared to 2015, respectively. (ITF, 2019).

This ITF modelling work has also considered the potential impacts of various disruptive technologies on CO_2 emissions from freight transport. These forecasts indicate that the use of 3D printing could reduce worldwide freight CO_2 emissions by 28% compared to the ITF's 'current ambition scenario' by 2050, while higher capacity trucks could reduce worldwide freight CO_2 emissions by 3% by 2050, and autonomous trucks could reduce freight CO_2 emissions by 1% by 2050. This ITF research estimates that, when taken into account with predicted increases in demand for freight transport, the deployment of all the disruptive technologies investigated (including introducing new fuel sources for long distance truck activity), together with other more conventional measures to improve vehicle technology and the efficiency of logistics operations, will result in worldwide freight CO_2 emissions being 12% lower in 2050 than they were in 2015, and 60% lower than the ITF 'current ambition' scenario in 2050 (ITF, 2019). These forecasts therefore indicate that worldwide freight transport will fall far short of achieving net-zero emissions by 2050, even in the most ambitious scenarios modelled. These modelling forecasts are shown in Figure 18. The ITF report also notes that achieving even this will require substantial new freight transport infrastructure and investment.

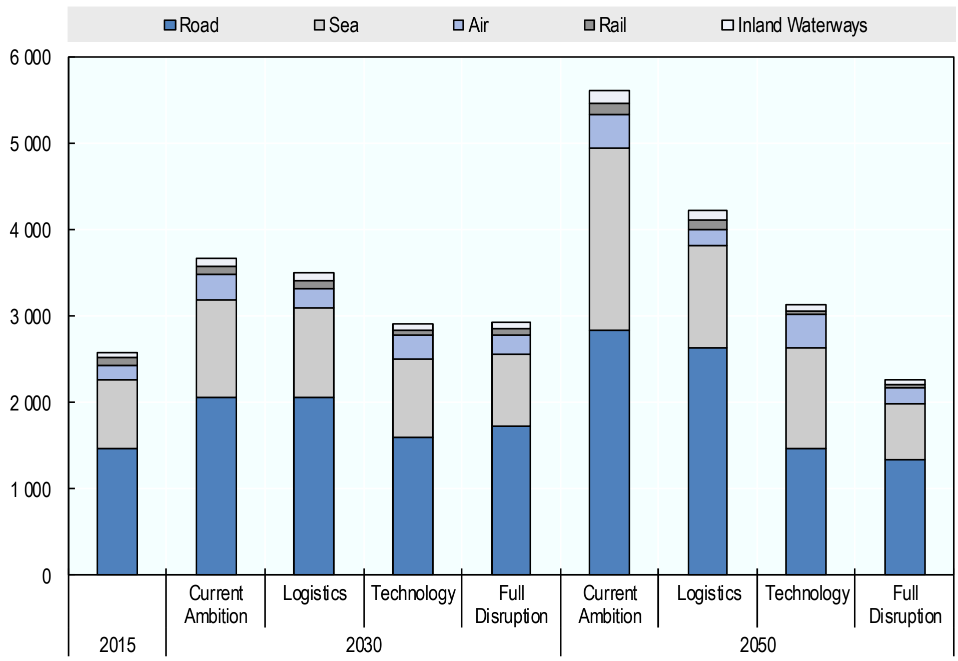

Figure 18: Projected CO_2 emissions from freight transport by mode, 2030-50 (million tonnes) (ITF, 2019)

Modelling of CO_2 emissions from maritime shipping indicates that the improved technologies of new vessels together with increases in the average ship size are likely to result in energy efficiency improvements across fleets of about 25% between 2018 and 2050. These are likely to vary from 20-30% depending on ship type. The use of speed reduction to optimise fuel consumption was forecast to have the potential to reduce CO_2 emissions by 8% by 2050 compared to 2018. It was also forecast that the use of zero carbon fuels can reduce CO_2 emissions by 64% in 2050 compared to 2018. These results indicate that energy efficiency technologies and speed reductions alone will be unlikely to achieve the IMO target of 50% reduction in CO_2 emissions by 2050. It should also be noted that this modelling work forecast demand growth in shipping activity would increase by 40-130% in 2050 compared to 2018 levels. Increases in shipping activity therefore have the potential to outweigh improvements in the energy efficiency of vessels (IMO, 2020).

Modelling of aviation (passenger and freight) indicates that the introduction of known and future aircraft technologies could provide a combined reduction in CO_2 emissions from UK aviation of 37% by 2050 compared to 2016 levels. Forecasts indicate that the use of sustainable aviation fuels could reduce CO_2 emissions from UK aviation by 32% reduction by 2050 compared to 2016. Aircraft operational and air traffic management improvements could reduce CO_2 emissions by 4% from UK aviation by 2050 compared to 2016. Meanwhile, carbon pricing through market-based measures could reduce demand and CO_2 emissions by 6% by 2050 compared to 2016 (Sustainable Aviation, 2020).

A survey of road freight transport experts, comprising respondents from government, the private sector, international organisations, NGOs and academia, conducted by the ITF in 2018 providing insights into the views of the 108 respondents concerning available logistics measures and technologies to reduce CO_2 emissions. Respondents were asked to score the effectiveness of each measure on a scale of 0 to 10. The results, whilst not quantifying the respondents' expectations about the absolute scale of CO_2 emissions reduction associated with each category, provide useful insight into those that these experts thought most useful (see Figure 19).

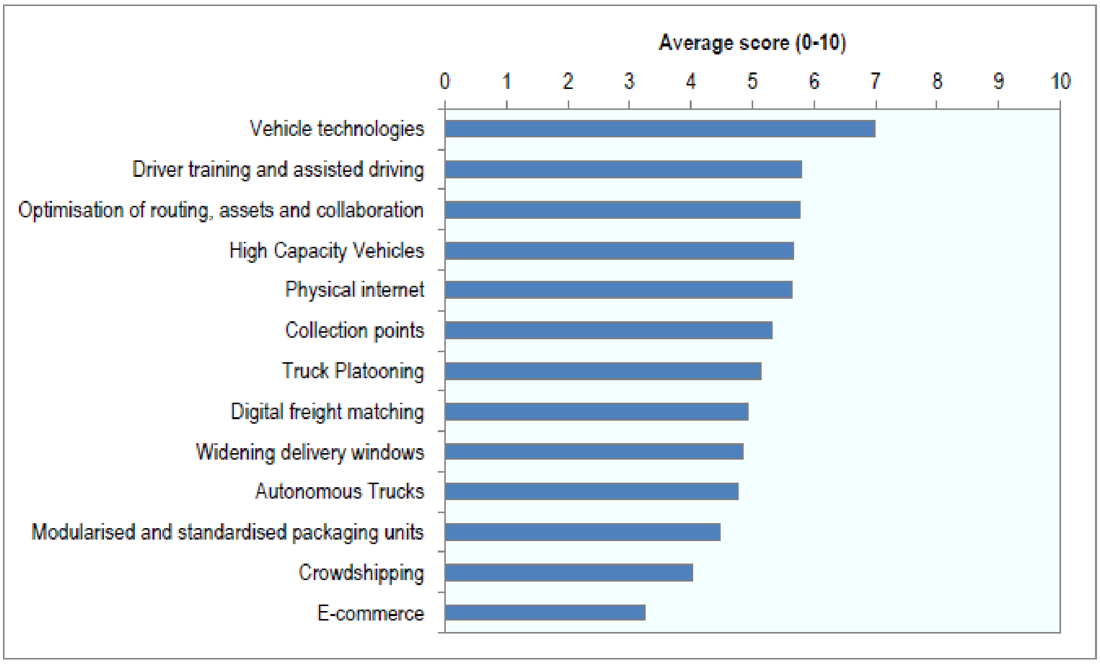

Figure 19: Respondents' views of the effectiveness of measures to reduce road freight CO_2 emissions (ITF, 2018)

Due to the difference in focus and coverage in many of the publications reviewed (with many concentrating on specific decarbonisation topics or transport modes) together with differences in research methodologies, and the lack of quantified forecasts provided in the majority of them, it is not possible to determine the extent of agreement and consensus between them all.

The freight decarbonisation roadmapping publications reviewed also provide little consideration of the predicted commercial take up of the various interventions and the barriers and challenges to doing so. However, they contain a rich source of detailed information about specific means by which to decarbonise freight transport, and this has been drawn on and summarised in the narrative review presented in the next chapter.

5 Detailed narrative review of literature

This chapter discusses the various freight decarbonisation measures and technologies included in the extensive body of literature identified and reviewed. Each of the eight categories of freight decarbonisation measure introduced in chapter 4 is addressed in its own section. Section 5.2 discusses the possible options for reducing demand for freight transport, while section 5.3 is focused on the opportunities for moving goods from road to less CO_2 intensive transport modes. Sections 5.4 and 5.5 cover the literature on ways of improving asset utilisation and the possible changes to how goods are moved in a supply chain. Section 5.6 examines the literature on digitalisation that can be used to support the efficient running of supply chains Section 5.7 discusses the ways of improving the energy efficiency of vehicles. Section 5.8 considers the various lower carbon fuels that can be used to power freight vehicles, while. section 5.9 examines the developments and infrastructure necessary to provide these fuels. Section 5.11 considers vehicle lifecycle CO_2 emissions, while section 5.11 discusses the policies and research necessary to ensure the implementation of technologies and measures necessary to move towards a net zero CO_2 emission target by 2050.

As with the rest of this report, the main focus of the review in this chapter is on road freight, especially trucks. However, summaries of non-road freight modes are also provided at the end of relevant sections, outlining the progress and challenges related to freight decarbonisation measures for them. This is intended to assist in providing insight into the relative situation for road freight compared to these other modes.

The major source of literature for the review presented in this chapter are the freight roadmapping publications already discussed in chapter 4, however these have been supplemented with references to other non-roadmapping literature where appropriate. Where quantitative information is available this has been included showing the contribution of the measures towards the decarbonisation goal. There is very limited assessment of the likely take up of any measures, nor their cost implications within the literature. The content of much of the literature is quite general and sometimes rather abstract. Many of the sources reiterate similar points about measures and technologies, but sometimes discuss them from a slightly different perspective or emphasis.

5.1 Overview of perspectives in key roadmapping literature

Before providing a detailed summary of the points raised in the reviewed publications, this section contains an overview of the general perspectives provided in some of the key road freight roadmapping literature consulted.

One key publication conducted a literature review to assess the vehicle technologies and infrastructure required to achieve zero carbon by 2050 (APC, EPC, 2019), and established that whilst information was available on conventional powertrain technologies, there was a lack of data on new technologies such as fuel cells and electric powertrains. This is echoed by other publications which also discuss the issue of insufficient knowledge to adequately measure the impact of certain new trends in freight transport (Transport & Mobility Leuven, 2017) (Carnevale & Sachs, 2019) (ITF, 2018). Some decarbonisation technologies that need to be adopted are not yet fully developed so rapid innovation is needed to ensure that these solutions can be quickly taken up. It is inevitable that future technological developments are uncertain and this, combined with political events and issues such as Covid-19, means a comprehensive roadmap is only as good as what is known at the time of its production.

A few of the roadmaps were published prior to 2017 and therefore discuss the EU plans for reaching a 30% CO_2 reduction by 2030 and 60% reduction by 2050, and include ways of improving the internal combustion engines (ICE). Whilst such measures remain important in the short term, more recent publications discuss the need for far quicker take up of zero carbon fuel technologies, encouraged by policies, to enable net zero freight transport to be achieved by 2050, with accelerated take up over the next 10 to 15 years widely mentioned (EASAC, 2019) (ITF, 2019) (Transport & Environment, 2017). Several publications refer to "the low hanging fruit" suggesting efficiency measures that are currently cost effective. These include, in a European context, fuel efficiency standards which could reduce fuel consumption by 30-50% by 2050, expanding rail capacity so that rail freight could increase from currently 18% to 23%, and improving logistics efficiency. Combined, one study suggests these measures could reduce road freight emissions by 36% by 2050, but to reach zero emissions by 2050 needs renewable, decarbonised electricity (Transport & Environment, 2017).

It is clear from the many publications examined that electrification of freight transport offers an extremely important potential for road freight carbon reduction, but there are challenges to be overcome for both vehicles and the storage of electricity. It has been suggested that without government intervention to prohibit the use of fossil fuelled vehicles, it would take 20 years for these vehicle fleets to be phased out and replaced with electrified vehicles (EASAC, 2019). Therefore, reductions on CO_2 emissions will not occur quickly enough to achieve net zero by 2050. Although electric vehicles are the way forward, this is highly dependent on the decarbonisation of the electricity sector which must be achieved in the next 10 to 15 years (EASAC, 2019).

It is not just electrification that has the potential to bring about a zero carbon era. This goal can only be met by 2050 with a combination of logistics operational efficiency measures together with new fuel technologies, and vehicle energy efficiency technologies such as vehicle aerodynamics, lightweighting and tyres, together with support for fuel efficient driving through advanced assistance systems and training. This latter option may be phased out as the introduction of autonomous vehicles becomes ubiquitous. Intelligent transport systems and digitalisation are also important to enable increased connectivity between vehicles and infrastructure to support platooning and autonomous vehicles. Progress to zero carbon freight can also only be achieved with the necessary support from political and legislative groundwork. In the future, sharing resources and cooperating will also help to achieve greater freight efficiencies and contribute to zero emissions (Transport & Mobility Leuven, 2017).

The EU White Paper of 2011 states that technical innovation can achieve a faster transition to a more efficient and sustainable transport system through three main factors (EU, 2011):

- Vehicles' efficiency through new engines, materials and design
- Cleaner energy use through new fuels and propulsion systems
- Better use of network and safer and more secure operations through information and communication systems

This is echoed in an IEA report “The future of trucks” (International Energy Association, 2017), which proposes what is referred to as the Modern Truck scenario and states that reduction in road freight CO_2 emissions to 2050 should come about through improved vehicle efficiency, systemic improvements in logistics, and increased uptake of alternative fuels.

Mullholland et al (2018) extend this idea with a detailed breakdown of measures and savings by truck type and parameters affected. They conclude that by 2035, fuel consumption per kilometre of new vehicle registrations needs to be progressively reduced by 35%, relative to a 2015 baseline. This can be achieved through data gathering and information sharing which are essential to realise the potential for improvement in logistics operations. The deployment of alternative fuels requires policy involvement to support research and development, the uptake of alternatively fuelled vehicles, adequate charging or refuelling infrastructure and the availability of alternative fuels. These measures and conclusions closely correlate with those mentioned and used by the roadmaps of the CfSRF and ALICE.

ERTRAC has produced comprehensive roadmap up to 2030 in a European context for longhaul and regional freight transport (see Figure 20) and for urban freight transport (see Figure 21). This includes the need for synchromodality to ensure the efficiency of long haul freight transport (ERTRAC, 2019).

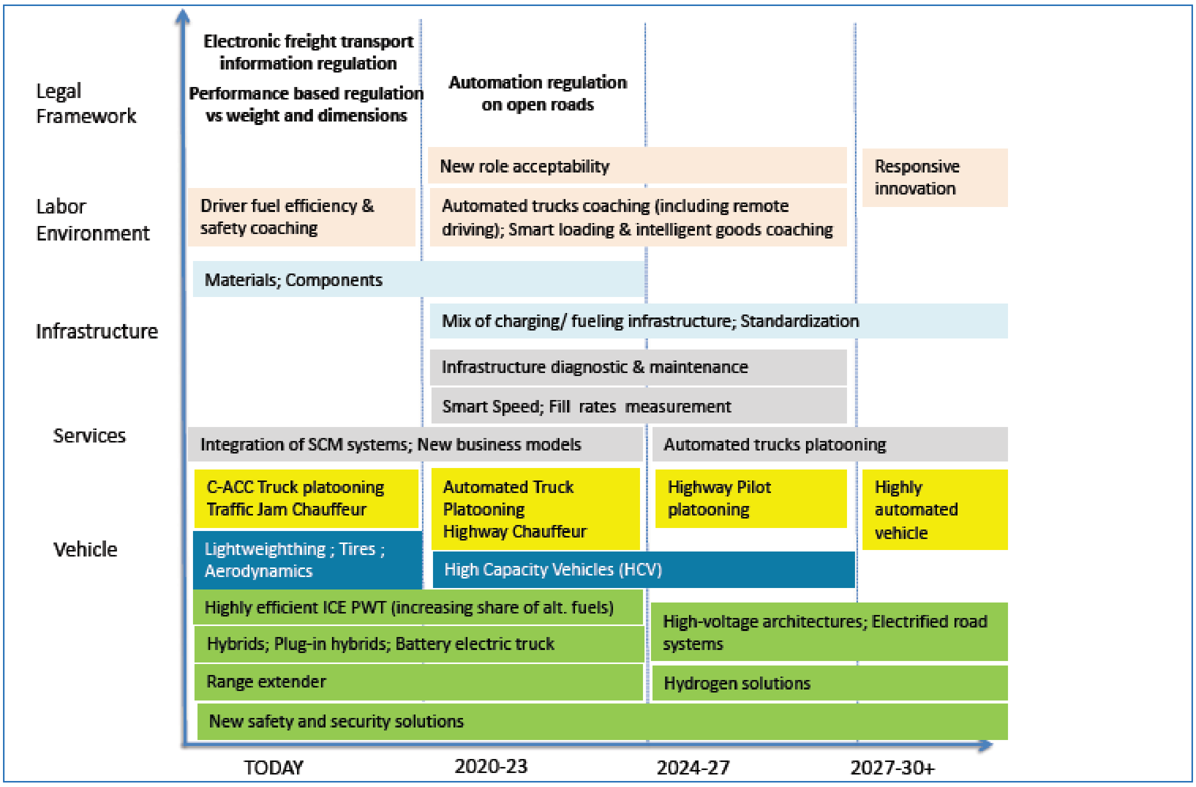

Figure 20: Long haul and regional roadmap to 2030 (ERTRAC, 2019)

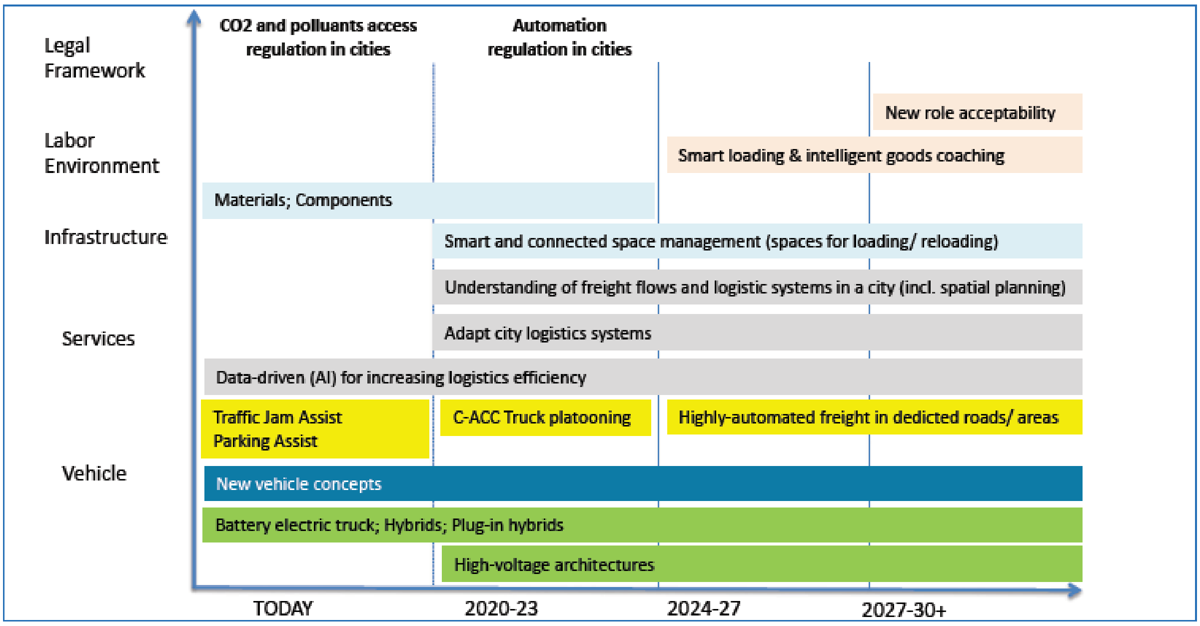

Figure 21: City distribution roadmap to 2030 (ERTRAC, 2019)

The UK national government set out a plan for all new cars and vans to be zero emission by 2040 (DfT, 2018) but more recently brought this forward to 2030 (Department for Transport, 2020b) (BBC News, 2020c). This UK Government plan focuses heavily on non-freight related road vehicles and is rather superficial when it comes to identifying and supporting specific measures. Although the UK Government has implemented some policy measures to support the electrification of some road vehicles, the plan does not address the need for additional generating capacity, merely a suggestion as to how peak in electric consumption can be smoothed. Its encouragement to use hydrogen also fails to address the challenges and potential energy inefficiency of this form of energy. This UK plan lacks specifics and is more focused on setting up committees, writing reports and running roadshows. The UK Government seems, from this plan, to be relying on industry and consumers to lead the transition to zero emissions by 2050. The only comment about enabling trucks to achieve zero emissions made in this plan concerns funding for the Energy Saving Trust to develop a freight portal so that truck operators have access to the implications of various decarbonising measures. This appears to be duplicating much of the work already done by organisations such as the CfSRF and FTA. The plan states that the UK Government will support the development and deployment of zero emission trucks by enabling “R&D, real world trials and demonstrations” without providing further details of the scale and timing of such support (DfT, 2018). The UK Government is currently drawing up a Transport Decarbonisation Plan (TDP) which is due to be published during 2021 and which should provide greater clarity of policies and funding.

Another important report by APC (APC, EPC, 2019) primarily focuses on propulsion and energy systems to reduce emissions by 2050 with a few comments on key areas such as ways of reducing demand and improving asset utilisation, and digitalisation and software systems to support the efficient use of road freight operation. One of the scenarios examined did address a physical logistics option by considering the increased use of urban hubs for last mile distribution. Although it is classified as a literature review, it quotes relatively few sources, most of which are literature emanating from the DfT or ETI, and there are few academic sources cited. The data identified in this report was collected for use in two modelling tools and covered the performance of various propulsion systems plus a detailed assessment of costs of the systems discussed, including infrastructure, and an estimation of how these would change up to 2050. One of these tools, ESME, is a Monte Carlo based simulation that assesses the uncertainties around future energy prices, and the cost and performance of energy technologies, for a wide range of sectors, including transportation, to produce the lowest total costs of ownership within given constraints. The second tool, Gas Well to Motion and Freight model, is truck focused to assess the behaviour of fleet purchasers and how vehicles will be deployed. Most importantly this model uses the expected frequency at which operators replace their fleet to assess the future uptake of vehicles, and hence the type of propulsion system and emissions, up to 2050. Although considered in the modelling, it's not clearly stated how battery efficiency will improve over the next three decades, but battery costs are expected to be lower than today, and hence total cost of vehicle ownership. Hydrogen costs are also assumed to reduce to 2050, but these are generally higher than other energies because of the more expensive infrastructure needed for refuelling stations. The scenarios considered were to identify the vehicle parc to achieve EU regulations of CO_2 reduction of 15% by 2025, 30% by 2030, and 50% by 2050.

5.2 Reducing the level of freight transport demand

This section discusses literature about reducing freight transport intensity and covers:

- Consumer behaviour
- On/re shoring of supply
- Dematerialisation
- 3D printing
- Circular economy

In comparison to other measures relatively little has been written in the publications reviewed about roadmaps for reducing the demand for freight. Where it has been discussed, it is often included as part of an overall plan involving other measures and only mentioned in passing.

Measures such as dematerialisation, 3D printing and the circular economy have the possibility of reducing the quantity moved but this doesn't apply to onshoring or nearshoring which doesn't physically reduce demand in terms of quantity moved (goods lifted), but it does reduce the tonne kilometres travelled (goods moved).

Freight demand generally depends on economic growth and international trade activity, together with other factors including population change, the importance of physical goods, transport costs, and the adoption of new technologies and retailing channels. Prior to Covid-19 and various trade conflicts, based on current patterns, global freight was expected to triple between 2015 and 2050, at an annual compound rate of 3.4% (ITF, 2019). According to these ITF forecasts of modes used for this growth, air freight is predicted to increase fastest at a compound annual rate of 4.5% to 2050 (albeit from a small base), followed by inland waterways (3.8%), maritime shipping (3.6%), road (3.2%), rail (2.5%). At this worldwide scale, maritime shipping would continue to be the most important freight transport mode in 2050 as it is now in terms of tonne-kilometres performed, accounting for approximately three quarters of the total (ITF, 2019). However, the World Bank suggests that Covid-19 could cause a decline of up to 4% in GDP below the world benchmark index, with Europe declining by about 3.85%. The IMF is predicting a 3% reduction in world GDP. Much of this expected reduction is in services and, in particular, tourism (World Bank Group, 2020). This decline is expected to be reversed by late 2021 and growth restored to expected levels by 2022 (PWC, 2020). In the future GDP rises may occur as a result of increases in the service sector which would mean less goods are moved thereby decoupling freight demand from GDP (ITF, 2018). This is a more likely scenario in developed countries.

The Covid-19 pandemic has also caused a rapid growth in e-commerce which is forecast to continue at the same levels. In the UK the share of e-commerce in retail rose from 17.3% to 20.3% between 2018 early 2020, but rose to 31.3% between the first and second quarter of 2020 (OECD, 2020). E-commerce volumes are approximately 50% higher than they were a year ago. In retail, it is inevitable that consumer behaviour will change over the decades to 2050, and freight transport will have to adapt to meet these changes. It is therefore important to understand what the demand for transport services will look like. Home shopping is likely to increase significantly and recently this has occurred faster than expected due to the Covid-19 virus. In the UK, to June 2019, home delivery accounted for 7.6% of all grocery sales. However, during the Covid-19 lockdown March 2020 online grocery sales were 13% higher than March 2019 (Kantar, 2020). However, the UK lags behind South Korea with 20.3% and China with 15.2%. Kantar predicts that online shopping will represent almost one third of FMCG sales in the Chinese mainland by 2025 and one quarter in South Korea (Kantar, 2019). With a cashless society becoming more apparent, UK grocery, and other online sales, are likely to increase significantly impacting the way freight transport will deliver to households. Innovations for a range of last mile delivery options will be essential (Wood, 2020).

Over many years, much of the growth in freight traffic has been driven by goods travelling longer distances between the point of production and consumption. This has been caused by balancing all the costs in a supply chain to reduce total production costs. The impact of transferring production and various manufacturing processes to low cost countries has meant freight travels much greater distances than if produced nationally or locally, and usually involving sea and air movements. In recent decades, there has also been a trend towards the centralisation of stockholding to serve markets across Europe, resulting in goods being held at large warehouses and distribution centres in order to reduce the costs of inventory. This has also resulted in increases in the distance over which goods are transported in many supply chains. The use of centralised warehousing tends to increase freight transport costs but these are more than offset by reduced inventory and storage costs (McKinnon, 2018). As companies and politicians begin to place greater importance on environmental sustainability, the distances over which goods are transported and the impacts associated with this is becoming more of an issue. The relationship between the price of fuel and transport usage was clearly illustrated in the 1970's when the price of oil rose dramatically, and companies started to add warehousing nearer to centres of demand to reduce the level of transport required. As the use of oil as a transport fuel is phased out there will be a rebalancing of supply chain costs. Companies attitude to risk will also change the way supply chains operate. The recent pandemic has raised the question of vulnerabilities in supply which means that there may be greater instances of manufacturing decentralising to much nearer the demand base (IFC, 2020) (Eley, 2019). The financial costs will be of significant importance, but the quality of goods produced together with road, rail and shipping infrastructure will also be important factors (International Energy Association, 2017) (Mulholland, Teter, Cazzola, McDonald, &

Gallachóir, 2018). The impact of this will be felt globally rather than within the UK, unless former international manufacturing facilities are established nationally. If reshoring involves movements between continents it will be more likely to impact sea and air than road modes (ITF, 2018).

Predicting the future is fraught with problems. The combination of so many factors, many of which are unknown, makes it almost impossible to have an accurate assessment (ITF, 2018). One prediction is that the sharing economy will increase and less goods will be purchased, particularly in large items such as cars. Significant advances in technology over the coming years will also change company business models, particularly in retail. Food supply chains will become shorter with climate change possibly making the growing of exotic foods more local. Veganism is growing and it's likely that less meat will be consumed (Eley, 2019). All this will result in less demand for freight transport services.

There is likely to be an exponential development of technology innovation in the coming years. An example of this is 3D printing which has provided the ability to print on demand, particularly for sectors such as aviation, defence, oil and gas. In the Covid-19 crisis 3D printing has enabled additional manufacture of personal protective equipment such as face shields, and ventilator valves (DHL, 2020a). As more goods become digitised, such as media products for example, there will be increased use of 3D printing. This technology allows the customisation of products closer to where the demand is located. However, this is likely to have a very small overall impact towards zero emissions, because it is limited by the type of product (EC-DC R&I, 2018) and according to ITF (2018), who conducted an opinion survey, this was one of the least likely trends to have any impact on reducing freight demand. In this report there was a wide variation in responses, a few of which indicated a high potential uptake, with the comment that this technology would reduce road freight volumes. These mixed views on the effect of 3D printing on transport demand means that the future impact is uncertain (McKinnon, 2018). Although 3D printing of spare parts and health care products are fairly common today, it is expected that more widely used 3D printing together with the decentralisation of production, localisation and nearshoring, will occur in the 2023 to 2030 timeframe and, when combined with these measures, will have a 10% to 20% reduction on greenhouse gas emissions (ALICE-ETP, 2019). Indeed, 3D printing may change the "just in time" concept to "print on demand" (International Energy Association, 2017). Another study has estimated that the use of 3D printing could reduce global freight CO_2 emissions by 28% compared to the 'current ambition scenario' by 2050 (ITF, 2019). However, it will never fully replace traditional or other digital manufacturing.

The circular economy reduces the need for new products by designing products that last longer and emphasise maintenance, repair, reuse/refurbish and recycle. With landfill sites rapidly filling up, it is essential that less waste is produced. Recycling and reusing end of life items as part of a circular economy will reduce freight demand. However, it needs recovery processes for a wide range of products to be established (EC-DC R&I, 2018). This is particularly true of batteries which are becoming more commonplace and may have an alternative end of life use as an electricity storage facility. Trial projects are currently underway to reuse old batteries for storing solar energy. However, the batteries need to be dismantled and it is very easy to damage the lithium-ion cells when taken apart (Holley, Energy firm wins project funding to re-use electric bus batteries, 2020). APC (2019) state that "creating a circular economy for automotive battery packs" is a long-term action taking 10 to 20 years to mass market. Products need to be designed for a circular economy so that valuable materials can be extracted and reused (APC, EPC, 2019). Materials from municipal and agricultural waste can be processed into energy and to manufacture synthetic fuels facilitating the circular economy. One publication suggests that a circular economy in sectors such as plastics, steel, aluminium and cement can reduce CO_2 emissions by 56% in Europe by 2050 through greater recycling and reuse, designing products that require less material and making them last longer (ETC, 2018).

In conclusion, this section has discussed the literature associated with reducing freight intensity in terms of demand and kilometres travelled. The outcome is extremely uncertain in this area but a suggestion of 10% to 20% reduction in GHG emissions may be possible if the above changes in behaviour and activity take place by 2040.

5.3 Shifting freight to lower-carbon transport modes

This section discusses the opportunity of taking advantage of the wide variation in carbon intensity between the various alternative transport modes including:

- Short sea shipping
- Rail
- Air
- Cargo bikes
- Synchromodality

Modal shift from road to less energy intensive modes has been encouraged by the EU and governments for many years (European Commission, 2016). However, road provides a level of flexibility and the ability to meet tight service level requirements at a competitive cost that often makes it difficult for other modes to compete. With a focus on reducing the energy intensity of road vehicles, through greater efficiency and the use of alternative fuels, there may be negative consequences for mode switching. The environmental benefits of rail and water freight over long haul road freight may narrow. But if these alternative modes also start to decarbonise then a gap would still remain.

Although use of alternative modes of transport is an important contribution to the reduction in carbon emissions, the literature is fairly limited, often being part of a discussion covering wider range of measures, and this general literature is also typically negative about the ability to grow the share of intermodal freight significantly. Rail, for instance, is reliant on heavy bulk materials some of which, such as coal, are in decline, and this reduction in traditional markets may make it difficult to meet the EU's target of moving 30% of road freight travelling over 300km to rail and inland waterways, by 2030 and 50% by 2050 (especially as modal share is measured in weight-based metrics).

The use of alternative modes of transport is largely dictated by differences in geography. Waterways are much more likely to be used for suitable commodities where there is a network of canals. Rail is predominantly used, again for suitable commodities, where the distances exceed 300km which is generally considered the breakpoint between rail and road costs (Verelst, 2016).

The UK's Department for Transport's Rail Freight Strategy has identified several factors that would potentially help in increasing rail freight traffic (Department for Transport, 2016). These include the need for investment in the rail network, protecting strategic capacity that has been achieved through freight enhancement schemes, new services and technologies aimed at intermodal port, construction, domestic intermodal, biomass, automotive and urban freight traffic which are seen as potential markets where rail share could be increased, reflecting the environmental and road traffic benefits of rail freight in track access charging, and improved communication and dissemination of the services and benefits that rail freight can offer.

The UK Government put in place a Strategic Freight Network fund of £235 million between 2014-2019 to improve the rail network to support rail freight growth (Department for Transport, 2020c). This funding was focused on specific projects around the network to improve rail freight operations including gauge clearance and capacity enhancement schemes on freight routes. The UK Government makes grants available to incentivise the movement of freight from road to rail and inland waterway through its Mode Shift Revenue Support (MSRS) Scheme. This scheme assists companies with the operating costs of running rail or inland water freight transport instead of road, where the former modes are more expensive. As part of this scheme grants are available to support the movement of intermodal containers by rail, and non-containerised freight by rail and all freight on inland waterways (Department for Transport, 2020e). In 2018-19, the UK Government provided £16 million through these freight grants (Office of Rail and Road, 2019). The UK Government also provides the Waterborne Freight Grant (WFG) Scheme to assist companies with the operating costs associated with running coastal and short sea shipping freight transport instead of road, where transport by water is more expensive (Department for Transport, 2020f). In November 2020, the UK Government carried out a public consultation into whether a trial of trucks with a maximum weight of 48 tonnes (4 tonnes greater than the current 44 tonne limit) should go ahead in which these trucks would be permitted to operate on ten selected routes for the transport of heavy containers to and from rail freight trains, to test whether it encouraged a shift of goods from road to rail transport. (Department for Transport, 2020b).

Rail freight operators in the UK require high quality train paths in order to be able to offer commercially viable services to customers. These require the ability for operators to provide freight services using appropriate trains with a suitable fast and reliable journey time. Existing rail infrastructure constraints in terms of speed, length, weight and gauge restrictions on key corridors can prevent this from being possible and have been identified as requiring improvements (Network Rail, 2017).

Rail, however, is often perceived by shippers, forwarders and more widely as a complex, bureaucratic and less agile option compared with road transport alternatives (EU, 2015). The key problems with rail are a lack of connectivity, insufficient volume, and not enough frequency, combined with high cost and long lead times (Verelst, 2016). The rail sector is only able to provide a limited offering compared to shipper's needs in relation to matching shipper's expectations on service, product and pricing. Rail freight volumes demand competitive commercial rates compared to road transport, whilst at the same time exploiting rail's inherent benefits with regards to energy efficiency and lower environmental impact in terms of noise, emissions and safety. Rail has generic advantages by operating within a controlled and secure environment. However, at present only 5% of UK rail freight tonne km currently use electric traction (Office of Rail and Road, 2019a).

Terminal handling costs and the requirement for road transport for pre and end haulage can erode rail's line haul cost advantage (Comtois, 2015). The reliance on long, relatively slow trains together with competition from passenger services for train paths also constrain rail's potential using existing operational, technical and commercial models. Weekend engineering work on the railway infrastructure also precludes the operation of 24/7 services and constrains rails ability to develop services for the certain industrial sectors.

If rail, and waterways, are to increase their share of loads carried there needs to be a stronger commitment to share information and transfer knowledge between modes (ERTRAC, 2019). Synchromodal systems are gradually becoming available that should make it easier to ensure smooth transition between the various modes of transport in a timely manner. These systems should also make it easier for shippers to plan their loads and to see where their goods are at any time and to make any necessary adjustments in case of delays.

There is also the issue of the fuel sources to be used in future by non-road freight transport modes. In the case of rail, an increase in rail freight using electric traction would be environmentally beneficial but it may not be cost effective, particularly where there are low volumes (EC, 2018). The decarbonisation of the fuel sources for freight moved by rail, maritime and aviation is likely to be more difficult to achieve than for long-distance road freight (see section 5.8.6 for further discussion).

There are a number of pneumatic tunnels under cities and these could be used for hyperloop systems involving magnetic levitation above rails and reduced pressure tubes, which will change the way consumers are serviced impacting last mile delivery. In the future, larger hyperloop systems could quickly move goods between regions of the UK which may considerably reduce the need for long distance trucks. Whilst futuristic, and probably not feasible before the 2050 target, companies are making significant investments into researching this technology such as Hyperloop Transportation Technologies, Transpod, DGWHyperloop, Virgin Hyperloop One, etc. The Swiss government are forecasting a 37% increase in goods transported in the next 10 years which would heavily congest the Swiss transport systems, so a group of experts are drawing up plans to build a 500km fully automated, three lane tunnel, called Cargo sous Terrain, or CST, to be operational by 2050 (Culley, 2020).

The literature on alternative modes for freight transport is limited, and fairly negative, but encouragement to use these forms of transport may come from the development of systems that enable synchromodality, which is discussed in section 5.6. There is plenty of discussion about the carbon saving benefits of using intermodal transport but very little detailed research how much CO_2 can be saved, nor how it should be done, or by when.

5.4 Improving asset utilisation

In this section the following topics are discussed:

- Collaboration
- Higher capacity vehicles
- Retiming of deliveries
- Deceleration

5.4.1 Road freight asset utilisation

Key factors driving operational inefficiency in the road freight transport industry are the high proportion of empty running (i.e. when vehicles return to their depots unloaded after having made a delivery) and low load factors (i.e. the weight and volume capacity of the vehicles is poorly used even when goods are carried). Empty running is a consequence of geographical trade imbalances and a lack of scale at companies moving the goods. Low load factors are mainly due to order fragmentation at shipper's premises following just in time production and working capital reduction policies. Over a period of 10 years the level of empty running and the capacity utilisation of a road-based freight vehicle has hardly changed. EU statistics show a range of between 24% and 28% empty vehicle running, and a capacity utilisation by weight ranging from 54% to 57%, over a 10 year period (Eurostat, 2018).

With a higher focus on costs, customers have been more demanding when it comes to deliveries. Companies define specific days and tight time windows for when deliveries are allowed, households are now used to next day delivery for certain goods, or even one hour or less delivery slots for FMCG goods. This has an impact on vehicle utilisation which is why collaboration has become more important. Transport collaboration is the main way to improve load efficiency, with on the road examples and strategic studies showing benefits (CO3 project, 2014) (Surtees, 2013) (Palmer, 2016). Collaboration has been around for over 20 years starting in the mid 1990's with suppliers and their customers collaborating vertically through vendor managed inventory and factory gate pricing, and followed in the mid 2000s with horizontal collaboration involving companies at the same level in the supply chain. Collaboration represents a step towards the physical internet (which is discussed in section 0), however, this has not grown at the levels expected for a variety of reasons notably (CO3 project, 2014):

- Collaboration is a minor part of the supply chain operation and is likely to save only a small amount of cost so doesn't warrant the effort required to make it work
- Concern about any company with whom they would be collaborating. Competition is still the norm, and collaboration requires trust and transparency among the collaborating companies.
- Collaboration has been sporadic over many years and there are many barriers that have been quoted as the main reasons for not collaborating.
- Many shippers use LSPs and fear that any lanes taken from their operation for collaboration may incur a net higher cost from the LSPs. A number of shippers interviewed indicated that their LSPs could be contacted on their behalf but the LSPs showed a great deal of unwillingness to participate, obviously fearing that their business would be negatively affected.

The use of technology and independent trustees to support collaboration is important with a need to identify collaborative opportunities on a daily basis and to protect sensitive information (CO3 project, 2014) (Palmer, 2019). This would enable better vehicle fill rates and reduced empty running.

However, there could be limitations on the number of companies in a collaboration with a couple of publications suggesting that at some point the coordination costs may become too high outweighing and savings from the collaboration (Guajardo, Rönnqvist, Flisberg, & Frisk, 2018) (Lozano, Moreno, Adenso-Díaz, & Algaba, 2013). Technology may be able to overcome this issue with game theory and AI techniques.

The significant recent increase in e-commerce and the continued expected growth has highlighted the poor vehicle utilisation of last mile deliveries. There are various attempts taking place to improve this through instances of crowd shipping and the use of urban consolidation centres and collection points (EC-DC R&I, 2018) (McKinnon, 2018).

Within most of the literature on collaboration there is little in the way of roadmapping type information, and where this technique is analysed in more detail it is under the auspices of the physical internet. This envisages open logistics services and seamless connected networks which would increase vehicle fill and reduce empty running thereby improving asset utilisation (Sense project, 2020). Based on various studies, collaboration through backhauling, co-loading and consolidation can achieve CO_2 savings of between 2% and 8% (CO3 project, 2014) (Palmer, 2016) (Palmer, 2019).

In the UK higher capacity vehicles (HCVs) such as double deck trailers have been used for many years, and a trial of longer semi trailers has been running for 7 years and proved very successful so may at some point become a permanent feature on British roads (Risk Solutions, 2018). HCVs have also been shown to be beneficial in terms of reduced trucks on the road and saving carbon, in those European countries in which they are permitted (McKinnon, 2018) (Piecyk & Allen, 2020). The UK Government carried out a public consultation in November 2020 into whether the longer semi-trailers trial should be ended and this length of vehicles be allowed to be used more widely in the UK (Department for Transport, 2020b).

Given that continued road freight growth is expected, maintaining current regulations on weights and dimensions would, all other things being equal, be expected to result in an increase in the number of goods vehicle movements and a relative increase in pollution, accidents and traffic levels arising from those movements. However, the nature of goods transported has changed and a larger proportion of loads shipped are now constrained by the available volume or deck area rather than the available payload weight. In the UK, HCVs would most likely be used for regular flows of low density products on primary distribution in sectors such as fast-moving consumer goods. It has been estimated that between 5% and 10% of the tonne-kms currently carried by articulated vehicles in the UK could potentially be transferred to HCVs of 60 tonnes or more (vehicles offering an increase in both available volume and payload). This represents a migration of up to approximately 11.8 billion tonne-kms per year. An analysis of the internal and external costs of freight transport has suggested that the ongoing costs could be substantially reduced. Carbon intensity could be reduced by up to 13% for one longer and heavier vehicle configuration (Knight, et al., 2008). This was based on diesel fuel. But, because the size of the vehicle means it would be more suited to long haul, HCVs of the future could be set up to use an ERS or hydrogen, resulting in even greater CO_2 reduction and reduced traffic congestion.

As with collaboration, HCVs have not been addressed in a roadmapping sense other than by ERTRAC (ERTRAC, 2019), in their strategic roadmap, which has suggested that HCVs would be permitted, Europe wide, in the 2020-2023 era, and also by Breemersch (Breemersch, 2017) who suggests that there are potential CO_2 savings of 3.5% by 2030 and 7.5% by 2050. No reference was made for the potential of these vehicles to become autonomous in the time period to 2050. Some of the literature refers to the need for regulatory framework for HCVs.

Traffic congestion occurs throughout the day but particularly in the morning and evening peak times of 7am to 9am and 4pm to 7pm respectively. About 80% of all freight movements occur during the day (Palmer & Piecyk, 2010). Freight transport operators could absorb congestion-related delays and revise their delivery schedules to accommodate longer transit times. In practice, however, congestion also causes variability in journey times from day to day, reducing the reliability of transport operation. Vehicles could be re-routed but this would incur extra distance, fuel consumption and carbon emissions. If possible, postponing travel to off-peak times would enable transport operators to use their vehicles more efficiently by taking advantage of free-flow traffic conditions. The benefits of rescheduling road freight transport operations are usually considered in the context of urban distribution. Deliveries, especially in urban areas, can be subject to several different types of time restrictions such as night-time restrictions imposed by local authorities at the point of delivery, access time restrictions in pedestrianised areas, area-wide loading and unloading time restrictions on the kerbside or delivery time restrictions imposed by the receiving unit. Research indicates that CO_2 savings of between 1.6% and 5.1% could be achieved by rescheduling deliveries to off peak periods and in particular to night time deliveries (Palmer & Piecyk, 2010). Further literature on this measure of retiming road freight to offpeak times is lacking with only brief references in (McKinnon, 2018) (ALICE-ETP, 2019).

As well as re-timing deliveries, the literature also mentions deceleration, JIT and widening delivery windows. Slowing vehicle speeds, either trucks or ships, to save fuel can reduce carbon emissions without impacting timing according to various publications (ITF, 2018) (McKinnon, 2018) (ALICE-ETP, 2019) with the estimate that ships could reduce fuel consumption by up to 19% for a 10% reduction in speeds, and for trucks a 12% reduction in fuel could be achieved by reducing speeds from 90 km/hr to 70km/hr on highways (ITF, 2018). The literature argues that JIT eliminates waste and contributes to less energy used. Narrow delivery windows will achieve customer satisfaction but inhibit the ability to fill vehicles effectively and route goods in an efficient manner. However, it is difficult to remove something once it has been given and a survey suggested that this goes against market trends and is unlikely to change (ITF, 2018).

5.4.2 Asset utilisation for other freight transport modes

In the case of rail freight in the UK there is a need to reduce end-to-end journey time and improve journey time reliability in order to achieve modal shift from road. The need to speed up average train speeds on key corridors has been identified as an important means by which to achieve this. This can be accomplished by increasing the maximum permissible line speed on a route, reducing the number of sections of low line speed, and increasing the quality of the train path (by minimising the number and duration of stops made in passing loops). The slowing and stopping of freight trains has a highly detrimental effect on their average speed as, given the weight of a heavy train, accelerating back up to full speed can take a considerable amount of time. Average speeds of some key corridors can be as low 15-25 miles per hour, so there is significant scope for improvement. Maximum line speeds for freight trains could be increased in the UK so that they can operate at speeds more similar to passenger train services, which would increase capacity on routes. Sections of low line speed could be enhanced, and heavy axle weight restrictions removed to assist freight trains in maintain a consistent speed and not need to decelerate and accelerate so frequently. Increased electrification of the rail network, permitting the adoption of more electric rather than diesel freight locomotives would also improve average freight train speeds, given the greater power they would provide especially on gradients and when hauling heavy loads (Network Rail, 2017).

Freight train length can also be increased to enable more goods to be carried per journey. At present, trains on some corridors in the UK are restricted by infrastructure limitations. The UK Government has an aspiration to achieve a length of 775 metres for intermodal trains, while some in the industry would like to see trains of up to 1500 metres for suitably light cargo. Rail infrastructure improvements on track and at terminals can be carried out to facilitate longer freight trains, which would increase the quantity of goods carried per train and would also permit the use of the network by trains from other European countries, which can be longer than those used in the UK. In terms of train weights (i.e. the combined weight of the train and the goods it carries) these also have the potential to be increased, thereby allowing more goods to be carried per journey. Maximum axle weights permitted are typically based on the strength of underline bridges, however derogations are permitted when required. Research into the impacts on infrastructure can be carried out to investigate the feasibility of increasing the permitted maximum axle weight of rail freight wagons. In order to be capable of carrying ISO containers which are used in maritime shipping on standard height rail wagons, greater rail gauge clearance is required in the UK. Low deck wagons are sometimes used to overcome such infrastructure, but they result in more expensive services due to higher maintenance and leasing costs and unused loadable train length. Infrastructure improvements can be carried out to permit the gauge clearance of ISO containers on more routes, without the need for low deck wagons (Network Rail, 2017).

The existing capacity on the UK rail network can also be increased by improved timetabling to create additional train paths, making use of unused train paths in more optimal timetabling, and the establishment of a new role to oversee and carry out activities on a cross-route basis nationally, across the entire rail. Referred to as a ‘System Operator’, such a role would help optimise current operations and timetabling as well as coordinate network improvements and ensure rail freight is well catered for in strategic planning (Network Rail, 2017).

As previously discussed, the fuel efficiency of maritime shipping can be improved by operating at slower speeds that optimise fuel consumption. This is often referred to as ‘slow-steaming’. However, slower speeds can result in the need for more ships to carry out the same quantity of work and may conflict with customer service requirements, so is more commonly used when there supply of shipping capacity exceeds demand (European Parliament, 2020). Modelling work suggests that speed reductions could reduce total ship CO_2 emissions by approximately

8% in 2050 compared to 2018 (IMO, 2020). When in port, rather than using on-board auxiliary engines, ships can be provided with power from port electricity supplies that has the potential to be produced from zero carbon sources and thereby reduce GHG emissions (European Parliament, 2020).

Improvements in air traffic management (ATM), airline operations and airport ground operations all have potential to reduce aviation GHG emissions. NATS achieved a 7% reduction in CO_2 emissions per flight over the decade since 2010 compared with a 2006 within the UK airspace it controls using ATM techniques, which is equivalent to a 1.4% reduction in UK aviation CO_2 emissions since 2010. Further ATM improvements that can be achieved include changes to airspace procedures to facilitate more direct routes and vertically efficient flight profiles, optimised aircraft speeds to allow greater fuel efficiency, and reductions in the holding of aircraft arriving at and departing airports. Much of this will be achieved through the use of improved data sharing and connectivity to facilitate improved network management (Sustainable Aviation, 2020). However, air traffic growth can undermine ATM efficiency gains. It has been concluded that without fundamental modernisation of UK airspace and its management, air traffic growth could increase CO_2 emissions by 8-12% per flight compared to current levels. New noise policies in the UK also have the potential to increase CO2 emissions per flight in built up areas (Sustainable Aviation, 2020).

Efficiency improvements in airline operations in the UK through higher load-factors, better fuel-loading, enhanced maintenance, better flight operational procedures and reductions in the on-board weight of aircraft have helped reduced to reduce CO_2 emissions per flight. There is continued scope to make energy efficiency improvements in airline operations in these areas, as well as through optimisation of aircraft speed, the use of onboard electronic systems, and reduced engine taxiing. It may also be possible at some point in future to fuel taxiing of aircraft on the ground from electric motors on the aircraft or from ground equipment based at airports. In terms of airport operations, aircraft on stands can in future be provided with airport power sources rather than using on-board auxiliary power units. It has been forecast that together these air traffic management (ATM), airline operations and airport ground operations measures could reduce UK aviation emissions by 4.7% by 2050 compared with 2016 (Sustainable Aviation, 2020).

This section has discussed the measures covered in the area of asset utilisation in the literature reviewed. Whilst there is much reference to such measures in this literature, the roadmapping element is weak, with few estimates of potential decarbonisation to 2050, or discussion of the steps required to achieve this.

5.5 Physical logistics systems

This section discusses the literature covering:

- Supply chain networks
- Regional and urban distribution hubs
- Platooning
- Autonomous vehicles
- Modular packaging
- The physical internet

Clearly, when trying to establish net zero carbon emissions from freight transport by 2050 it is important to consider the changes in physical logistics systems that may take place over the next three decades. To understand what might change it is important to take into account situations which may affect the economy and consumers' purchasing arrangements. The Covid-19 crisis, for instance, has altered the norms of human society in relation to their consumption patterns and behaviour. Home deliveries have increased substantially in the last 15 years, and this is likely to be a permanent and continuing change. As the behaviour and consumption patterns of consumers change this in turn affects the way in which supply chains operate and are organised to fulfil these changes in demand patterns. As market disruption takes place, such as in the case of Amazon and others in online retailing, non-disruptor companies also have to adapt and amend their supply chain operations and organisation to adjust to the way consumers are acting. Traditional high street stores, for instance, need to innovate or they will not flourish and succeed. Changing the way customers are serviced to counter the "Amazon effect" is having important impacts on the way goods are transported.

In the US Amazon are currently purchasing abandoned mall department stores for use as fulfilment centres bringing home delivery to consumers, according to Amazon, to within 10 minutes. There is also a move to turn redundant city centre parking areas into micro fulfilment centres to service consumers and stores (Culley, 2020). Further disruption is likely to take place beyond online shopping that will have implications for freight transport and supply chain operations. For example, when autonomous cars are introduced car rental rather than purchase might be become the norm, and the need for city centre parking may be reduced.

With 30% of non-food e-commerce sales returned, supply chain networks are having to change accommodate these changing patterns of behaviour. This, in turn, affects how consumers behave, which again may further affect supply chain systems. Any roadmap will have to accommodate these inter related factors.

In a supply chain network, hubs or regional consolidation centres (RCC's) can be used to receive full truck loads of multi drop orders (i.e. LTL quantities) from various sources such as central or regional distribution centres. These goods are then consolidated and cross docked into efficient vehicle loads for final customer delivery. This is all linked to the collaboration concept discussed in the previous section. Because customer delivery costs are usually higher than supply costs, particularly if customer deliveries are LTL, regional consolidation centres are usually located in the vicinity of customers, in order to reduce the transportation cost of final delivery. However, there is also the opportunity for RCCs to act as primary consolidation centres and receive loads from suppliers, for backloading to company distribution centres.

This is common in FMCG retailer networks. Studies have shown that cost and CO_2 savings of up to 27% and 45% respectively, can be achieved with RCCs (Palmer, 2016) but the barriers to collaboration continue to impede the development of this model. The main benefits come from the opportunity to backhaul goods between RCCs thereby reducing empty running and maximising vehicle fill, in order to efficiently get the goods into the locality of its delivery. This business model supports the development of the physical internet discussed later in this section.

Similar to a RCC, an urban consolidation centre (UCC) is intended to relieve traffic congestion by reducing the number of freight vehicles entering a city. This, in turn, can improve air quality and reduce greenhouse gas emissions, particularly where hybrid or electric vehicles are used. There are several examples of UCC's in the UK such as Meadowhall in Sheffield, Broadmead in Bristol and at Heathrow airport The basic principle of a UCC has been lauded for many years and freight transport benefits have been shown (Palmer & McKinnon, 2011), but this is often offset by the issue of who will pay for the UCC. In the examples above this has often been met by local councils or EU grants. In the case of Heathrow airport, a privately run business, companies have been told they must use the UCC for servicing stores inside the terminal buildings.

City councils are introducing more stringent legislation to reduce traffic congestion, noise and the impact of local pollutants such as carbon monoxide and particulate matter. Consequently, some cities have put in place congestion charges and introduced ultra-low emission zones, plus, for freight transport operations, restrictions on which roads can be used at night, and loading/unloading constraints. There have been many logistics initiatives to reduce these impacts including the use of electric trucks and bikes, and the use of urban consolidation centres (UCC). The purpose of a UCC is to reduce the number of vehicles operating in an urban area thereby reducing the impact of congestion and making vehicles with multi drop routes operate more efficiently. The urban consolidation centre concept is based on modifying the supply chain of deliveries into a city, with all its inherent problems of congestion, noise, etc, from a single company delivering part loads direct to one or more customers, to sending the goods into an UCC, typically located at the boundary of an urban area, where the goods are merged with goods from other companies, and then despatched on appropriate common vehicles serving those companies customers. UCCs will be encouraged in cities as economic, social and environmental pressures influence government and local authority policy. As with RCCs, collaboration is therefore key to a successful UCC operation. Several studies that have shown significant improvement in load factors, reduction in kilometres travelled and CO_2 savings of between 25% and 80% (McKinnon, 2018). Another study considered the increased use of urban hubs for last mile distribution and established that demand was moved from HGVs to other smaller vehicles resulting in a higher number of medium and light goods vehicles in the urban area, but overall the total transport emissions were reduced because of the opportunity to use zero emission vehicles (APC, EPC, 2019). Transport for London has also identified the potential for an increase in the number of smaller vehicles used due to the use of UCCs and logistics micro hubs and that this would need to be managed to minimise traffic congestion (Advanced Propulsion Centre UK, 2018).

Where UCCs were modelled the results indicated reduced operating cost as well as emission savings but this relates to transport operations only and do not include the cost of running the UCCs and micro hubs. This could make this option more expensive overall and thereby less commercially attractive. Therefore, achieving the carbon reduction benefits associated with it may necessitate external support from public sector bodies (Tricker, White, & Molho, 2019). Although last mile delivery operations are mentioned occasionally in the roadmapping literature reviewed, both RCCs and UCCs are rarely specifically discussed, instead being considered as part of the general consideration of load consolidation.

Several studies and experiments have shown that vehicle platooning, typically with several articulated vehicles driving with small gaps between them, reduces the air drag (and therefore leads to fuel savings) for all vehicles in a platoon, but for the lead vehicle in a manner similar to a boat tail effect (Alam, 2014). However, because the savings for the lead vehicle are lower and therefore, unless all vehicles in the platoon are from the same company, creating platoons may be an issue. Platooning can reduce CO_2 emissions by up to 16% from the trailing vehicles and by up to 8% from the lead vehicle (Winder, 2016). Another study shows fuel savings between 5% and 15% with three trucks travelling at 80km/hr (Carnevale & Sachs, 2019). It has been suggested that 10% of long haul freight could be in platoons by 2030 resulting in a 1% CO_2 saving, with up to 40% of long haul freight platoons by 2050 with 4% CO_2 savings (Transport & Mobility Leuven, 2017). These savings are considerably less than those stated in the other studies by Winder and Carnevale & Sachs, but are based on a different premise. The first two are based on the actual savings whist the vehicles are in a platoon, whereas in practice a platoon may only be formed for part of a journey, so the last study was measured against the entire journeys of those vehicles in a platoon. Based on a survey of experts from around the world, the feeling is that truck platooning will become common between 2020 and 2030 (ITF, 2018).

Designing a mechanism for the fair distribution of benefits is still an open question in platoon planning but there have been some attempts to solve this. Other (less-dynamic) settings where distribution of benefits is an issue mostly make use of cooperative game theory. With the advent of new technologies and emission free fuels, platooning will still be of benefit. The savings associated with platooning all stem from the reduced air-drag that trucks experience. Therefore, even with alternative technologies or fuel sources, the energy consumed by trucks would be lower and this would again result in savings. Work has shown that even a simple two truck platoon can produce significant benefits (Bhoopalam, Agatz, & Zuidwijk, 2018).

Platoons can be created in an ad hoc fashion dynamically whilst on the road or can be planned in advance. There are also four types of platooning that could occur up to 2050 as follows: (i) human driven, (ii) human driven with following trailing drivers resting, (iii) hybrid platooning, and (iv) fully automated platooning.

Vehicle to vehicle and vehicle to infrastructure communication systems would be needed to support each of these platooning operations without compromising safety. The allocation of roads to support platooning is an important factor and policies would need to be put in place for this measure to fully benefit from the savings that can be made (Bridgelall, Patterson, & Tolliver, 2020). It has been suggested that truck platooning could form the first step towards automated driving. The European Automobile Manufacturers Association, ACEA, produced a roadmap showing the steps required for the introduction of semi-automated truck convoys by 2025 as reproduced in Figure 22.

Figure 22: EU roadmap for truck platooning (ACEA, 2017)

One of the main reasons behind the development and promotion of autonomous trucks is to address the issue of driver shortages, to ensure constant eco driving and to reduce vehicle operating costs. Labour costs comprise the largest component of vehicle operating costs has significant cost saving potential if drivers are replaced with technology and, in addition, autonomous trucks do not need to stop for mandatory rest breaks.

Until autonomous trucks become ubiquitous, human eco driving techniques ensures that vehicles are operated in the most fuel efficient manner but inevitably there will be lapses on the part of the driver. This would not occur in fully autonomous vehicles but even then a person will still need to be behind the wheel. It has been suggested that their role may become that of cargo managers involving communication with shippers and customers, theft deterrence plus loading and unloading (Transport & Mobility Leuven, 2017). One study has suggested that autonomous trucks could become lighter by foregoing the need for reduced crash and body structures due to a lack of driver misuse (Advanced Propulsion Centre UK, 2018).

If driverless trucks and platooning become a reality this may have consequences for freight shifting from rail and water to road due to potential operating cost savings. Such an outcome could result in an increase in freight transport carbon emissions (EASAC, 2019).

Initially driverless trucks would operate on specific routes such as hub to hub. These vehicles will need to be supported by computer systems capable of managing these operations and, fundamentally, there must be policies in place to cover all eventualities. Governments and organisations around the world are currently examining the implications of auonomous driving in anticipation that this technology will be ready for use in a few years time. According to expert opinion, it has been suggested that autonomous trucks could become a reality in the decade following 2030 (Transport & Mobility Leuven, 2017) and, that in conjuction with platoons on long distances, this could reduce fuel consumption by about 10% due to less harsh braking and acceleration (EASAC, 2019). The issue of electrifying autonomous trucks is addressed with a suggestion that this type of truck could travel 24/7 and that the business case would be harmed if it had to stop for charging. It would therefore be ideal if dynamic charging could be introduced (Transport & Environment, 2020).

Figure 23, reproduced from ACEA, shows the processes that need to be undertaken over the following years to enable autonomous vehicles to be used on the roads in Europe (ACEA, 2019).

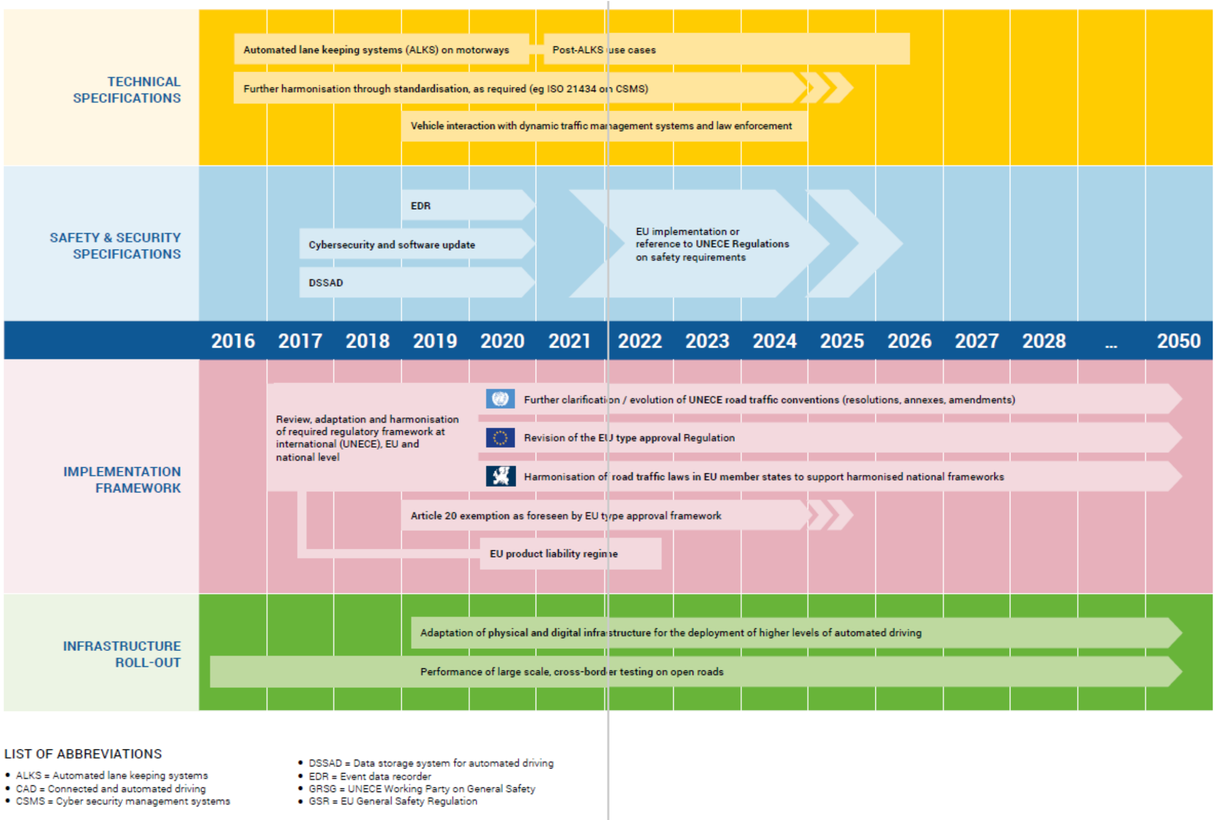

Figure 23: Steps towards the deployment of automated driving in the EU (ACEA, 2019)

The only publication that has addressed the energy impact of autonomous vehicles includes a figure derived from the US Energy Information Administration, 2017 (APC, EPC, 2019). It identifies a number of benefits and outcomes of autonomous vehicles use and the related estimated change in energy consumption associated with each (see Figure 24).

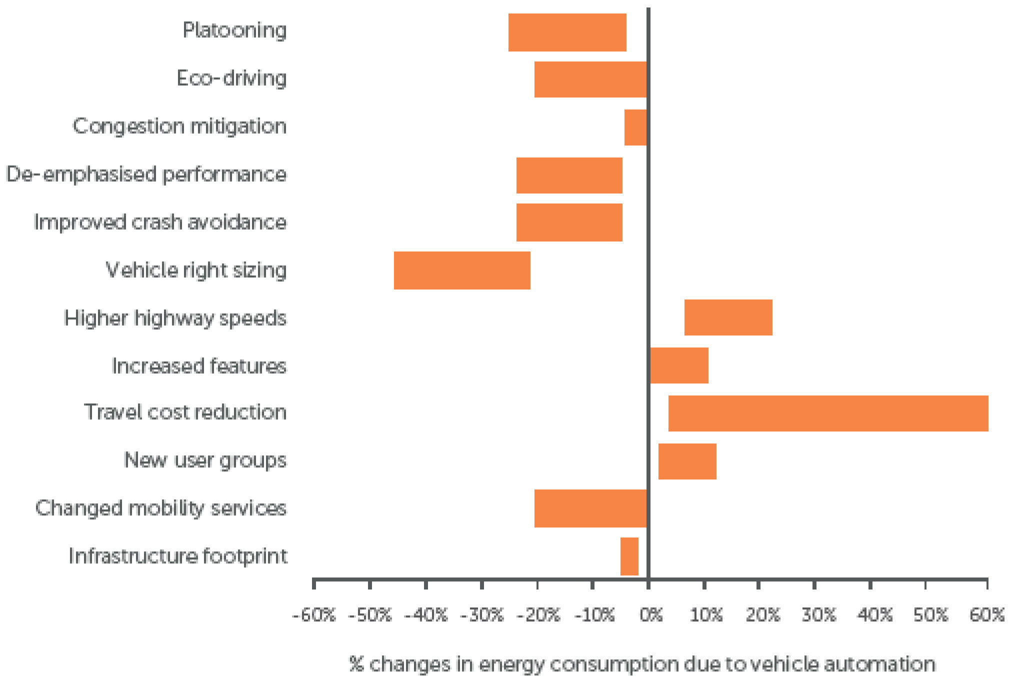

Figure 24: Automated vehicle factors and their respective impacts on fuel consumption (APC, EPC, 2019)

The inefficiency of current road freight transport features frequently in much of the literature reviewed. But there is a belief that large efficiency gains and benefits can be achieved by managing flows in a more integrated way (Sense project, 2020). This is the concept referred to as the Physical Internet (PI).

The idea of PI, first put forward by Montreuil (Montreuil, 2011), is to create an open hyperconnected global logistics system which can distribute products in modular units seamlessly from origin to destination, in a manner similar to the digital internet. It will operate with systems that support a set of collaboration protocols and smart interfaces to ensure goods are moved in the most efficient and sustainable manner. The concept is being encouraged by organisations in the USA and China, plus the EU, through the technology platform ALICE which was set up for the purpose (Matusiewicz, 2020). Key to the success of PI is the need for companies to achieve a higher level of collaboration, and this means a revolution in logistics information systems and business practice is also required. Sections 5.2 to 5.7 of this chapter all relate to measures that are compatible with PI.

For PI to operate efficiently it needs the use of interlocking, smart, reusable modular loading units. A classic example of a modular loading unit is the 40ft container which has been around for decades. There have been a few studies undertaken that have considered this requirement and work in the Moduluschca project came up with an optimal 11 different sizes (Matusiewicz, 2020). These sizes reflect the type of goods supplied by a wide range of shippers and tries to mimic the packet concept of the digital internet.

For the PI concept to be successful a great deal of work and effort would be required. This includes a considerable amount of research, as well as a far greater degree of cooperation between companies. There have been over a 100 research projects sponsored by the EU looking at different aspects of the PI. One roadmapping publication focussing in detail on the subject of PI provides a comprehensive list of actions that would have to be achieved by each decade (ALICE-ETP, 2020), many of them covered in different parts of this report. It does not mention any individual CO_2 savings, nor costs, but refers to PI helping achieve the aim of being net zero by 2050. Indeed, this ALICE report suggests that for an expected 300% increase in freight demand only 50% more assets would be required if PI is applied.

5.6 Digitalisation

Digitalisation will be extremely important to support the various vehicle technologies and measures discussed in the previous sections. This section covers the literature on:

- Artificial intelligence
- Internet of things
- Predictive analytics
- Big and broad data
- Telematics
- Route planning
- Intelligent transport systems
- Freight exchanges

In the literature examined there has been great emphasis on computing technology as a means of making freight transport more efficient and with it subsequent decarbonisation. With platooning, autonomous vehicles, vehicle to grid systems, the control of traffic on highways, etc., a huge amount of data will be captured and processed. With this increase in data comes the need for legislation and governance to ensure there is security over who collects, controls and owns the data.

Data has been described as the “new oil” in that it is a valuable commodity and that in the future there will not be freight transport operators in the conventional sense, but instead data companies that deliver goods, an advancement of the current position held by companies such as Amazon.

The increasing acquisition and analyses of data to manage freight transport in the ways described may have a negative effect in that digitalisation itself needs a huge amount of energy to run the data centres (EC-DC R&I, 2018). However, digital solutions for freight transport are likely to outweigh their specific energy requirements resulting in a net reduction in overall energy consumption.

At the moment, like supply chains, digitalised systems are fragmented in that there is no interconnectivity between them. At the national and international level, legislation is also fragmented, and there are closed systems (company data) and open systems (traffic, weather, etc data). This makes it difficult to achieve some of the decarbonisation opportunities necessary to achieve net zero emissions from freight transport. Digital tools are needed that are able to provide fast, detailed and transparent information and designed with open connections for access to other systems. The data required to manage freight transport on a national and international scale is often held by private commercial companies but access to some of this data by public entities is essential to achieve the full decarbonisation benefits from such activities as traffic management and strategic planning. For the physical internet (described in section 0) harmonisation of systems, standardisation and interoperability are cornerstones for a successful outcome. To achieve this is complex because it requires the involvement of many stakeholders such as shippers, logistics service providers, road and traffic managers. It also requires public authorities at a national, regional or local level to make sure any infrastructure investments are in place at the right time. All this is important for the future of smart and autonomous trucks as well (ERTRAC, 2019).

For freight transport route planning and road navigation systems, awareness of time of day, congestion, and up to date traffic information plus open data such as forecasted weather conditions and predictions of likely congestion due to factors such as sports events are essential to predict accurate arrival and departure times. With these factors and taking into account topographical features such as hills, ramps, road side parking areas and junctions, using a fuel efficient route as opposed to the fastest or shortest route can achieve fuel savings of between 5% and 10% (ITF, 2018) (EASAC, 2019). Increasingly AI and machine learning are being used to make more accurate predictions of truck travel times. Data within a commercial enterprise such as transport flows, traffic management and congestion are important for their own efficiency, but this big data is important for city and transport planners and researchers as well so that society as a whole can benefit by enabling the optimisation of public and private transport systems. Obviously, the main concern is commercial sensitivities, but this arises because a survey has found that sharing of data is inhibited by a lack of trust, lack of transparency and loss of control (CO3 project, 2014). However, there are ways to overcome this by anonymising the data and a high level of governance to ensure strict security.

A key enabling technology for logistics applications is the rollout of next-generation wireless networks that can significantly increase the benefits from connectivity in the supply chain. This is essential for the development of the complex systems necessary to support advanced vehicle technologies. ERTRAC argues that in the short term it is important to "*master the complexity and affordability built upon modularity, scalability, standardization, systems-of-systems and maintenance"* and to develop decision strategies for automated driving of heavy-duty commercial freight vehicles. These should include solid state laser scanners and vehicle location strategies, with specific focus on the safety aspects of sharing tasks between automated and human controlled operations. In the medium term they suggest that on board systems could include AI and machine learning systems all integrated with vehicle, infrastructure, and traffic management and back-office systems. In the long term even more advanced systems are suggested involving "*sensors and perception analyses*" based on "*neuronal computers and human-machine cooperation strategies"* (ERTRAC, 2019). As an example, a system of systems approach incorporating AI will allow synchromodal booking and tracking of shipments, automatic rescheduling or reconfiguring in case of delays or disruption and ensure a predictable and reliable service.

With all this connectivity it is important to ensure the resilience of systems and to protect against malicious attacks. Concern for cyber security and digital resilience must be uppermost in the thoughts of developers because any failure could undermine commercial trust in the technologies. There needs to be a systematic approach to identify any vulnerabilities and mitigate all risks in a safe and sustainable way.

These systems of the future should be, “secure, robust, scalable and resilient open architectures and protocols to enable full interoperability. Internet of Things (IoT) and Artificial Intelligent (AI) will enable efficient capture, storage, management and interpretation of data, while transport businesses will strive to exploit new data-driven revenue streams. Big Data analytics enables a range of new and improved services to be developed and state of the art cybersecurity ensures reliable and secure ICT services” (ERTRAC, 2019). This same publication emphasises that cooperation between transport providers is an essential factor in enabling these systems to be developed and operated successfully. These systems of the future are also a key enabler for the Physical Internet (ERTRAC, 2019).

With this prediction of open, interconnected systems, freight exchanges or logistics marketplaces may have a questionable future, but could well prove useful as a launch pad for developing future systems. In the short term, these systems support the optimisation of transport operations in real time by matching loads to reduce empty running and increase vehicle fill. Although these systems have been around for a long time, they have not been that successful, largely due to shippers’ concerns about data security, insurance, liability, and fraud, how any disruptions to the service are handled, and the current difficulty of integrating these systems into company transport management systems (DHL, 2020a). In other words, the same concerns as beset the issue of company collaboration previously described.

Railways are becoming digitally enabled, in terms of their infrastructure, train operation and capacity allocation. Improved signalling system capability, route planning, timetabling and systems for adapting to real-time situations have the potential to help enhance journey time reliability, average speed, and capacity utilisation, which can assist rail freight services in providing improved customer service and environmental benefits (Network Rail, 2017).

To achieve the immense overhaul of current systems to support the decarbonising technologies of the future needs a complete change of mindset within companies. Something that has proved extremely difficult to change over the last 15 years.

5.7 Increasing energy efficiency

This section examines the literature associated with:

- Engine
- Aerodynamics
- Driving style
- Tyres
- Lightweighting

Vehicle energy efficiency measures are very important in the transition towards zero emission freight transport, but, even after zero carbon fuels are introduced, other technologies and measures will remain valid to help minimise the amount of energy used and make vehicles more cost effective to run. In the transition period, ICEs can achieve CO_2 emission reductions through improving engine performance. For LGVs this means fuel savings from variable transmission ratios, improved valve timing, better combustion control and advanced fuel injection systems supported by ICT to manage engine performance. For HGVs efficiency improvements could come from waste heat utilisation and electrification of auxiliaries. One publication suggests LGVs could reduce CO_2 by 20% from these measures (EASAC, 2019) while another suggests 4% for LGVs and 18% for long haul HGVs (Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018).

A poorly tuned truck can increase fuel consumption and emissions by between 1% and 3% (McKinnon, 2018). The importance of ensuring an engine is operating efficiently combined with other energy reducing measures offer significant potential for CO_2 reduction with optimum fuel consumption.

The ability of aerodynamics to improve fuel consumption is related to the vehicle's operation and this is directly connected to the speeds at which it travels. Reducing aerodynamic drag by 10% causes a 3.9% reduction in fuel consumption at 90 km/hr and 3.4% reduction at 80 km/hr (Transport & Mobility Leuven, 2017). The potential for reducing fuel consumption through aerodynamics has been estimated to be 6% by 2030 and 9% by 2050 (Transport & Mobility Leuven, 2017). Individual aerodynamic measures could improve fuel consumption by 0.5% to 3% depending on the type of truck (Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018). In cities, where trucks are constantly accelerating and braking, employing cooperative adaptive cruise control which interacts with other vehicles and traffic signal control can reduce emissions by between 8% and 13% (ITF, 2018). There is a need for further research into the cumulative fuel saving when a combination of vehicle energy efficiency measures are applied (ITF, 2018).

In the SRF modelling work, driving style was constantly identified as one of the more important measure to reduce fuel consumption (Greening, Piecyk, Palmer, & McKinnon, An assessment of the potential for demand-side fuel savings in the HGV sector, 2015). Survey work suggests that over 80% of respondents have not fully implemented techniques available to optimise driving style (ITF, 2018). This same study also mentions driver training in Poland and Romania which produced fuel consumption savings of 12% and 9% (ITF, 2018). One of the problems with driver training is that it tends to produce initial successful improvements but gradually becomes poorer over time. With short term training and medium term combined training and in cab ICT support, a CO_2 reduction of 8% has been suggested for long haul trucks (Transport & Mobility Leuven, 2017). Prior to the deployment of autonomous trucks, technological developments to support better driving are essential. With both driver training and on-board technology, an average 10% reduction in fuel consumption can be achieved (ITF, 2018). One such in-cab technology uses a green to red traffic light system with audio cues to prompt adjustments to driving style. Tests conducted by academia indicates a 15% reduction in fuel consumption, as well as reducing the number of vehicle faults reported by 40% (SMMT, 2020). Interestingly, one publication points out that fuel consumption reductions are highest (up to 25%) where there are interruptions to a continuous speed such as at junctions, traffic lights and bends, but there is limited benefit on congested roads or motorways (ITF, 2018).

Energy efficient tyres that improve rolling resistance can improve fuel consumption with a CO_2 reduction estimate of 7.5% by 2030 and 12.5% by 2050 (Transport & Mobility Leuven, 2017). If energy efficient tyres are combined with automatic tyre pressure systems, the potential energy saving reduction has been estimated in the range of 0.5% to 12% for articulated vehicles (Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018). A recent study by SRF-

SA with Michelin and other companies showed that low rolling resistance tyres reduced CO_2 emissions by 8% to 10% for an articulated truck running at 80 km/hr on a test track (Kienhöfer, Saxe, Na, & Cebon, 2019).

Lightweighting vehicles is particularly relevant for transporting heavy goods in that it allows more freight to be carried thereby reducing the kilometres travelled. But it is also important for volume constrained goods because less fuel is used. If a vehicle can be made 30% lighter in weight then there is a potential to reduce the energy intensity (the vehicle load and distance travelled) by between 11% and 18% (McKinnon, 2018). Another publications suggests that trucks could potentially reduce vehicle weight by up to 7% in the next 10 years with a consequent CO_2 reduction of 2% to 3% by 2030 and 2.7% to 5% by 2050 (Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018).

Combining aerodynamics, lightweighting and energy efficient tyres can reduce emissions by up to 20% in LDVs (EASAC, 2019). Another estimate suggests this benefit to be less than 10% for trucks generally (ALICE-ETP, 2019). Additional energy saving efficiencies such as automatic transmission could achieve fuel savings of 0.5% to 2.5% and the introduction of idling technologies could save 2.5% (Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018).

About 5 years ago, the UK Department for Transport undertook a technology survey to understand the energy saving priorities of companies. Although many of the operators had adopted a wide range of measures, the results indicated that there was still a great deal of potential (DfT, 2018). Figure 25 shows the percentage of measures adopted by the operators who took part in the survey.

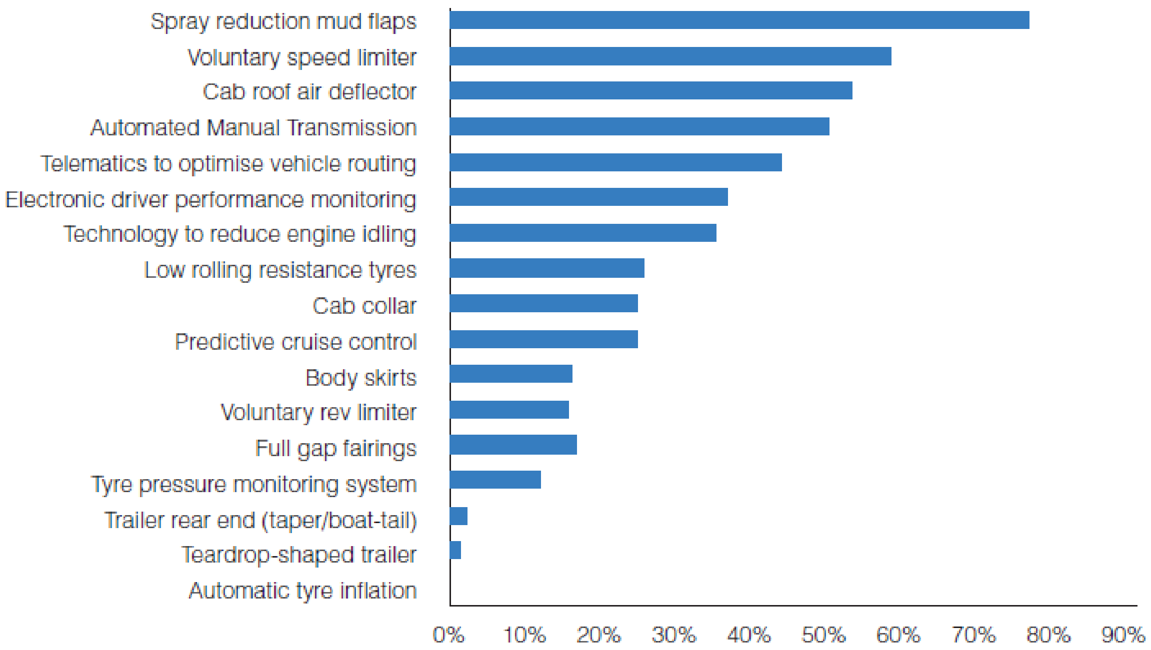

Figure 25: HGV Technology survey 2015 (DfT, 2018)

EU-wide CO_2 emission standards for the heaviest categories of trucks (rigid and articulated trucks with a gross vehicle weight over 16 tonnes, and with 4x2 and 6x2 axle configurations) was implemented in August 2019, setting targets for reducing the average emissions from these new trucks for 2025 and 2030. Truck manufacturers will have to achieve 15% fleet-wide average CO_2 emission reductions for these new trucks from 2025 (compared to the baseline period of 1 July 2019–30 June 2020). A 30% reduction target for CO_2 emissions from new trucks from 2030 has also been set, which will be reassessed in 2022. It is planned that all trucks, as well as buses and coaches will be subject to these 2030 targets (European Union, 2019). It is expected that these 2025 targets will be met through manufacturers using vehicle energy efficiency measures including low-rolling resistance tyres, improved lubricants, improved aerodynamics, improved turbocharging, predictive cruise control, friction reduction, cooling fans, air compressors, and improved selective catalytic reduction (SCR) for diesel trucks, as well as through the production of CNG, LNG and battery electric trucks.

EU-wide CO_2 emissions reduction targets for LGVs were phased in since 2014. With a target of 175 g CO_2 per km for the EU fleet-wide average emission of new LGVs between 2017 and 2019. This target was reached ahead of target, with the average emissions of new LGVs registered in 2019 of 158 g CO_2 per km. The target from 2020 onwards is 147 g CO_2 per km. Manufacturers of heavier LGVs are allowed higher emissions than manufacturers of lighter LGVs. Manufacturers have to pay an excess emissions premium for each LGV registered if the average CO_2 emissions of their fleet exceed their target in a given year, which is currently set at €95 for each g/km of exceedance (European Union, 2017). LGV CO_2 reduction targets of 15% reduction from 2025 on, and 31% reduction from 2030 on (both compared to 2021 LGV CO_2 emissions levels) have been set, with manufacturers able to obtain relaxations of up to 5% in any year if a given proportion of their LGV fleet is low- or zero-carbon (15% of the fleet from 2025 on, and 30% from 2030 on) (European Union, 2019a).

The energy efficiency of ships can be increased through improved ship designs and their propulsion systems. Energy efficiency improvements of approximately 15% can be achieved by retrofitting existing ships and up to 55% for new vessels. Such technology-based energy efficiency improvements have led to GHG emissions reductions of 20-30% from maritime shipping since 2008. However, due to the long replacement cycles which are typically 20-30 years for vessels, reductions in GHG emissions due to such vessel improvements have changed relatively little since 2015 (Energy Transitions Commission, 2020). Modelling work indicates that further vessel efficiency improvements could reduce total GHG emissions by approximately 20-30% depending on ship type by 2050 compared to 2018. These include technology improvements in ships' engine and auxiliary systems, waste heat recovery, propellers, lubrication, hull coating, lightweighting, the use of wind power and solar panels and improved hull and propeller maintenance (IMO, 2020).

Comparisons of the comparative fuel efficiencies of existing aircraft in in use UK airlines' fleets and their equivalent model available from the same manufacturer indicate that fuel efficiency improvements through technology and design have improved by 14-30% depending on make and model of aircraft. These energy efficiency gains are achieved as airlines upgrade their fleet (Sustainable Aviation, 2020).

Modelling results forecast that currently known aircraft entering service due to fleet replacements will improve fleet-average fuel efficiency of UK aviation by 17% by 2050, compared to 2016. Much of this improvement will be achieved by 2040. The development and introduction of both conventional and hybrid-electric future aircraft types from 2035 onwards and pure-electric aircraft for flights of up to 400km are forecast to have the potential to further reduce fleet CO_2 emissions within UK by 24% by 2050, compared with 2016 (Sustainable Aviation, 2020).

As well as considerations about reducing carbon emissions through improving the energy efficiency of vehicles when in use (through improvements to factors such as engines, aerodynamics, tyres, and vehicle tare weight through lightweighting) it is also necessary to take account of the vehicle production process itself. The many components which go into making a LGV, truck, ship, rail locomotive and wagon, and aircraft all require material use, manufacturing processes and distribution within vehicle manufacturing supply chains. These components, processes and logistics activities also result in considerable carbon emissions being expended during vehicle production. There is also the issue of vehicle disposal at the end of its productive life and the carbon emissions associated with this. In order to fully account for the carbon emissions associated with freight vehicles, it is necessary to take account of the entire life cycle processes of the vehicle from cradle to grave (involving vehicle production, fuel production, vehicle use and vehicle disposal (see section 5.10 for further discussion of total carbon emissions associated with freight vehicles over their life cycle).

5.8 Switching to lower-carbon energy

This section discusses the options for reducing or eliminating the carbon content of the energy used in freight transport under the following topics:

- Battery electric road freight vehicles
- Electric road systems
- Hydrogen for road freight vehicles
- Synthetic biofuels for road freight vehicles
- Non-road freight transport fuels

Making the transition from fossil fuel to alternative power sources is essential to achieve net zero CO_2 emissions for freight transport by 2050. In terms of road transport, the UK Government is set to stop the sale of fossil fuel cars and LGVs by 2030 and six of the major truck manufacturers in Europe have agreed to cease manufacturing diesel engines by 2040 (Department for Transport, 2020d) (Holley, 2020d), but this could be a significant financial commitment for companies. However, one publication suggests that light and medium duty electric trucks are currently cost competitive and larger vehicles will become cost-competitive with diesel road vehicles during the 2020s (Transport & Environment, 2020). This is based on the total cost of ownership since the initial cost may be higher but the running costs lower, assuming diesel and electricity prices stay approximately constant in relation to each other. (ERTRAC, EPoSS and ETIP SNET, 2017). There will be a transitional period towards 2050 which would see a small increase in the use of LNG and CNG fuelled road vehicles, and would also include the use of hybrid vehicles, and ICE vehicles with more efficient powertrains (EASAC, 2019) (ETC, 2018).

In line with government legislation, all the truck manufacturers are developing and phasing in zero emission vehicles over the coming years and phasing out fossil fuelled vehicles. Daimler recently announced that they will only sell zero emission road vehicles by 2039 (Transport &

Environment, 2020). They are currently developing a long-haul battery powered truck with a range of 500km (Motor Transport, 2020), but there was no mention of the cost or weight penalty associated with this vehicle. Scania are also developing a hybrid truck with pantograph for electric road system (ERS) operation. Volvo, Renault, MAN and DAF all produce battery-powered trucks of varying sizes. Iveco is partnering with Nikola to produce a battery electric truck in 2021 with a 500km range (Transport & Environment, 2020).

Prior to zero carbon emission HGV technology becoming widely available at affordable prices, there will be a need to continue to make use of transitional, lower carbon fuel options. A small proportion of operators already make use of biomethane which is produced from the anaerobic digestion of fresh organic waste and which can provide substantial carbon savings compared to diesel. For instance, the UK retailer John Lewis plans to switch all its HGVs to biomethane, a biogas, by 2028 to reduce their CO_2 emissions by approximately 80% (John Lewis Partnership, 2019). Liquid biofuels can also be used. Biodiesel comprises rapeseed, palm oil or waste cooking oils blended with diesel at proportions that can be used in existing HGV engines. The use of waste cooking oil is associated with greater carbon savings than the other two sources, which are especially grown and harvested for the purpose and which can therefore impose other GHG and sustainability impacts (Hamelinck, Spöttle, Mark, & Staats, 2019) (Gross, 2020). Biofuels currently account for approximately 2% of distance travelled by surface transport in the UK (Committee on Climate Change, 2019).

Much of the use of biofuels in UK road transport came about as a result of the UK Renewable Transport Fuel Obligation (RTFO) introduced in 2007 which requires major suppliers of road and non-road mobile machinery to either meet their obligation by redeeming Renewable Transport Fuel Certificates or by paying a fixed sum for each litre of fuel which they wish to ‘buy-out’ of their obligation. They obtain these certificates by producing renewable fuel that is verified to be from a sustainable source. The biofuel supplied in the UK in 2019 constituted 5% of total road and non-road mobile machinery fuel. Of this, 62% was biodiesel, 28% was bioethanol, and the remaining 10% comprised biomethanol, biomethane, off-road biodiesel and biopropane. Sixty nine percent of this biofuel was produced from waste feedstocks, with 79% of biodiesel coming from used cooking oil and 43% of bioethanol coming from corn (with other sources including starch slurry, wheat, sugar beet and sugar cane). Overall, these verified renewable fuels achieved an average GHG saving of 83% in 2019 (Department for Transport, 2020h).

Advanced biofuels are further discussed in section 5.8.4. The use of natural gas (CNG and LNG) in trucks can theoretically reduce CO_2 emissions by about 15-25%, but any escaped methane during the gas supply and vehicle use can reduce and even negate these carbon reduction benefits (EASAC, 2019) (Transport & Mobility Leuven, 2017).

Modelling undertaken by the EC has established that only a combination of electric and hydrogen powered heavy road vehicles can achieve net zero emissions by 2050 (EC, 2018). The report argues that using hydrogen for long haul heavy vehicle operations would avoid the need for significant amounts of biogas which could then be used in more difficult to decarbonise transport such as aviation and shipping. They also state that the extra demand for electricity can be somewhat compensated by reduced demand from energy-efficient household appliances (EC, 2018).

Sections 5.8.1 - 5.8.5 address road freight vehicles, while section 5.8.6 considers maritime shipping, rail and aviation.

5.8.1 Battery electric road freight vehicles

All the roadmapping publications examined indicate that electrification of vehicles is one of the major means of achieving zero emissions by 2050, but this is based on 100% renewable electricity and no constraints on the production of freight vehicle batteries (ICCT, 2020). This latter option may be an issue, without further technological development, due to scarcity of raw materials.

At the present time, battery powered freight vehicles are generally a maximum of 16 tonnes and are used on a relatively small scale. When the charging infrastructure improves, demand is expected to rise for battery-powered LGVs and for lighter trucks which are used for operations involving relatively short daily distances. This increase in demand should result in lower battery costs. This will be complemented by improvements in battery technology which may support the use of batteries in some longer haul truck operations (APC, EPC, 2019). Research and development efforts are on-going for electrifying these larger vehicles using batteries, but remain some years away due to the battery weights required. Journeys with distances over 200 km in the UK in 2019 accounted for 44% of total HGV tonne-kilometres performed. Articulated trucks accounted for 91% of the total truck tonne-kilometres performed on these journeys with distances of over 200 km in the UK in 2019 (Department for Transport, 2020n). This combination of journey length and the growing use of the heaviest types of trucks makes the application of battery technology difficult for trucks. Vehicle manufacturers are currently focusing on providing battery technology for trucks of up to 26 tonnes gross weight with ranges of up to 200 km. DAF is testing vehicles of up to 37 tonnes gross weight but with a range of only 100 km with no current production plans (Transport & Environment, 2020).

The main current application for battery electric trucks is in urban delivery operations. This is due to the relatively short journeys involved and the use of lighter trucks both of which permit battery use, together with the growing imposition of Low Emission Zones in urban areas which seek to improve local air quality (International Energy Agency, 2020) (SLoCaT, 2018). In these urban operations, smaller trucks are characterised by having peaks in acceleration, slow traffic and standstill, which are ideally suited to battery powertrain technology. During the transition period towards zero emission trucks, plug in hybrids will have the benefit of being less dependent on an off-site charging infrastructure and the flexibility of range extending ICE when required. (ERTRAC, EPoSS and ETIP SNET, 2017).

Long haul truck operations are characterised by fairly constant speeds for longer periods with sporadic peak power demands and fairly low speeds at the beginning and end of journeys. In the short-term, electric hybrids could offer some carbon saving potential as long as payload does not suffer. One report suggests that fully electric trucks would only reduce greenhouse gas emissions by truck by 71% and LGVs by 63% by 2050 (Transport & Environment, 2017). One of the reasons for this is that only 60% of goods vehicles could run as full electric, with special purpose vehicles including those used in the construction and waste sectors and emergency vehicles, requiring more power (Deloitte, 2016).

The charging of battery electric trucks can be at a depot, at a destination, and on the public highway. If this process can be managed correctly, then one publication suggests that with current models able to travel up to 300km, half of all truck activity could be driven by battery electric trucks in the EU. With new models under development supposedly with a 500km potential, it has been estimated that with such a range that approximately two-thirds of all kilometres driven in the EU could be carried out by battery electric trucks (Transport & Environment, 2020).

5.8.2 Electric road systems

Long haul trucks generate the greatest proportion of road freight CO_2 emissions, and it is one of the more challenging issues to find cost effective measures to eliminate the emissions associated with these operations by 2050 (Transport & Environment, 2017). Electric road systems (ERS) and hydrogen are currently the main technologies being considered plus possibly battery and synthetic or advanced biofuels.

A report has identified 17 different viable electric road systems which can be categorised in three options: (i) wireless inductive systems, (ii) inductive rail in road systems, and (iii) overhead catenary systems, with all three options undergoing various trials, and some being economically viable (TRL, 2018). The report states that the overhead catenary option is more suited to taller vehicles such as trucks whereas the in-road systems are suited to all truck types. Unlike inductive systems, which are more expensive and less efficient, overhead catenary systems are considered to be a more cost-effective solution to truck long haul driving. It is suggested that by using ERS freight operators can save between 57% and 82% of diesel fuel costs, and up to €20,000 for a 40-tonne truck travelling 100,000 km per year using an overhead catenary system (TRL, 2018).

Several important questions concerning ERS need to be answered. These include: who should fund the installation of the equipment; who should fund the operation and maintenance of the system; how much will users pay to use the system; how much vehicle owners are willing to pay to install and maintain the equipment; who should receive payment by the ERS users; and how long it will take to repay the initial investment? (TRL, 2018).

The infrastructure cost of setting up an ERS would be considerable and in the initial phase some means of fair costs to users needs to be established (ITF, 2018). This could be done through an on-board charging mechanism which records the amount of electricity consumed or by a road tolling system. The usage of the technology and electricity price mark-up needs to be high enough make ERS viable and to ensure a satisfactory payback for the initial setup and annual operating costs (TRL, 2018). However, it should be noted that the payback period on infrastructure costs in the private sector is higher than the public sector. In addition, the government would potentially need to replace the lost revenue from fuel tax with other taxes which may impact the viability of an ERS. The best business model for an ERS is for it to be constructed with government funding and with an initial subsidy to encourage take-up. Government typically has a longer payback period than the private sector and is better placed to invest in the infrastructure costs of implementing ERS technology to reduce CO_2 emissions from heavy-duty, long-distance transport.

A cost benefit analysis of all three types of ERS was undertaken by TRL (see Table 9).

Table 9: ERS breakeven and balance after 20 years (TRL, 2018)

	Mark-up 10%		Mark-up 65%	
System	Break-even year	Savings after 20 years	Break-even year	Savings after 20 years
Inductive_{min}	>20 years	- 9.0 M£	>20 years	-2.9 M£
Inductive_{max}	>20 years	-0.4 M£	6	5.7 M£
Overhead_{min}	>20 years	-4.0 M£	>20 years	-0.2 M£
Overhead_{max}	>20 years	-4.7 M£	>20 years	-1.0 M£
Rail_{min}	>20 years	-0.4 M£	6	4.7 M£
Rail_{max}	>20 years	-2.5 M£	13	2.7 M£

With a 10% mark-up none of the systems broke even after 20 years. There are a number of factors that affect the feasibility of an ERS, namely electricity prices, discount rates, traffic levels, EV take up, technology penetration, and capital/maintenance/administration costs. The analysis from TRL showed that of the three ERS methods, overhead catenary systems had the lowest installation and operating costs but is limited to use by trucks, whereas inductive systems had the highest costs, but could be used by all vehicles (TRL, 2018).

A study of overhead catenary ERS for the UK calculated that it would cost approximately £19 billion to implement across the motorway network and for the construction of substations, thereby covering 65% of total truck activity. This investment in electrification infrastructure could have a payback period of 15 years, using the profit margin on electricity sales to vehicles. In addition, it was estimated that the pantograph-electric HGVs used by operators would have a payback period of 18 months, due to the lower energy costs (Ainalis, Thorne, & Cebon, 2020).

In another study, modelling was used to look at battery, hydrogen fuelled vehicles and overhead ERS. The catenary system wasn't selected by the model for any strategies because of the high infrastructure costs (APC, EPC, 2019).

Another report also provides an overview of the three different electric road system options and lists the current trials taking place, (as at April 2019), with an assessment of their benefits and disadvantages (Gustavsson, Hacker, & Helms, 2019). It does not provide a road map as such but gives an indication of the total cost of ownership that can be achieved with these systems compared to other zero emission energies, and in relation to diesel, for the 2020 to 2030 timeframe. The methodology used to calculate this total cost of ownership comes from (Plötz, et al., 2018). Figure 26 is reproduced from this publication; the average cost is shown by the green bars, and the black vertical line represents the range of costs derived from various studies.

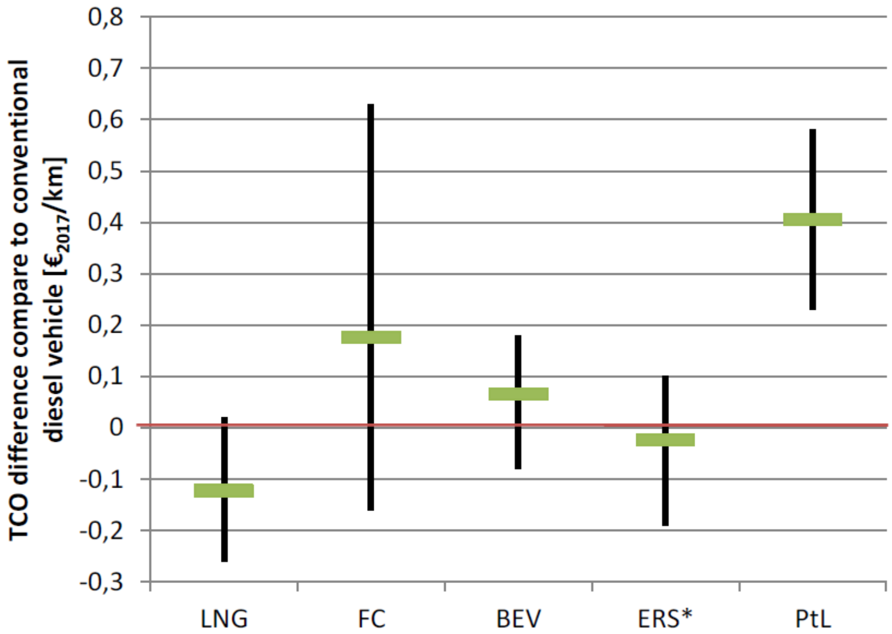

Figure 26: Differences in total cost of ownership (TCO) for different complementary drive systems (Plötz, et al., 2018)

The publication by (Gustavsson, Hacker, & Helms, 2019) does not identify the CO_2 saving potential for any of the systems studied, nor any overall estimate of CO_2 savings. Nor does it address any policy or research implications but does provide a list of factors that any ERS design should consider as follows:

- Interactions between infrastructure and vehicle configurations
- Restrictions (technical, legal, social acceptance)
- Degree of electrification (continuous versus partial electrification)
- Costs of infrastructure versus cost of vehicles
- Number of ERS compatible vehicles (market ramp-up)

One report states between 40% and 60% of long haul trucks could potentially have a catenary system by 2050 but the biggest barrier is setting up the charging infrastructure. In an apparent contradiction, in the same report, it has also been suggested that 90% of all long haul truck registrations will have the catenary technology by 2050 (Transport & Environment, 2017). In Europe it has been estimated that 38% of highways could be electrified by 2050 with 34% of truck traffic in France running on 2860km of highway, and 60% of trucks in Germany running on 4000km of road by 2030. However, electric roads will not cover all the journeys made by these trucks or any of the entire journeys they make from origin to destination, as the ERS will only be installed on the main road network. Therefore, trucks using ERS will require other zero emission fuel source to complement this technology, which could be provided by batteries or hydrogen.

5.8.3 Hydrogen for road freight vehicles

Although hydrogen has zero tailpipe emissions there are some significant issues with its production and use. The most common method is steam reforming which uses fossil fuels and without carbon capture and sequestration (CCS) is very polluting, but the other option is electrolysis of water using electricity, but this is very inefficient because it has lower levels of energy. In Germany with the current mix of power generation methods it has been estimated that trucks powered by hydrogen emit twice the amount of greenhouse gas emissions as diesel (ITF, 2018).

Hydrogen is three times less efficient than direct electrical charging and there are high costs associated with the vehicle and technology, plus the refuelling infrastructure (Transport & Environment, 2017) (EC-DC R&I, 2018). Due to the nature of the gas, hydrogen needs special high pressure storage facilities which can take up 40% of the energy in the fuel from leakage. Due to the pressurised storage tank, electric motors and batteries, hydrogen fuelled vehicles will be at least one tonne heavier than a conventional diesel truck (Transport & Environment, 2017). Daimler trucks are currently trialling the use of higher density liquid hydrogen instead of gaseous hydrogen which would give the trucks a range of 1000km (Motor Transport, 2020). The temperature regime at which hydrogen fuel cells operate has to be controlled as they can only use water, not steam or ice (Wertheimer, 2018).

Despite this currently being an inefficient and costly form of energy, a number of publications have argued that there are benefits to be had based on the flexibility it can provide (EC-DC R&I, 2018) (ITF, 2018) (DfT, 2018). The energy to weight ratio is ten times greater than lithium-ion batteries, it is lighter, and occupies a smaller volume (Wertheimer, 2018). This means a hydrogen powered truck can travel greater distances than a battery powered truck and it can also be filled more rapidly. The use of hydrogen can also help avoid the electricity network upgrades required at depots for electric battery use, and hydrogen filling stations can serve more vehicles than EV chargers due to faster refuelling times (Staffell, et al., 2019). In addition, if hydrogen becomes the chosen fuel source for other energy uses for industry and electricity and heat generation and the required production infrastructure is put in place, then this may well have important implications for the availability and cost of hydrogen for use in transport.

In November 2020, Volvo and Daimler Truck signed an agreement for a joint venture to develop, produce and commercialize hydrogen fuel-cell systems for use in trucks (Daimler, 2020). In December 2020, an alliance entitled ‘H2Accelerate’ (H2A) was launched with the intention to create the necessary conditions for the eventual mass production hydrogen fuelled trucks. Partners include Shell, Daimler Truck, Iveco, Volvo and OMV. The partners expect that it will take approximately a decade to reach scale. It will commence with some of the partners’ customers making an early commitment to hydrogen-based trucks, and to begin using them in regional clusters and along European high-capacity corridors with hydrogen refuelling station provision. The H2Accelerate partners intend to work together to seek public funding for initial pre-commercial projects during the first five years of the roll-out, as well as engaging with policy makers in efforts to encourage a policy environment that supports the scale-up that would be required in hydrogen production and distribution, hydrogen truck production and a European refuelling network (Shell, 2020).

Hydrogen has the potential to allow transport to go further and, given the constraints, it is potentially appropriate for rail where it is uneconomic to electrify lines.

5.8.4 Advanced biofuels and synthetic fuels for road freight vehicles

Advanced biofuels and synthetic renewable fuels can also contribute towards reducing road freight emissions, especially in the transition towards electric vehicles. None of the roadmapping literature provide any details to show how biofuels might be used in any transition to zero emissions, only that they have a contribution to make. Fossil fuels are hydrocarbons in that they contain hydrogen and carbon. If hydrogen could be produced from a zero carbon source such as renewable energy and combined with CO_2 taken directly from the air through CCS or as a biproduct from industrial processes, then there is the potential to create these near zero carbon fuels

Advanced biofuels such as ethanol, methanol, fatty acid methyl ester, hydrotreated vegetable oil or biomethane (either compressed or liquefied) can be made from waste material such as sewage sludge, landfill gas or from residues from agriculture, households and the food industry (CE Delft; Eclareon; Wageningen Research, 2016). There are also new technologies involving algae. The original production method of these fuels used sugars, starch and vegetable oils which it has been argued (Transport & Environment, 2017) produces more well to wheel emissions than fossil fuels. In the transition period to 2050 these biofuels can be blended into fossil fuels to reduce the carbon content. Indeed, hydrogenated vegetable oil can be directly substituted for diesel. The main problem is availability of the necessary biomass material to manufacture the biofuels, because these would also be demand from the chemicals and material sectors who would be producing sustainable bio-based products. The biomass raw material could compete with food production or cause deforestation or loss of biodiversity (Carnevale & Sachs, 2019). Modelling shows that advanced biofuels can contribute a 4% saving in emissions across all modes of transport by 2050 (Transport & Environment, 2017). A report from the Low Emissions Freight Trial (LEFT) stated that after a one year trial the well to wheel greenhouse gas savings with biomethane were between 69% and 81% for all types of vehicle journey (Holley, 2020a). This trial also showed that fixed and variable running costs could be recouped in two years, and that methane slip was not an issue if fuelled with RTFO certified biomethane. Biofuels has an advantage over renewable sources such as wind and solar in that it has the flexibility to provide power when there is no wind and poor solar intensity. It has been estimated that the amount of biogas produced could more than double by 2030 (CE Delft; Eclareon; Wageningen Research, 2016).

According to (Moon, 2020) ICE has a future on long haul trucks for the next two decades but as a hybrid so that it can be switched to electric within urban areas for instance. These can be used with renewable biofuels such as hydrogenated vegetable oil (HVO) derived from waste by-product sustainable sources and which requires no infrastructure investment and is totally compatible with conventional diesel engines without any modifications. It is referred to by truck manufacturers as a drop in fuel because it is a complete replacement for diesel. It can also be mixed with mineral diesel, so there is no need for separate tanks in depots or vehicles. Moon (2020) also states that there is no detriment to fuel economy, and in urban operation HVO can slightly improve it. It is used extensively on the continent, particularly in Scandinavia, but hardly at all in the UK, but awareness is growing, with multiple suppliers of the fuel. However, it is in short supply, and 10% to 15% more expensive than diesel. It would be more suited to companies who have depot fuel bunkers available, receiving bulk supplies. With half a million HGV trucks registered, many of them being long haul, there is a limit on the amount of HVO available, but no information on this has been found.

Zero emission synthetic renewable fuels are created using renewable electricity to produce gas such as methane, or liquid such as methanol to power trucks. Synthetic liquids could also include diesel and kerosene manufactured from biomass using a technique known as Fischer-Tropsch which converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons (Transport & Environment, 2017). These synthetic liquids could be of particular importance for certain hard to abate modes of transport such as the airline sector and special purpose trucks that require additional power, but they may also be more appropriate for use in other harder to decarbonise sectors and geographical areas (Carnevale & Sachs, 2019). In shipping, restriction on sulphur oxide emissions were imposed globally in 2020, so the pressure is on shipping lines to comply and become more sustainable. Stena AB is quoted as being very focused on sustainability and has been operating a methanol fuelled ferry between Sweden and Germany for five years (Wartsilla, 2020). In the transition period these synthetic and bio fuels could be blended with fossil fuels, and then used as a complete fuel in hybrid trucks. However, the ability to manufacture the volume of these fuels sustainably and cost effectively is limited and not sufficient to meet demand (Transport & Environment, 2020). Another publication argues that synthetic fuels could completely decarbonise the freight sector but would require a considerable amount of electricity to do this and 5 times less efficient than the electricity required for battery or e-highway trucks al (Transport & Environment, 2017).

5.8.5 Summary of fuels for road freight vehicles

The previous sections of this chapter have considered the literature on a range of zero carbon fuels to drive road freight vehicle powertrains. Table 10 table provides an overview of different zero carbon energy fuels that could be used to power trucks (Plötz, et al., 2018).

Table 10: Comparison of different powertrains (Plötz, et al., 2018)

	Fuel cell (FC)	Battery electric (BE)	Overhead catenary (OC)	Synthetic fuels (PtG /PtL)
Motors and technology	Electric motor and fuel cell with hydrogen as energy storage	Electric motor and battery as energy storage	Electric motor and power from overhead lines, if necessary with battery as energy storage or additional combustion engine	Internal combustion engine and pressurized gas or liquid tank as energy storage device
Conversion steps Fuel production from electricity	Conversion to hydrogen (electrolysis)	Direct Use	Direct Use	Conversion to hydrogen (electrolysis) and further to carbonaceous fuel
Efficiency today with the use of renewable electricity	Circa	Circa	Circa	Circa
tank-to-wheel	40 – 50 %	90 %	90 %	35 – 40 %
well-to-tank	60 – 70 %	90 %	90 %	50 – 60 %
well-to-wheel	25 – 35 %	80 %	80 %	20 – 25 %
Technological readiness level of vehicles	Several test projects (TRL 6-7)[11]	First commercially available vehicles (TRL 8)[11]	Several test projects (TRL 6-7)[11]	Conventional vehicles
Key challenges	Infrastructure development and increased power requirements due to high conversion losses, cost reduction in fuel production	Limited range, long charging time and payload losses	Infrastructure development, acceptance, integration in logistics processes	Strongly increased power demand due to highest conversion losses, cost reduction in vehicle and fuel production

Some of these energies are more efficient than others (Institution of Mechanical Engineers, 2020). Transport & Environment show a comparison of the energy efficiency of fuel production and use for 2020 and 2050 (see Figure 27).

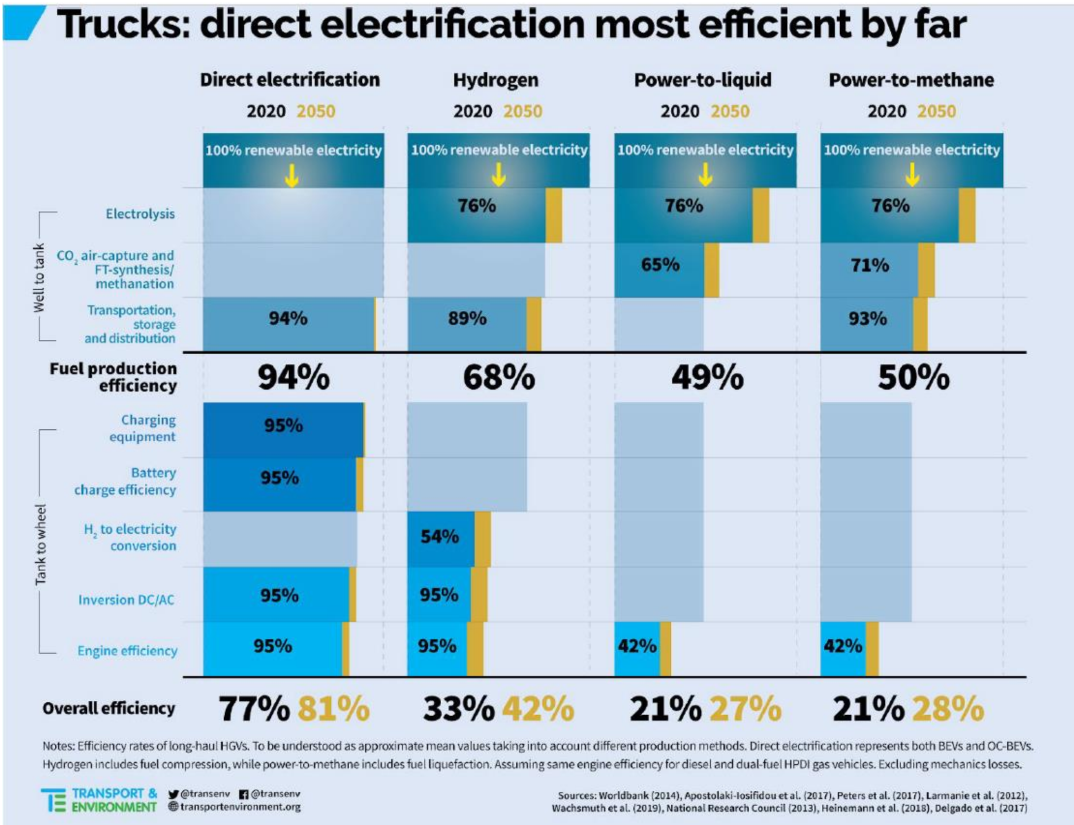

Figure 27: Comparison of energy efficiency of four fuels (Transport & Environment, 2020)

In a 2018 survey by ITF, respondents were asked when these alternative energies might be in widespread use. The responses are shown in Figure 28.

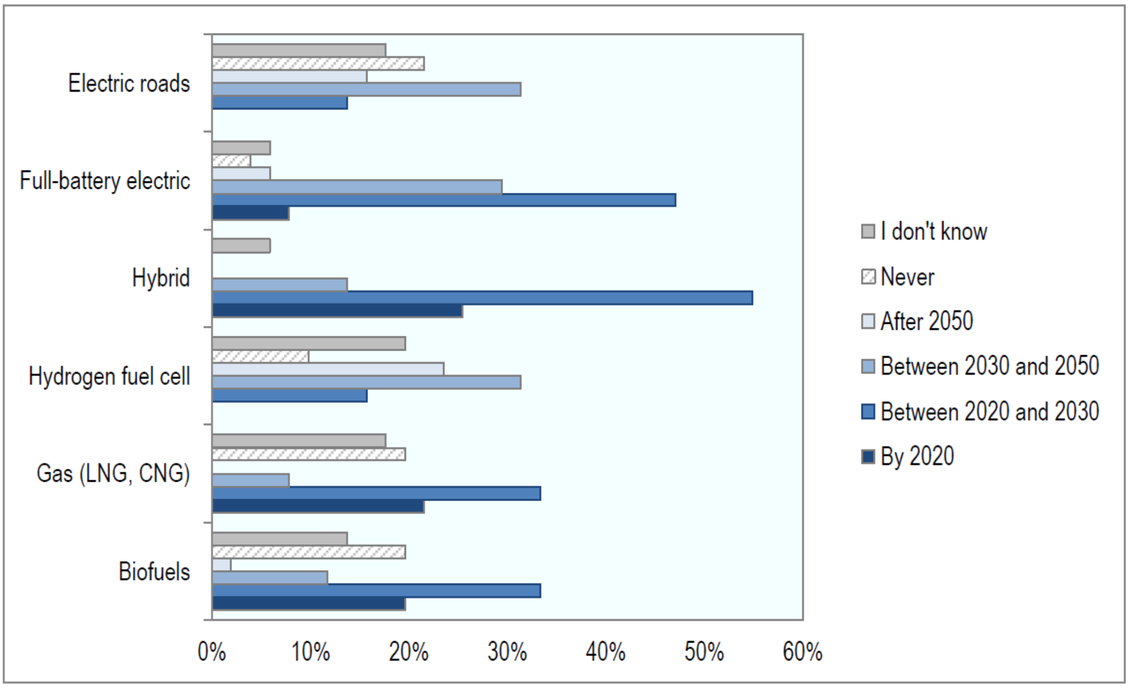

Figure 28: When will these alternative fuels be in widespread use (ITF, 2018)

A study in Germany that analysed the economic costs of achieving carbon-neutral long haul road freight transport by 2050 for four different types of energy showed that strong electrification was the lowest at €100 billion followed by liquid and gaseous biofuels at around €200 billion and the highest being hydrogen at just under €300 billion (Öko-Institut, 2016).

Both electric (battery and ERS) and hydrogen offer potential as energy sources to decarbonise truck operations. There is currently no clear preferred option for long-haul truck operations but decisions will need to be made soon considering all the technological development, planning infrastructure implementation, vehicle manufacturing and vehicle uptake required if there is to be any opportunity to achieve road freight decarbonisation by 2050 (Ricardo Energy & Environment, 2019).

5.8.6 Non-road freight transport fuels

Rail is the simplest of the non-road modes for which to achieve zero CO_2 emissions, given that much of the UK rail network is already powered by electricity. However, at present, the vast majority of freight trains in the UK are powered by diesel, as many sidings on which they operate not currently electrified, meaning achieving zero CO_2 emissions will still be difficult and expensive. One option for decarbonising rail freight in the short term includes electrifying, where it is cost effective to do so those parts of the rail network used by rail freight. This increased electrification would also improve average freight train speeds, given the greater power they would provide especially on gradients and when hauling heavy loads. Other short term options include greater use of diesel-electric hybrid locomotives (10 of these Class 88' dual mode' freight locomotives are currently in use) and the use of biofuels (either blended with diesel or pure biofuel). Hybrid trains have the disadvantage that the need for carrying multiple traction methods increases weight, complexity and maintenance requirements. It is unlikely that sufficient quantities of biofuel will be available for rail freight decarbonisation in the UK. CNG or LNG could also be used to power freight trains but these are not carbon-free and would also raise safety issues and would require greater numbers of fuel supply vehicles than are required for diesel operations, resulting in more complexity and possibly impacting the viability of rail freight (Network Rail, 2020) (Transport Scotland, 2020).

In the longer term, routes to zero CO_2 emissions for rail freight operations identified in the UK include greater network electrification and using bi-fuel locomotives (either overhead electric and battery electric, or overhead electric and hydrogen fuel cell) (Network Rail, 2020). Concerns have been expressed that achieving zero emissions rail freight in the UK is likely to result in substantial costs for new infrastructure or locomotives. If these costs were not met, probably from public expenditure, then UK rail could only achieve zero emissions by transferring rail freight to other modes, such as zero emission trucks (National Infrastructure Commission, 2019). Further research about how best to decarbonise rail freight operations in the UK is currently taking place that will inform government and industry policy making (Rail Industry Decarbonisation Taskforce, 2019).

In addition, some freight trains in the UK are used for rail engineering and maintenance works. Electric-only is not a viable option for these trains as they often have to operate when the overhead electrical supply has to be switched off (Network Rail, 2020). Hydrogen powered train trials have taken place in various countries (BBC News, 2020a) (Alstom, 2018). The UK's first trial run of a hydrogen powered train occurred on 29th September 2020 with a 25-mile journey in the West Midlands, with the aim to become operational in 2021 (BBC News, 2020a). In Germany a train has started running with roof mounted hydrogen tanks and Alstom has stated that it will convert some trains in the UK from electric to hydrogen to have the flexibility of travelling on non electrified lines and to meet government targets to cease diesel trains running by 2040 (Staffell, et al., 2019). As with hydrogen powered trucks, these trains will be less energy efficient than electric trains (EC, 2018).

Like trucks, rail could also benefit from various mechanisms to recover on-board energy such as regenerative braking and energy storage devices, and power electronics that are less energy intensive (Carnevale & Sachs, 2019).

For maritime shipping, in the short term, natural gas (LNG and LPG) and biofuels can be used instead of oil (heavy fuel oil and marine diesel oil). There are already several hundred LNG-powered ships in use (European Parliament, 2020). Biofuels can be used in existing ship engines without the need for major modifications and investment. However, both natural gas and biofuels result in continued, albeit reduced, CO_2 emissions, and long-term biofuel supply for shipping is uncertain and demand for biofuels from other non-transport sectors is likely to be high (Energy Transitions Commission, 2020).

In the longer term, it is expected that zero carbon fuels, produced via industrial processes, will be developed that can be used in place of fossil fuels for long-distance, deep-water shipping. There are several possible options available. These include hydrogen which could be produced from electrolysis using renewable electricity. However, the direct use of hydrogen by ships poses storage capacity difficulties given its low volumetric density, together with safety challenges. Hydrogen could also be used in the production of several other fuels. These include methanol which could be produced from hydrogen together with CO or CO_2, but unless Direct Air Capture was used (which is still in developmental stages), would, like biofuels, still result in CO_2 emissions. Synthetic diesel, produced from hydrogen and CO_2 could be used in existing ship engines, but this fuel technology is still being developed and is predicted to be expensive both in terms of capital costs and production costs. Ammonia could also be produced from hydrogen. It could be used as a marine fuel without the volumetric density problems and storage space requirements of using hydrogen directly. However, the use of ammonia requires developments in engine and fuel technology and production facilities, has fuel and bunkering infrastructure requirements, and has implications for safe handling given its toxicity. All of these longer-term fuel options for shipping present challenges in terms of the developments in engine and fuel technology they require, the fuel production and bunkering infrastructure they would require, their handling and safety issues and regulations needed, and the financial costs associated with them. At present, ammonia is generally deemed to be the most viable of these fuels (Getting to Zero 2030 Coalition, 2019) (Lloyd's Register and UMAS, 2019) (Lloyd's Register and UMAS, 2020) (Energy Transitions Commission, 2020) (Department for Transport, 2019) (European Parliament, 2020). Modelling work forecasts that zero carbon fuels have the potential to reduce CO_2 emissions from maritime shipping by 64% in 2050 compared to 2018 (IMO, 2020).

Longer term zero emission fuels for inland waterways, coastal shipping and short distance deep water shipping, include battery electric or hydrogen fuel cells options. In addition, port-based zero emissions fuel sources can be used to power all vessels while in port (Energy

Transitions Commission, 2020) (International Chamber of Shipping (ICS), 2020) (Carnevale & Sachs, 2019).

Aviation is the most difficult freight transport sector in which to decarbonise the fuel source, as there is a relative lack of lower-carbon fuel alternatives or zero CO_2 emission options available at present (Department for Transport, 2020c). 'Sustainable aviation fuels' (SAFs) have been identified as the most promising form of lower-carbon fuel sources. These are produced from biomass or recycled carbon wastes and residues such as household waste or waste gases from industrial processes that result in fuel that has at least 60% reduced life-cycle CO_2 emissions compared with fossil fuels (Sustainable Aviation, 2020). In the UK a collaboration between British Airways, Shell and Velocys will develop the country's first commercial scale waste-to-renewable jet fuels plant, which is expected to result in approximately a 70% reduction in GHG emissions compared with conventional jet fuel (Department for Transport, 2018). The building of this plant received planning permission in 2020, and it is hoped that fuel production will commence in 2025 (Velocys, 2020).

Another option is the production and use of synthetic fuel derived from a power-to-liquid production route (Energy Transitions Commission, 2020). This would most likely involve extracting hydrogen from water through electrolysis using renewable electricity, which would then be combined with CO_2 gathered from the atmosphere to produce a liquid hydrocarbon fuel that could be used in existing jet engines without major modification (Murphy, 2018). The development of other types of aviation fuel, such as hydrogen, would require entirely new aircraft design and airport refuelling infrastructure. Electrification may have a role to play in aviation at some point in the future, either combining batteries with liquid fuel or fully electric, for short range flights. An aviation industry body foresees such short haul electric flights becoming possible by 2040, but this battery technology has yet to be developed (Sustainable Aviation, 2020).

5.9 Energy systems

The previous section discussed the different types of power drivetrains. This section covers the systems needed to support the energy used by the trucks. Literature has been examined covering:

- Battery technology
- Renewables
- Hydrogen production
- Smart grid technology
- Storage
- Synthetic fuels
- Carbon capture and sequestration

To achieve a full decarbonisation of the road, rail, shipping and aviation freight sectors new technologies and energy carriers are needed, and in that regard renewable decarbonised electricity is essential, not only for battery charging or through road systems, but also for the conversion of fuels and gases such as hydrogen, bio and synthetic fuels.

5.9.1 Battery technology

It is inevitable that batteries will improve over the coming decades as new technology is developed. Batteries are produced using mainly lithium, graphite, nickel and cobalt. These are sourced from many countries some of which are inhospitable or politically problematic locations. This presents a potential supply risk, and the social and environmental impact of sourcing these raw materials should also not be understated. With an increasing demand for vehicle batteries, there needs to be an upscaling of production but some of the raw materials, such as lithium and cobalt, are in short supply (Carnevale & Sachs, 2019). Demand for lithium is predicted to double by 2025 with Australia and Chile accounting for about 75% of the volume shipped (The Conversation, 2017). The mining, processing, refining and manufacture supply chain for each mineral could present a bottleneck at any point resulting in shortages, particularly if all these processes are concentrated in one country which then becomes politically destabilised.

However, alternative materials are being considered and battery technology will evolve with new developments in advanced lead acid and nickel metal hydride (APC, EPC, 2019). A deep-sea rock has been discovered that contains four ingredients necessary for battery production namely nickel, cobalt, manganese and copper, which, it is claimed, would reduce the mining carbon footprint by 75%. This statement came from a peer reviewed paper authored by the University of Delaware’s Centre for Minerals, Materials and Society and claims that compared to land-based mining, sea-based mining would disrupt far less area, some 2,100km^2 instead of 156,000km^2 for land. The study also states that there is likely to be an expected 500% increase in mineral requirements for clean technologies though a date has not been specified (Searles K. , 2020a).

CO_2 emissions associated with battery manufacturing vary by country, due to the proportion of electricity generated from zero carbon sources, with batteries manufactured in Asia having lifecycle emissions around 20% greater than in Europe or USA (Hausfather, 2019).

There are a large number of research projects looking at battery technology. Rapid advances in lithium-ion technology could displace current lead acid and nickel metal hydride (NiMH) batteries (Advanced Propulsion Centre UK, 2018). The need for faster charging and higher energy densities is stimulating research into new chemicals and, in particular, anode material to replace graphite which has been used for 25 years. This needs to be done without increasing the weight of batteries and within a cost that will encourage companies to use the technology. One of the biggest problems with batteries is the length of time it takes to charge. Current research is looking at electrolytic components to improve lithium ion batteries (APC, EPC, 2019). A recent innovation can cut charging time by two thirds by dissipating the amount of heat generated by charging, which allows the electrolyte plates to be positioned closer together and speed up the charging process (The Times, 2020b).

Battery recycling has been discussed in some of the literature, with a suggestion that the complete lifecycle should be included to make sure batteries are fully sustainable in the long term (DfT, 2018) (EC-DC R&I, 2018) (ITF, 2018). A key risk in the roadmap is the lack of any sustainable high volume solution for end of life recycling (Advanced Propulsion Centre UK, 2018). Processes need to be put in place to ensure that, through reverse logistics, the scarce raw materials can be recovered from large numbers of end-of-life batteries thereby supporting the circular economy. In addition, batteries are made up of a large number of cells or modules and if one of them fails the entire battery needs replacing, so a very small defect can result in a large replacement overhead (DHL, 2020). Batteries are also hazardous, so if a vehicle crashes and any of the cells are damaged the chemicals may interact to generate a huge amount of heat causing other cells to ignite. It is claimed that an electric vehicle would burn for longer than an ICE vehicle and may even reignite some time after the incident, so clear safety and planning regulations are needed (BBC News, 2020b).

Batteries can also have a second life. After establishing the safety, reliability and performance of second life batteries, these could be used for electricity storage at the grid level. There are numerous examples of this using first life batteries including the Hornsdale Power Reserve, developed by Tesla, in South Australia, and NEC Energy Solutions in Hawaii. Two of the largest second life battery programmes are currently taking place in the UK with the SmartHubs project and in France with Advanced Battery Storage using Renault batteries (Holley, 2020b). The batteries will be charged and discharged to balance out the electricity networks demand. Also in the UK, Nissan are working on a similar scheme called xStorage and claim “the home storage unit gives Nissan's electric vehicle batteries a 'second life'.“ (Nissan, 2020). Charging and discharging of batteries installed in vehicles could also be used to smooth out the peaks and troughs of electricity demand by using a vehicle-to-grid system (DfT, 2018). This could offer a cheaper and greener option than using large scale battery systems.

APC provide a number of predictions in relation to batteries as follows (Advanced Propulsion Centre UK, 2018):

- Rapid advances in lithium-ion technology could displace some existing battery chemistries but are also stimulating research into lead acid batteries
- Optimising current graphite anode technology will complement enhancements in lithium-based cathodes, but as new chemistries are developed and charging rates increase new anode technologies will be needed
- Lithium-based cathodes will predominate in the short term but new cathode materials are required to deliver cost reductions, better energy/power densities and greater recyclability
- The desire for improved range, reduced cost and faster charging rates will stimulate innovative battery pack designs, increased packing densities and innovative cell-module-pack concepts
- Advances in battery management, most notably to deliver improved thermal management strategies, will be required before battery performance can be extended
- Mobilising numerous industries to collaborate with the automotive sector to appropriately recycle or re-use batteries will determine their credibility as a long term powertrain solution

Whatever form batteries take in the future, it is clear that only renewable electricity should be used to charge them if zero emissions are to be achieved.

5.9.2 Renewables

According to Graeme Cooper, the electric vehicle project director at the National Grid, if everyone switched to battery powered road vehicles overnight it would only increase power demand by 10% which is "well within range of manageable load fluctuations" (The Times, 2020a). However, there are still likely to be load fluctuations, so to ensure a constant supply, peaks and troughs will need to be smoothed. Whilst it is possible to import electricity, the smoothing of the electrical peaks is imperative to minimise the cost and development of power generation. There have been a number of initiatives in this area.

Renewable electricity production is increasing. In the UK wind turbines generate about 20% of total output (GridWatch, 2020). There are innovative developments taking place in offshore wind farms run by Shell and Eneco, by using surplus electricity on windy days to produce hydrogen through electrolysis and to charge batteries at sea. The hydrogen fuel cells will be turned back into electricity when required. Supporting this are floating solar panels next to the turbines so that a continuous supply of electricity can be produced if there is insufficient wind, and peaks and troughs can be dampened (The Times, 2020).

There are also a number of "smart solutions" being trialled. These include active network management systems that can manage peaks and troughs remotely by momentarily interrupting the electric flow to certain flexible devices, such as electric vehicles, at peak times (Element Energy Ltd, 2015). Another is demand side response signals which can request selected customers to stop charging at certain times of the day. Another solution is local intelligent EV charging control which can allocated a fixed capacity to several EVs for a set period of time. (Element Energy Ltd, 2015). Peak use of electricity is planned between 17:00 and 20:30 with underutilised capacity at other times of the day. Using time varying tariffs (dynamic pricing) can be used to manage demand and minimise greenhouse gas emissions (EASAC, 2019). Using these smart solutions can reduce the need for additional infrastructure and could provide benefits of up to £40bn by 2050 (DfT, 2018). These smart solutions have also been referred to as the internet of energy which means that using digitalisation to manage the energy demand can improve grid reliability and has the potential to reduce energy costs (EC-DC R&I, 2018). Over the decades to 2050 there may be areas of high demand where there are large numbers of plug-in trucks with the need to reinforce the electricity grids in those areas (Advanced Propulsion Centre UK, 2018).

Renewable power is cheaper than fossil fuel in some parts of the world and, as investments in the various technologies increases, prices will fall. China is the major manufacturing country for solar panels and electric cars, and is a major hub for battery production (BBC News, 2020).

Electricity generation is becoming more decentralised. As well as the main fossil fuelled and nuclear power stations there are numerous smaller renewable installations ranging from offshore windfarms, solar farms, plus wind and solar generation on houses and industrial premises. and vehicle to grid systems. Rolls Royce are planning to build 16 mini nuclear power reactors across the UK (BBC News, 2020d).

5.9.3 Hydrogen production

As stated in the previous section, hydrogen is only 25% energy efficient once it reaches the vehicle, but research is going on to try and improve this efficiency. One such project is looking at the use of metal hydride which can absorb and release hydrogen in a controlled way and would eliminate the compression chamber in which hydrogen currently needs to be stored (Holley, 2020c). Another is a project led by Brunel University and backed by Shell and BP, with £1.4m of UKRI funding, which aims to look at the development of hydrogen microbubble liquid fuels (Brunel University, 2020).

Despite this inefficiency, hydrogen is an important fuel in the aim for zero emissions. Apart from transport it can support heating, energy storage and industrial processes. It has been suggested that it is unlikely that the UK will be able to fully electrify heating and transport before 2050, so hydrogen will be fundamental to decarbonise long haul freight, rail, shipping and aviation (Searles K. , 2020). However, generating sufficient emission free hydrogen required by the transport sector in the short term would require carbon capture and storage.

Two particular advantages hydrogen has over batteries is that it does not require the scarce minerals mined unsustainably in politically unstable regions, and the end-of-life management is cost efficient (Searles K. , 2020). Hydrogen vehicles are quick to refuel and there is less of a weight penalty than batteries.

5.10 Vehicle lifecycle CO_2 emissions

The many components which go into making a LGV, truck, ship, rail locomotive and wagon, and aircraft all require material use, manufacturing processes and distribution within vehicle manufacturing supply chains. These components, processes and logistics activities also result in considerable carbon emissions being expended during vehicle production. There is also the issue of vehicle disposal at the end of its productive life and the carbon emissions associated with this. In order to fully account for the carbon emissions associated with freight vehicles, it is necessary to take account of the entire life cycle processes of the vehicle from cradle to grave (involving vehicle production, fuel production, vehicle use and vehicle disposal.

Life cycle analysis (LCA) can be used to analyse the carbon emissions associated with entire vehicle life, as well as all other environmental impacts. However, LCA is time-consuming and expensive to conduct, subject to data availability and data quality challenges, and requires fundamental considerations about where to draw system boundaries, with these boundaries having important implications for the results. LCA studies applied to vehicles is sometimes only applied to specific life cycle stages rather than the entire vehicle life cycle, and sometimes only focus on a particular vehicle make and model rather than more generically, and, in some studies, only considers certain components (e.g. batteries) rather than the entire vehicle in question. Assumptions made in LCA studies concerning vehicle lifetime mileage and fuel consumption have an important bearing on the results.

A study of carbon emissions over the entire life cycle of road vehicles commissioned by the Low Carbon Vehicle Partnership included a literature review of LCA studies, which identified far more research concerning cars than of trucks or LGVs (Ricardo, 2018). Twenty-one publications were identified that address trucks and LGVs. Most of these publications considered diesel-fuelled vehicles, while some compared these vehicles to those powered by natural gas or hybrids. This report indicates that for conventional ICE cars, vehicle production accounts for 15-30% of CO_2e emissions, fuel production and distribution ('Well to Tank') for 10-15%, vehicle fuel consumption during use ('Tank to Wheels) for 60-70%, and end of life disposal for less than 3%. By comparison, for a large, heavy, diesel-powered truck, vehicle production accounts for 1-3% of CO_2e emissions, fuel production, distribution and vehicle fuel consumption during use for more than 95%, and end of life disposal for less than 1% (Ricardo, 2018). The difference between conventionally-fuelled cars and large, heavy trucks is explained by the comparative fuel consumption and annual mileage of these two types of road vehicle. Conventional ICE LGVs, lighter trucks, and trucks not being used intensively to travel long distances are likely to lie somewhere between these results for cars and heavy, large trucks. Given that LGVs have far lower average mileages than trucks and fuel consumptions that are more similar to cars than trucks, they are likely to have life cycle CO_2e emission profiles more similar to cars than trucks.

As for large, heavy trucks, the vast majority of life cycle CO_2e emissions of conventionally-fuelled ships, rail locomotives/wagons and aircraft, are likely to be associated with fuel production, distribution and vehicle fuel consumption during use, given their productive lifespan, the substantial distances they travel, and their high fuel consumption.

More research into the life cycle CO_2 emissions of freight vehicles is likely to be carried out in future, especially in relation to such vehicles powered by lower and zero carbon fuels. At present, any such studies are limited to cars.

In comparison with fossil-fuelled cars, cars powered by electric battery, vehicle production accounts for 20-60% of CO_2e emissions, and fuel production and distribution ('Well to Tank') for 20-60%, and end of life disposal for less than 3% (Ricardo, 2018). Various LCA studies have produced differing results about whether fossil-fuelled or battery electric cars produce more life cycle CO_2 emissions. These differences are due to the size of vehicles studied, the proportion of zero emission electricity in the country studied, and assumptions made about fuel consumption, driving patterns, and vehicle usage. Recent research indicates that in general in European countries, battery electric cars produce lower CO_2 emissions over their lifetime than conventional fossil-fuelled cars, but that in countries with coal-intensive electricity generation, these benefits are smaller, with battery electric cars having similar lifetime emissions to the most efficient conventional cars (Hausfather, 2019).

Both in terms of battery manufacturing and where the vehicle is used, the means by which electricity is generated in any given country has an important bearing on the lifecycle CO_2 emissions of battery electric vehicles. Without decarbonisation of electricity generation, battery electric vehicles will remain far from zero emissions.

5.11 Policy measures and future research

Some of the literature reviewed provides recommended policies and research needed to support the uptake and use of the various freight decarbonisation technologies and measures described. Some of the literature merely states that additional policies and research are required but without being specific. For instance, a report published by three technology platforms linked to the EU focuses on setting milestones to achieve the CO_2 reductions required in the timescale to 2030, but does not include what needs to be done and by whom, other than stating a range of unspecified policies need to be adopted to encourage the achievement of those milestones (ERTRAC, EPoSS and ETIP SNET, 2017). Several publications provide policies and research targeted at specific measures such as biogas, battery technology or platooning, for instance (CE Delft; Eclareon; Wageningen Research, 2016) (Carnevale & Sachs, 2019) (ACEA, 2017).

A report by APC defines two drivers in their roadmaps related to policies and research. The first driver is legislation that is known and agreed, and can therefore be followed over a fixed time. The second is a prediction based on research, and policies that need to be legislated, to enable measures and technologies to be developed and taken up by commercial bodies (Advanced Propulsion Centre UK, 2018). The timing of these roadmaps is not clear, and there are considerable uncertainties as to how quickly technologies will be adopted or phased out.

Several publications make it clear that ambitious policy and research measures are needed to ensure the target of zero emissions can be achieved by 2050 (Transport & Environment, 2017) (International Energy Association, 2017) (EC-DC R&I, 2018) (ALICE-ETP, 2019).

A report looking at the future of trucks worldwide provided a list of policy measures required to overcome barriers for companies investing in decarbonising measures, and a list of freight decarbonisation policy measures that also identifies the level of government needed to address each (International Energy Association, 2017). Both of these lists can be found in Appendix E.

In their 2017 report, Transport & Environment also provided a list of policy measures which can be found in Appendix F (Transport & Environment, 2017). In a 2020 report, the same organisation stated that EU wide policies should be developed to only focus on zero emission technologies, which should include phasing out by 2025 of infrastructure targets for CNG and LNG fuels (Transport & Environment, 2020). This same 2020 report also states that strong policies should be adopted to support three zero emission truck technologies, namely plug-in electric trucks, electric trucks charging dynamically through an electric road system, and hydrogen fuel cell trucks. This should include binding targets set for infrastructure development to electrify the TEN-T core road network by 2035, supported by the necessary power generation capabilities. This report also supports hydrogen as a complimentary power system and that EU ports should be used as refuelling hubs (Transport & Environment, 2020).

Another publication identified ten freight transport suggestions for EU policy makers (EASAC, 2019). These can be found in Appendix G.

End of life recycling of batteries is not currently economical, being more expensive than the raw materials. It has been argued that regulations are needed to ensure batteries are recycled (Carnevale & Sachs, 2019).

All of the above policies are aimed at supporting the development, acquisition and operation of zero emission technologies. This was echoed in a recent article about six of the major EU truck manufacturers agreeing to phase out diesel engines by 2040. One of the requests was for governments to stop supporting fossil fuels and impose higher carbon taxes as an incentive to companies to move to zero emission trucks. Through their institute body, ACEA, they also want widespread investment in energy grids to drive the change (Holley, 2020d).

The policies mentioned above should be aligned with the requirements of all industry stakeholders to ensure that they are combined with improved operational efficiency and cost savings to guarantee freight sector support of all policy initiatives (ITF, 2018). Lack of any support scheme may reduce the willingness of any freight operator to adopt zero emission measures.

Several of the publications reviewed provide details of future research requirements. A list of research requirements outlined by the European Commission can be found in Appendix H (EC, 2018). A list produced by the Advanced Propulsion Centre (APC) and the Energy Systems Catapult can be found in Appendix I (APC, EPC, 2019), and a list of research required into battery technologies by APC by can be found in Appendix J (Advanced Propulsion Centre UK, 2018).

6 Making progress towards freight decarbonisation

6.1 Challenges and barriers to freight decarbonisation

Eight categories of freight decarbonisation measures have been discussed in this report, namely: (i) reducing the level of freight transport demand, (ii) shifting freight to lower-carbon transport modes, (iii) improving asset utilisation in freight transport, (iv) organisation of physical logistics systems, (v) digitalisation of freight transport and logistics, (vi) increasing energy efficiency of freight transport vehicles, (vii) switching to lower-carbon energy, and (viii) energy systems for freight transport. There are a range of challenges and barriers that need to be overcome in relation to these measures if freight decarbonisation is to be achieved. These include:

- **Technological readiness** – many measures depend on technological advances either to make them available at all, or to ensure that the contribution of the measure/s to decarbonisation is as great as possible.

- **Demonstrations, trials and pilots** – the measures that are novel and have yet to be introduced may require various forms of testing including demonstrations, trials and pilots before they are ready for widespread implementation.

- **Infrastructure implementation and support** – some measures, especially new vehicle fuels, require the implementation of supporting infrastructure, such as refuelling and recharging networks and facilities in the case of electric batteries and hydrogen, and road electrification in the case of ERS. As well as the infrastructure work required, it also comprises any related town and country planning considerations that need to be dealt with. Where freight operators are expected to implement infrastructure (such as depot recharging for electric vehicles) this may well require the provision of advice and support.

- **Investment and funding requirements** – investment and funding may be required to support various aspects of the measures including for technological developments, demonstrations and trials, infrastructure implementation, acquisition/implementation by freight operators.

- **Regulations and legislation** – new regulations may be required to permit the use of new technologies (such as new fuels and their safe use, and autonomous vehicles and platooning), legislation may be required to ban the sale or use of old polluting technologies, and changes to existing regulations may also be required to maximise the potential benefits of measures (such as permitting off-peak deliveries to sites, and altering vehicle size and weight regulations).

- **Fiscal policy** - tax policies, user charges and grants at either a national or local scale may be required to encourage user acceptance and the widespread uptake of new and existing technologies by freight operators.

- **Information and publicity campaigns** – information and publicity campaigns may be needed to help encourage user acceptance and the widespread uptake of new technologies and optional logistics operations. These may take the form of information dissemination, the running of events and the provision of training sessions.

Table 11: Indicative analysis of the technological readiness and other requirements of categories of truck decarbonisation measures

Freight decarbonisation categories	Technological readiness	Demonstrations and trials requirements	Infrastructure requirements	Investment and funding requirements	Regulations and legislation requirements	Fiscal policy requirements	Information and publicity campaign requirements
Reducing the level of freight transport demand	[amber]	[amber]	[amber]	[amber]	[green]	[green]	[green]
Shifting freight to lower-carbon transport modes	[green]	[green]	[red]	[red]	[green]	[red]	[red]
Improving asset utilisation	[green]	[amber]	[amber]	[green]	[red]	[green]	[green]
Organisation of physical logistics systems	[amber]	[amber]	[green]	[green]	[amber]	[green]	[green]
Digitalisation	[amber]	[amber]	[amber]	[amber]	[amber]	[green]	[amber]
Increasing energy efficiency	[green]	[green]	[green]	[green]	[amber]	[green]	[green]
Switching to zero carbon energy	[red]	[red]	[red]	[red]	[amber]	[red]	[amber]
Energy systems	[red]	[red]	[red]	[red]	[amber]	[red]	[amber]

Key

[red]	Poor Technological Readiness / High Requirements
[amber]	Medium Technological Readiness / Medium Requirements
[green]	High Technological Readiness / Low Requirements

An indicative analysis has been carried out with respect to the likely challenges and barriers for each of the eight categories of truck decarbonisation measures (see Table 11). Some of the categories of road freight decarbonisation (including 'Reducing the level of freight demand', 'Improving asset utilisation', 'Organisation of physical logistics systems', and 'Increasing energy efficiency') contain measures that differ markedly in terms of technological readiness and other requirements, so the table reflects the perceived situation for each specific measure. It is intended to provide a broad-brush indication of the current state of technological readiness and the other requirements at the category level. The table indicates that the two categories associated with zero carbon fuels ('Switching to zero carbon energy' and 'Energy systems') face greater technological and other requirement issues than other categories of freight decarbonisation measures. They are followed in terms of outstanding challenges and barriers by modal shift from road to rail, with rail freight also subject to a major zero carbon fuel challenge.

Most national and international governmental action to date in terms of decarbonisation has been focused on establishing targets for carbon emission reductions by given dates. Little regulatory action has been taken by governments to assist in achieving such targets in freight transport or other sectors.

Government efforts in terms of regulation concerning freight decarbonisation is currently most focused on passing legislation to phase out the sale of new fossil fuel vehicles. However, these regulations are limited to LGVs, and even then, have only occurred in some countries to date. National governments are not currently passing legislation for the phasing out of fossil fuelled HGVs due to the lack of a fuel selection that is technologically and commercially viable and the fuel and transport infrastructure developments that would be necessary to support it. These same technological and commercial vehicle viability hurdles also exist in relation to rail, shipping and aviation, with the added complication that shipping and aviation are not governed solely at national scale, so require international agreements which take longer to arrange and implement.

The decision about which zero carbon fuel option will be selected for long-distance truck operations has not been made in any country so far, and commercial and public-funded research continues into each of the various options including batteries, ERS and hydrogen. Clearly a decision will need to be made about which of these energy sources will be pursued given the timescales associated with technological development, trials infrastructure implementation and widespread vehicle acquisition. However, it remains unclear whether national governments intend to make such a definitive ruling.

Other change in national government regulations in the UK or elsewhere is also currently non-existent in terms of preventing or permitting various types of road freight vehicle technologies or logistics operations that can have a bearing on carbon emissions, such as allowing Higher Capacity Vehicles to operate on major road for long-distance movements, permitted off-peak deliveries and collections at certain locations, and competition law which currently prevents company collaboration.

There may well be uncertainty and confusion among stakeholders about how should and will take action to achieve freight transport decarbonisation by 2050. This is indicated by an expert opinion survey on road freight decarbonisation involving 108 respondents (from government, the private sector, international organisations, NGOs and academia), 80% of whom were European. Results showed that opinions were extremely divided about who will bring about transformation of the road freight sector in the coming decade, with 29% of respondents citing government and regulators, 21% citing new market entrants (including mega e-commerce retailers), 16% citing retailers, 15% citing logistics operators, 13% citing vehicle manufacturers, and 4% citing energy companies (ITF, 2018).

The literature review of roadmapping publications focussing on freight transport decarbonisation carried out as part of this report has indicated that these studies have not been carried out by freight operators. Many have been produced by governmental bodies, academics, consultants and third sector organisations. A few have been produced by trade associations and professional bodies. When these roadmaps identify innovations that are required or provide recommendations and measures that should be researched and/or adopted, they typically fail to take freight operators and freight users sufficiently into account and include these operators in their thinking. Instead, these recommendations tend to be directed at governmental bodies, infrastructure providers and those engaged in the provision of future zero carbon fuels for freight vehicles. However, freight operators and users have a key role to play in freight decarbonisation. These companies will choose the decarbonisation measures available that are most cost effective. There is a need for greater consideration and inclusion of freight transport operators and users in roadmaps and the recommendations and outputs that these exercises result in.

6.2 Freight decarbonisation via lower-carbon fuels and vehicle replacement

There are a range of barriers to freight uptake of new vehicles and vessels powered by lower carbon fuel sources. These include: the technological availability of vehicles powered by different fuel sources, the capital costs of such vehicles, the availability and capital cost of recharging and refuelling infrastructure, uncertainty about future fuel prices/taxation and investment payback periods, corporate separation between owners and operators of vehicles as well as between the vehicle owner and the fuel purchaser, and the views and practices of banks and other institutions that provide financing for vehicle acquisition.

Replacement cycles for freight vehicles and vessels vary by mode. LGVs and HGVs in the UK both had an average age of 7 years in 2019. However, some are kept for substantially longer periods, especially those with specialist handling equipment and other expensive adaptations. In 2019, 29% of HGVs and 34 % of LGVs were at least 10 years old (Department for Transport, 2020r). Rail freight locomotives in the UK have a typical operating lifespan of 25-35 years, for ships it is usually 20-30 years but longer for some ship types, and for aircraft it is also often 20-30 years (Energy Transitions Commission, 2020) (Lloyd’s Register and UMAS, 2019) (Mason, 2020) (Sustainable Aviation, 2020).

All of these freight vehicle acquisitions take place in the private sector, with freight operators either buying them outright or, more often, using financing or leasing arrangements to acquire them. Both new and second-hand vehicle markets exist. Given the long vehicle replacement cycles in the rail, shipping and air freight sectors, new vehicles that come into use between 2020-2030 will remain in operation until 2050. So, unless new fuel technologies are developed and commercialised in the next few years, vehicles that are introduced in the next few years fuelled by conventional fossil fuels will still be being used by the UK’s 2050 net-zero CO_2 emissions target.

Institutions that make finance available for freight vehicle acquisition represent important stakeholders in the uptake of lower-carbon and zero emission vehicles. By pledging to ensure that a proportion of the finance they make available is used for the purchasing of such vehicles they can assist in freight decarbonisation goals. Such a scheme has been established in the maritime shipping finance sector. Known as the ‘Poseidon Principles’, it has put in place a framework for assessing and disclosing the decarbonisation alignment of ship finance portfolios. Targets have been set that aligned with the policies of the IMO (International

Maritime Organization), including its ambition for greenhouse gas emissions to peak as soon as possible and to reduce shipping's total annual CO_2 emissions by at least 50% by 2050 (Poseidon Principles, 2019). Twenty financial institutions involved in ship finance have signed up to the scheme and together they account for approximately one third of global shipping finance. Fifteen of these signatories publicly disclosed the climate alignment of their shipping portfolios for the first time and the end of 2020. This involves measuring the difference between a ship's carbon intensity (grams of CO_2 emitted by the ship in moving one tonne of goods one nautical mile based on the type and size of ship) and the carbon intensity it requires to be in line with the vessel's decarbonization trajectory to meet the IMO targets (Poseidon Principles, 2020). ING, the banking and financial services company, has also established its own scheme called the 'Terra approach' to align its lending and investment to CO_2 emissions goals in the Paris Climate Agreement, which it is applying to its finance in sectors including shipping and aviation (ING, 2020). Further schemes such as these could be implemented by financial institutions in freight vehicle financing sectors for road, rail and aviation to help ensure that lending decisions are focused on decarbonisation and thereby help encourage and support the availability of capital for zero and lower-carbon vehicle acquisition.

Freight decarbonisation achieved through the implementation of lower-carbon fuels/energy systems via new vehicles and infrastructure together with related national and international regulation is likely to require substantial public funding to support research and development, vehicle trials, and the transport and energy infrastructures required for each mode. In the case of battery electric road vehicles, the Electric Vehicle Energy Taskforce, which brings together the public sector with key stakeholders from the automotive, energy and vehicle user industries in the UK, has recognised that the careful planning of the vehicle recharging network and its interoperability, both in terms of physical and commercial systems, is crucial to EV uptake (Electric Vehicle Energy Taskforce, 2020). To achieve road freight decarbonisation by 2050, the majority of trucks purchased in the period 2035-2040 must be zero emission vehicles. To achieve this will require that major government planning and support will be required to commence before 2035 and to continue thereon in relation to vehicle demonstration projects, information campaigns, stimulating vehicle production, making alterations to vehicle size and weight regulations, fuel taxes and user charges to encourage uptake (Element Energy, 2020). In addition, capital grants or loans from the public sector may also be required to increase rapid vehicle uptake, as already takes place in some countries. In the UK, for example, grants have been made available both by national and urban authorities to encourage the uptake of zero emission and cleaner LGVs and HGVs. The Office for Zero Emission Vehicles, a team working across the UK Government, makes grants available for the uptake of electric vehicles. It provides grants of up to 20% of the purchase price of LGVs that have CO_2 emissions of less than 75g/km and can travel at least 16km without any emissions at all, and trucks that have CO_2 emissions of at least 50% less than the equivalent conventional Euro VI vehicle that can carry the same capacity, and which can travel at least 16km without any emissions at all (Office for Zero Emission Vehicles, 2020). It also makes grants available to companies for the installation of workplace electric vehicle charging infrastructure. This provides companies with financial support of up to 75% of the capital costs of the purchase and installation of up to 40 electric vehicle charging points (Office for Zero Emission Vehicles, 2020a).

Also nationally, as part of the UK Government's Clean Air Fund, local authorities can apply for funding to help support freight operators replace or retrofit their vehicles and improve local air quality. Funding can be made available to support operators replace older diesel LGVs with alternative fuel sources such as electric or LPG, and to retrofit or replace older diesel trucks (DEFRA, 2018). In London, Transport for London made grants available to small businesses (with up to 50 employees) in 2020 to assist them meet the requirements of the Ultra Low Emissions Zone (ULEZ). Grants of £7,000-9,500 for replacing non-compliant LGVs with electric LGVs, and £15,000 for replacement or retrofit of larger trucks to meet to the ULEZ emissions standards were made available (Transport for London, 2020).

6.3 Freight decarbonisation via other means

The other six freight decarbonisation categories (namely, reducing the level of freight transport demand, shifting freight to lower-carbon transport modes, improving asset utilisation in freight transport, organisation of physical logistics systems, digitalisation of freight transport and logistics, and increasing energy efficiency of freight transport vehicles) are typically left by national governments to the private sector to implement without any regulatory intervention. Areas in which regulations do exist that could potentially be amended to increase the efficiency of logistics operations include tightening truck and LGV CO_2 emission limits, the allowance of the use of higher capacity trucks, the times at which road-based delivery and collections are permitted to take place at different sites, any unnecessary road restrictions concerning where freight vehicles are allowed to operate that result in longer than otherwise needed, and competition law that prevents collaboration between large companies in the same sector.

As previously discussed, all of these six freight decarbonisation categories already contain available measures that can reduce freight transport CO_2 emissions. While none of these categories or specific measures will in themselves result in zero CO_2 emissions, applied together they can contribute to important CO_2 emission reductions in freight transport. These categories and specific measures are especially important given the lack of technological readiness of zero carbon fuels and energy systems for trucks, rail freight, shipping and air freight. Such carbon-free fuels and energy systems for freight vehicles may not be available for a considerable time yet due to these technological challenges, as well as the replacement cycles for many of these vehicles and vessels.

Freight operators will introduce such (non carbon-zero fuel) measures if their introduction will result in financial and other commercial benefits along with environmental benefits including CO_2 emissions reduction (a so-called commercial and environmental win-win). Given the lack of governmental regulation in relation to these categories of freight decarbonisation, many companies will be reluctant to implement them if the investments required do not have a viable business case based on a suitable financial payback period or if they do not pay for themselves over any given timescale. Even if the implementation of such measures would result in commercial benefits with a suitable payback period, some companies may still not implement them if they require new financial borrowing arrangements to meet their capital costs. This is especially true in the case of smaller operators, which make up a sizeable proportion of road freight operators, and companies primarily working in other sectors that have small in-house vehicle fleets to transport goods.

There is currently much uncertainty concerning the likely extent of CO_2 emissions reduction associated with each of these six categories and specific measures for freight decarbonisation due to limited attempts at quantification in existing research. In addition, the uptake of these measures is likely to vary considerably by commodity, the sector of the economy being served and customer service levels offered, as well as the existence of a viable financial return from any investment required. The uptake of some of these measures depend on factors well beyond freight transport considerations. This is especially the case for measures in the 'reducing the level of freight transport demand' category (such as 3D printing, the dematerialisation of products, sourcing strategies and location of suppliers used, and consumer behaviour) which depend on a wide range of business considerations beyond freight transport and logistics. It is also the case for measures in the 'shifting freight to lower-carbon transport modes' category as transferring goods from road to rail, or air to sea depends on many business considerations and can often also depend on the extent of transport infrastructure investment by public and private bodies (for instance, the level of investment in rail track and rail termini, seaports and airports) as well as the availability of freight vehicle access in case of transport networks with limited capacity that are shared with passenger transport such as rail freight.

6.4 The likelihood of achieving zero GHG emissions from freight transport by 2050

As a result of the lack of technological readiness of zero carbon fuels and energy systems, and the limited measurement and monitoring of the extent of CO_2 emission reductions among operators that do implement any given freight decarbonisation measure, and the partial uptake of decarbonisation measures by freight operators, it remains far from clear whether or not net zero freight decarbonisation by 2050 is likely to be achieved.

Analysis presented in this report shows the slow progress towards freight decarbonisation in the UK between 2008 and 2019 (see chapter 3). Although freight decarbonisation is likely to accelerate in the UK, especially as lower-carbon and zero carbon fuels become more readily available at viable prices across the various modes, it remains to be seen whether this will occur in time to meet the net zero GHG emission target by 2050 set by the UK Government. In order for this to be met, there will need to be far greater uptake by operators of measures in the other six categories of freight transport decarbonisation discussed in this report. These measures do not rely on lower-carbon or zero carbon fuel sources being available).

The history of fuel technology innovation and implementation indicates that it is a slow process. Much emphasis is being placed in UK policy thinking and CO_2 emission forecasting on producing low-carbon or zero carbon hydrogen, on Carbon Capture and Storage (CCS) in fuel production, and on CO_2 removal from the atmosphere (referred to as 'negative emissions technologies' which includes Direct Air Capture of CO_2 with storage (DACCS)) (Committee on Climate Change, 2020a). Previous technology breakthroughs and commercialisations in the energy sector have taken decades to achieve due to the time taken to develop the technology, scale it up, deal with legal and regulatory issues concerning planning permission, health and safety, and environmental protection, and to put it place financing mechanisms for it.

Renewable energy sources (wind, bioenergy, hydro and solar) accounted for 37% of UK electricity generation and 12% of total UK energy consumption in 2019 (compared with 24% and 9% in 2016, respectively. Renewable energy accounted for 9% of UK transport energy consumption (excluding aviation) in 2019, compared to 5% in 2016 (BEIS, 2020). At a global scale, it is estimated that in 2018 approximately 13% of worldwide total energy supply was produced from renewable sources (IEA, 2020). However, the majority of this comprised fuelwood and charcoal which is widely used in developing countries for heating and cooking and is not a sustainable fuel source.

Estimates indicate that the demand for electricity in the UK will approximately double by 2050, and this does not take account of the electricity that would be required for the production of hydrogen (Committee on Climate Change, 2020). Another study has estimated that, despite the increase in UK electricity production from zero carbon sources in the last decade, continued growth at this rate will only provide approximately 50% more electricity in the UK in 2050 than is currently produced, and that this will only be sufficient to power approximately 60% of the UK's current energy demand (Allwood, et al., 2019). If both of these estimates are correct, there will be insufficient electricity production to meet current needs in the UK and it will therefore be necessary to bridge this gap by making equipment more energy efficient and altering operations and behaviours to reduce energy demand.

In addition, given that some forms of freight transport, namely aviation and deep-sea shipping, will not be capable of being powered by electricity by 2050 even if sufficient quantities are available, they will need alternative fuel solutions. The main options currently being advocated for shipping include the use of hydrogen to produce ammonia and the use of CCS. However, fuel experts have been discussing and working on CCS for twenty years and there are currently no full-scale CCS power stations operating, and in the UK there are currently no plans for an initial CCS power station. Despite there being no current use of CCS in the UK, the Committee on Climate Change forecasts that it will be responsible for approximately 100 million tonnes of CO_2 removal in 2050. Likewise, it forecasts that despite less than 1 TWh of UK energy was produced from low-carbon hydrogen in 2019, this will account for 225 TWh in 2050 (Committee on Climate Change, 2020a). Both the use of hydrogen and CCS are likely to be expensive and the technologies may well not be available at scale by 2050.

Some of the publications reviewed as part of this report are of the opinion that zero carbon fuels and their supporting infrastructure will be in place in time to facilitate their widespread penetration of freight transport operations by 2050. However, some research is more sceptical. A study carried out for the National Infrastructure Commission assessed the time it will take in the UK for new fuels for road freight to reach widespread take-up in the market including all the technological developments, and demonstrations required, and the time taken to achieve substantial market penetration. The work indicated that this would take 18-47 years for battery-electric trucks, 32-60 years for ERS, 38-63 years for advanced synthetic fuels, and 33-57 years for hydrogen. In the baseline scenarios constructed in this study (based on current trajectories) it was assumed that advanced biofuel will fuel approximately 10% of road freight by the mid-2030s with no further growth beyond that date, that battery-electric trucks would be limited to around 40% of the market by 2050, that a fleet of hydrogen powered trucks would be developed during the 2040s but, because of the constrained supply of hydrogen fuel and necessary infrastructure, would only account for approximately 5% of the total freight vehicle fleet by 2050, and that none of the UK highway network will be electrified by 2050 due to scale of public investment it would require. Overall, this study estimated that the baseline scenario, based on current trajectories without ambitious Government action, less than 50% of the UK road freight fleet will be decarbonised by 2050 (using biofuels and battery-electric trucks). In an ambitious scenario with significant Government help with technology and infrastructure, it was estimated that approximately 75% of the UK truck fleet would be decarbonised by 2050 (with battery-electric trucks). So, even in this ambitious scenario, net zero carbon road freight is not expected to be achieved by 2050 in the UK (Cambridge Economic Policy Associates LLP (CEPA) and Frazer-Nash Consultancy, 2019).

Other research has also indicated that current technologies and governmental policies are insufficient to achieve decarbonisation of transport in the European Union by 2050 (CE Delft, 2017). Given such views about the lack of market penetration of zero carbon fuels by 2050, some researchers are therefore arguing that the focus should be on achieving absolute zero rather than net zero CO_2 emissions by 2050 (Allwood, et al., 2019).

This viewpoint indicates the importance of freight transport measures that increase the energy efficiency of freight transport operations and vehicles, together with other logistics decarbonisation measures including reducing the demand for freight transport, and modal shift from road to rail and air to sea in moving towards zero CO_2 emissions from freight transport. The studies reviewed in section 4.4, that have provided quantified forecasts of the CO_2 emission reduction potential in developed western European countries from a wide range of measures, suggest that truck CO_2 emissions could be cut by between 30-60% by 2050 without taking account of zero carbon fuels.

Research indicates that CO_2 emissions reduction will be much more difficult to achieve in aviation and shipping than in road freight due to the fuel source requirements of the vehicles and operations. In aviation, there is no expectation of zero carbon fuels by 2050, only more sustainable fuels with lower-carbon content, so there will have to be greater emphasis on other means including improved aircraft energy efficiency, operations, air traffic management and carbon pricing to reduce demand. Similarly, if the provision of zero carbon fuels for shipping does not materialise at commercial scale as may well the case, greater emphasis will have to be placed on improving vessel energy efficiency, operations, and reducing demand.

Research that has taken account of worldwide freight transport indicates that progress towards decarbonisation at a global scale by 2050 will be far less than when just taking developed countries into account as change will be far slower in developing than developed countries (ITF, 2019). Taking into account the predicted growth in demand for freight transport and the continuation of decarbonisation measures already announced by the end of 2018 (a so-called 'current ambition' scenario), these forecasts indicate that total worldwide freight transport operations will emit 118% more CO_2 emissions in 2050 than in 2015 (a 94% increase for domestic freight transport and a 157% increase for international freight transport). The implementation of additional measures not yet announced to improve the efficiency of freight transport (a so-called 'high ambition' scenario) including revised land-use policies, more stringent carbon pricing, the rapid uptake of renewable electrification, and a substantial reduction in the transport of coal, oil and gas is forecast to result in total worldwide freight CO_2 emissions in 2050 being 21% greater than in 2015. This 'high-ambition' scenario results in worldwide freight CO_2 emissions that are 45% lower in 2050 than the 'current ambition' scenario (ITF, 2019).

In terms of surface freight transport only (i.e. road, rail and inland waterway) these forecasts indicate that, taking into account the predicted growth in demand for freight transport and the continued implementation of current measures announced by the end of 2018, surface freight CO_2 emissions in 2050 will be 122% higher than in 2015 in non-OECD developing countries, compared to 39% higher in developed OECD countries. Even in the 'high ambition' scenario,

CO_2 emissions from surface freight transport are forecast to increase by 16% in developing non-OECD countries in 2050 compared to 2015 levels, compared with a 63% fall in developed OECD countries (ITF, 2019).

In addition to carbon emissions either at the vehicle tailpipe or in fuel production and supply, which much of this report has been concerned with, there is also the issue of vehicle lifecycle CO_2 emissions, which takes account of vehicle production and disposal as well. While for large, heavy duty trucks, ships, aircraft and rail locomotives, due to their long lifespans, high fuel consumption and substantial distances travelled, CO_2 emissions from vehicle use are likely to substantially outweigh those emitted during vehicle production and disposal, the latter still need to be taken account of. In the case of LGVs, lighter trucks, and trucks not being used intensively to travel long distances, the CO_2 emissions from vehicle production and disposal, and fuel production are of greater importance in lifecycle CO_2 emissions.

7 Conclusions

The UK Government took initial steps to set legally binding targets for CO_2 emissions in 2008 as part of the Climate Change Act. This committed the UK to an 80% reduction in CO_2 emissions by 2050 relative to the levels in 1990, which in 2019 was increased to a 'net zero' CO_2 emissions by 2050. However, UK Government estimates indicate that CO_2 emissions from road freight operations worsened over the period 2008-2018 as a result of greater truck and LGV activity and the continued shift towards the use of larger, heavier trucks. This data indicates that total GHG emissions from UK rail, and from UK domestic and international shipping fell over this ten year period. However, total GHG emissions from international aviation to and from the UK increased over this period as a result of the growing number of flights, despite improvements in aircraft energy efficiency per unit of distance travelled.

This report has examined roadmapping publications related to achieving net zero CO_2 emissions in freight transport by 2050. A total of 53 publications were included in a systematic review and the vast majority of them have been published since 2017. The freight decarbonisation topics most frequently considered in these roadmapping publications are lower and zero carbon fuel sources and the energy systems required to supply these. These are followed in frequency by measures to improve vehicle energy efficiency.

Relatively few of these roadmapping publications have produce quantified forecasts of the contributions that various freight decarbonisation measures, including revised logistics operations, vehicle energy efficiency improvements and lower carbon fuels, can potentially make in these decarbonisation efforts. Where such forecasts exist, these have been summarised and compared in this report. None of these forecasts indicate that net zero freight decarbonisation can be achieved, in the developed countries in which they have been carried out, by 2050. In addition, one study of worldwide freight transport forecasts that, due to expected growth in freight demand to 2050, even ambitious decarbonisation measures will result in total worldwide freight CO_2 emissions in 2050 being 21% greater than in 2015 (ITF, 2019).

It is widely expected that in future all LGVs in the UK will be powered by electric batteries, and this is already beginning to happen, especially in urban areas where increasingly stringent vehicle emissions are already being implemented. However, many issues need immediate attention if net zero CO_2 emissions from road freight are to be achieved, completely or even partially, in the UK by 2050. Most importantly, a choice needs to be made at a national government level about the zero carbon fuel source to be developed for long-distance truck operations. Many of the roadmaps reviewed are unquestioning about the future availability of zero carbon trucks. However, unless such a decision is made very soon, and the necessary levels of funding made available to support fuel technology, trials and pilot schemes, and transport and energy infrastructure, there is little prospect of the widespread deployment of zero carbon trucks in the UK by 2050. Even with such a decision and public funding, little time remains given the time needed for developing this technology and infrastructure, its testing, the town planning hurdles that need to be addressed and the time it will take for substantial uptake of such vehicles, given existing fleet replacement cycles.

The situation is even more challenging in terms of zero carbon fuels and vehicles for rail freight, shipping and air freight, given the technological challenges these modes pose, together with the fact that changes to shipping and air freight fuels have to be taken at an international rather than national level.

Given these challenges concerning the widespread availability of zero carbon freight fuels and vehicles in time for the 2050 net zero target, other freight decarbonisation measures including vehicle energy efficiencies and logistics operations measures are likely to continue to have important roles to play. These measures will need to achieve high levels of penetration, far greater and more radical than at present. This will require the combined efforts of all stakeholders including policymakers, vehicle manufacturers, vehicle financing organisations, freight transport operators and users of freight transport services. Greater joint working between these stakeholders and clarity between stakeholders about how should and will take action to achieve freight transport decarbonisation is required.

Much of literature examined has been quite rightly focussed on energy saving measures and zero carbon fuels as these will produce the greatest CO_2 reduction needed by 2050. However, the other measures discussed in this report are also an important contribution, not only to the target of net zero by 2050, but also to more efficient and sustainable freight transport operations. An era when transport externalities are also minimised by running fewer kilometres resulting in less congestion, fewer accidents, less noise, less damage to infrastructure and better air quality, not only from using zero emission fuels but also from less particulate matter produced by brakes and tyres.

In the absence of widespread zero carbon truck uptake in the UK by 2050, together with a possible similar failure in rail freight, air freight and maritime shipping, other measures may be required in addition to far greater uptake of vehicle energy efficiencies and more radical logistics operations measures if net zero freight transport is to be achieved. In such a situation, it is also likely to be necessary to consider how the demand for goods and services that result in freight activity can be managed and reduced without causing economic difficulties and hardship.

Looking to 2050, it is not possible to think in today’s terms. It is necessary to understand how the coming decades will change the experience for the customer. This will affect how supply chains operate and therefore the approaches necessary to achieve net zero. Currently, there is an intolerance of delay, with companies offering to supply or requiring delivery in very short and tight time windows. For home delivery, households are also expecting goods to be delivered promptly. This approach seems to be incompatible with the aim of achieving net zero and is difficult to remove once given. However, mitigating actions can help as described in chapter 5.

Data is crucial to understanding the impact of various measures. However, the availability and quality of data can be the weakest area in any analysis and has been described as “challenging to source” from industry in one publication (APC, EPC, 2019) and particularly difficult from a literature review alone. Although some modelling has taken place, it is difficult to be precise about the potential savings of any measure, particularly when any measure is evolving at a fast pace or has yet to be developed. Much research has taken place in academic institutions and not fully demonstrated in a real-world environment. Data is also of crucial importance in supporting policy making.

This review of roadmapping publications focussing on freight transport decarbonisation has indicated that many of these direct their considerations and recommendations at governmental bodies, infrastructure providers and those engaged in the provision of future zero carbon fuels for freight vehicles. However, freight operators and users have a key role to play in freight decarbonisation. There is a need for greater consideration and inclusion of freight transport operators and users in future roadmaps and the recommendations and outputs that these exercises result in.

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Appendix A – Roadmapping publications included in the systematic literature review

Author and year	Geographical coverage	Only freight transport considered?	If more than just freight considered, what else is included	Transport modes included	Only decarbonisation addressed or also other issues?
(ALICE-ETP, 2019)	EU	Yes	-	All	Decarbonisation only
(Transport & Environment, 2017)	Europe	No	Passenger transport	Road	Decarbonisation only
(Carnevale & Sachs, 2019)	International	No	Power, industry, transport and buildings	All	Decarbonisation only
(EC-DC R&I, 2018)	EU	No	Energy, transport agriculture, land use, industry	All	Decarbonisation only
(McKinnon, 2018)	International	Yes	-	All	Decarbonisation only
(Walsh, Mander, & Larkin, 2017)	UK	Yes	-	Shipping	Decarbonisation only
(Murphy, 2018)	EU	No	All aviation	Aviation	Decarbonisation only
(Staffell, et al., 2019)	International	No	All hydrogen fuel cell use	All	Decarbonisation only
(Sense project, 2020)	EU	Yes	-	All	Decarbonisation only
(CEPI, 2018)	Europe	Yes	-	Road	Decarbonisation only
(EASAC, 2019)	EU	No	All road transport	Road	Decarbonisation only
(Advanced Propulsion Centre UK, 2018)	UK	No	All automotive vehicles	Road	Decarbonisation only
(DfT, 2018)	UK	No	All automotive vehicles	Road	Decarbonisation only
(APC, EPC, 2019)	UK	Yes	-	Road	Decarbonisation only

(Gustavsson, Hacker, & Helms, 2019)	International	No	Electric Road Systems for heavy duty vehicles	Road	Decarbonisation only
(ERTRAC, EPoSS and ETIP SNET, 2017)	EU	No	All electric road vehicles	Road	Decarbonisation only
(ERTRAC, 2019)	EU	Yes	-	Road	Decarbonisation, highly-automated and connected freight transport
(Transport & Mobility Leuven, 2017)	EU	Yes	-	Road	Decarbonisation, road safety and freight operational efficiency
(ITF, 2018)	International	Yes	-	Road	Decarbonisation only
(CE Delft; Eclareon; Wageningen Research, 2016)	EU	No	Biogas for all industrial uses	Road	Decarbonisation, energy security and resource efficiency
(TRL, 2018)	International	No	Electric Road Systems for heavy duty vehicles	Road	Decarbonisation only
(Transport & Environment, 2020)	EU	Yes	-	Road	Decarbonisation only
(Krause, et al., 2020)	EU	No	All road transport	Road	Decarbonisation only
(ACEA, 2019)	EU	No	Autonomous road vehicles	Road	Decarbonisation, air quality, driving efficiency, road safety, accessibility
(ACEA, 2017)	EU	Yes	-	Road	Decarbonisation, air quality, driving efficiency, road safety
(Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018)	International	Yes	-	Road	Decarbonisation only
(International Energy Association, 2017)	International	Yes	-	Road	Decarbonisation and energy demand

(CE Delft, 2017)	EU	No	Passenger transport	All	Decarbonisation only
(Cambridge Economic Policy Associates LLP (CEPA) and Frazer-Nash Consultancy, 2019)	UK	Yes	-	Road & Rail	Decarbonisation only
(Committee on Climate Change, 2019)	UK	No	Housing, domestic heat, industry, transport, agriculture, energy infrastructure	All	Decarbonisation only
(Electric Vehicle Energy Taskforce, 2020)	UK	No	Electric road vehicles	Road	Decarbonisation and uptake of electric vehicles
(Gross, 2020)	International	No	Passenger transport	All	Decarbonisation only
(Hamelinck, Spöttle, Mark, & Staats, 2019)	EU	No	Biofuels in freight and passenger transport	All	Decarbonisation, energy and food security, land use and employment issues
(ICCT, 2020)	International	No	Passenger transport	All	Decarbonisation only
(Institution of Mechanical Engineers, 2020)	UK	No	All light duty road vehicles	Road	Decarbonisation only
(International Energy Agency, 2020)	International	No	All electric vehicles	All	Decarbonisation, EV charging infrastructure, costs, energy use and battery materials
(National Infrastructure Commission, 2019)	UK	Yes	-	All	Freight efficiency, decarbonisation, impacts on traffic congestion and infrastructure needs
(SLoCaT, 2018)	International	No	Passenger transport	All	Decarbonisation only
(Tricker, White, & Molho, 2019)	UK	No	Passenger transport	Road & Rail	Decarbonisation only

(Committee on Climate Change , 2020)	UK	No	All sectors of economy	All	Decarbonisation only
(Element Energy, 2020)	UK	No	All heavy duty road vehicles	Road	Decarbonisation only
(Ricardo Energy & Environment, 2019)	UK	Yes	-	Road	Decarbonisation only
(Greening, Piecyk, Palmer, & McKinnon, An assessment of the potential for demand-side fuel savings in the HGV sector, 2015)	UK	Yes	-	Road	Decarbonisation only
(Greening, Piecyk, Palmer, & Dadhich, Decarbonising road freight, Future of Mobility: Evidence Review, 2019)	UK	Yes	-	Road	Decarbonisation only
(Department for Transport, 2020c)	UK	No	Passenger transport	All	Decarbonisation only
(Lloyd's Register and UMAS, 2019)	International	No	Passenger transport	Shipping	Decarbonisation only
(Lloyd's Register and UMAS, 2020)	International	No	Passenger transport	Shipping	Decarbonisation only
(Department for Transport, 2019)	UK	No	Passenger transport	Shipping	Decarbonisation only
(Department for Transport, 2018)	UK	No	Passenger transport	Aviation	Decarbonisation, economic growth, connectivity, reliability, noise, air quality, safety and security

(Sustainable Aviation, 2020)	UK	No	Passenger transport	Aviation	Decarbonisation only
(Rail Industry Decarbonisation Taskforce, 2019)	UK	No	Passenger transport	Rail	Decarbonisation only
(Network Rail, 2020)	UK	No	Passenger transport	Rail	Decarbonisation only
(ITF, 2019)	International	No	-	All	Decarbonisation, transport activity and transport growth

Appendix B – Comparison of technologies between ALICE and SRF roadmaps

alice - A framework and process for the development of a ROADMAP TOWARDS ZERO EMISSIONS LOGISTICS 2050, December 2019			SRF Roadmapping technologies
FREIGHT DEMAND GROWTH IS MANAGED	• Supply chain restructuring	• Redesign of a logistics network's nodal points, distribution hierarchy and inter-related transport flows to minimise distances travelled and optimise load factors.	Restructuring of the supply chain network
	• Localization and nearshoring	• Localising production close to consumption where feasible, such as agriculture produce, and nearshoring of inbound materials closer to manufacturing	Local manufacturing/on shoring
	• Decentralization of production and stockholding	• Moving production stockholding and sales closer to consumers. As an example, we can see many retailers that are expanding their inventory management to include stores.	Restructuring of the supply chain network
	• 3D printing	• 3-D printing of spare parts, selected products or parts of products that can be combined with manufacturing closer to markets, while acknowledging that raw materials still need to be transported	
	• Dematerialization	• Reducing the physical quantity of goods, products and packaging needed to deliver consumer value. Possibilities are product re-design, waste minimisation, recycling, digitisation, miniaturisation, material substitution, and postponement of dispersing products to new markets.	
	• Consumer behavior	• Influencing consumer behaviour through awareness-raising and education on their purchasing habits and encouraging re-use, refurbishment, remanufacturing and recycling. Whether last-mile home delivery reduces carbon emissions depends on how this service is delivered and if it replaces a consumer shopping journey with a motorised vehicle that generates more emissions. It needs to consider lead time and delivery time and move in the opposite direction of the "one hour" and "same day" delivery.	Extending delivery times/relaxation of JIT pressures
TRANSPORT MODES ARE SMARTLY USED AND COMBINED	• Increased use of rail • Increase use of short sea shipping and inland waterways • Modular road transport • Cargo bikes	• Providing a wider free modal choice other than road has been a long-time ambitious objective to achieve lower emissions per tonne-km. To realise this opportunity, it is important that rail, waterborne and low emission modes deliver more against the needs of the users in the different contexts: price, quality, service level, reliability and	Use of alternative transport modes
	• Multi-modal optimization	• Optimising the combination and complementarity of different modes and linkages between them by adding, providing better access to, and optimising transhipment possibilities. An example is optimising ship-port interfaces to reduce the waiting time for ships. It includes minimising waiting times for trucks (or other modes) at terminals. Another example is the use of high capacity road freight transport vehicles, including the European Modular System, in the first and last road legs of combined and multimodal transport operations which could reduce the number of vehicles used by one-third.	
	• Synchromodality	• Optimising and flexible use of different modes and routes in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for its (inland) transport. It also includes the combination of cargo with different time speeds requirements or that could act as ballast for other goods (i.e. the usage of the network is maximised).	

alice - A framework and process for the development of a ROADMAP TOWARDS ZERO EMISSIONS LOGISTICS 2050, December 2019			SRF Roadmapping technologies
FLEETS AND ASSETS ARE SHARED AND USED TO THE MAX	• Load optimization	• Adjust truck size to load. Higher freight efficiency is achieved as the amount of freight hauled per litre of fuel used is reduced. So, the fuller the load compartment the better overall efficiency. Matching the size of the vehicle with the load volume or weight contributes to efficiency.	
		• Optimising use of vehicle space. Optimise the loading of vehicles taking the vehicle and freight dimensions into account, which can be enhanced using software. Improvements of the load factor of the vehicle through physical techniques such as efficient unit loads, and a combination of mechanical and manual loading may be necessary.	
	• Load consolidation and asset sharing	• Horizontal collaboration (companies at the same level of the logistics chain, either shippers or providers, form partnerships to bundle loads or make use of the same vehicles/assets).	
		• Combined freight and warehouse exchange platforms (platforms for exchanging information between carriers, freight forwarders, logistics service providers (LSPs) and shippers to facilitate new orders and collaboration, including backhauling).	Freight exchanges/IFTS supporting PI
		• Pooling and bundling/cross-docking that are optimised to facilitate load consolidation from different suppliers and shippers.	Synchronised consolidation
		• Mixed load and weight volume. Non-traditional heterogeneous pallets built from a mixture of products where the degree of pallet density is lower compared to their traditional counterparts.	
		• Urban consolidation centres (group shipments from multiple shippers are consolidated onto a single truck/transport vehicle for delivery within a city or urban area).	Use of urban consolidation centres
		• Crowd-shipping (recruiting citizens to serve as couriers using their private vehicles to pick up and drop off parcels along routes they are taking anyway).	
		• High capacity vehicles can consolidate bigger load volumes and weights for longer distances.	Use of larger and heavier vehicles (long haul only)
		• Many software management tools are available to help reduce empty running by finding additional freight to haul given each fleet's capabilities with routes, equipment, time, and other variables.	Freight exchanges/IFTS supporting PI
		• Utilisation of public transport modes such as underground freight trains during non- operating hours or even combining freight and public transport in a way that does not affect current schedules.	
	• Reduce empty moves - backhauling	• Refers to the practice of picking up or delivering cargo on return or round trips as compared to returning with empty vehicles or vessels.	Backhaul / Fronthaul
	• Modular packaging and boxes	• Redesign of product packaging, transport boxes and containers for optimal fit to product and for modularity, to allow efficient handling, consolidation and pooling. This can be combined with re-usable containers (RCs), in anticipation of the implementation of the Physical Internet concept.	
	• Open transport networks and warehouses	• This solution looks for a systemic load consolidation and optimisation in which the capacity in logistics sites and transport networks could be made available for the use of the stakeholders in a more optimised way (i.e. following physical internet principles). This includes the possibility of a different approach in which flows from different stakeholders are combined: multi supplier-multi-retailer. Software, operative and business models available are still not capable to provide collaborative tactical and operational planning, do not support dynamic planning, cannot link to traffic data and they are not able to support arrangement of multi- party transport flows and inventory management via shared hubs and warehouses, paperless processes, cost sharing and allocation.	

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FLEETS AND ASSETS ARE ENERGY EFFICIENT	• Cleaner and efficient technologies	• Tyres. Low rolling-resistance tyres can be designed with various specifications, including dual tyres or wide-base single tyres. It is noted that wear and tear of tyres also generate PM emissions.27	Use low 'rolling-resistance' tyres
		• Aluminium wheels. These wheels replace common steel wheels and are intended to reduce vehicle weight and heat dissipation while improving fuel efficiency.	Fit super singles??
		• Idling-reduction technologies. These include auxiliary power units and generator sets, battery air conditioning systems, plug-in parking spots at truck stops and thermal storage	Reduce engine idling
		• Automatic transmission. Moving from manual to automatic/automated manual transmission can greatly improve efficiency. Adding gears, reducing transmission friction and using shift optimisation in manual automated or fully automated transmissions can also improve drivetrain efficiency.	Adopt automated manual vehicle transmission
		• Low-viscosity lubricants. Oils with less internal resistance to flow that decrease engine mechanical losses, thereby reducing fuel use.	Use of lubricants with lower viscosity
		• Oil by-pass filtration system. Secondary filtration unit with the purpose of super-cleaning engine oil, extending lifetime. It has high contaminant-holding capacity and filters out the smallest particles to include sludge and soot in special cases.	Use of fuel additives
	• Efficient vehicles and vessels	• Fleet renewal. Effectiveness and cost-effectiveness of early replacement of old vehicles to improve air quality, reduce dependence on oil, CO2 emissions and increase road safety.	
		• Light-weighting. Broadly, all HDV vehicle types except utility trucks could cost-effectively reduce weight by upwards of 7% within the next ten years. Weight advantage offers a greater degree of freedom in vehicle design and performance.	Reduce vehicle tare weight
		• Use mega-vessels and freight trains. The frequency of shipments can be reduced by increasing the volume transported per shipment. There is a trend towards mega vessels able to hold 20.000+ Twenty-Foot Equivalent Unit (TEUs) combined with freight trains that go beyond the common 600 750 metre lengths.	
		• Autonomous trucks. Driverless vehicles which are fully automated and are operated remotely. Managing fleets of autonomous trucks may bring important economic benefits that should and could be translated into low emission energy sources.	Autonomous vehicles
		• Autonomous rail services. Driverless trains which are fully automated and are operated remotely.	
	• High capacity vehicles / duo trailers	• High-capacity vehicles. Refers to an increase in a truck's size with heavier payloads, leading to a smaller proportionate increase in fuel consumption. Hence, leading to less fuel than smaller trucks per each unit of freight. The European Modular Concept (EMS) and duo-trailers are specific types.	Use of larger and heavier vehicles (long haul only)
	• Driving behaviour/eco driving	• Practice of eco-driving in such a way as to minimise fuel consumption (i.e. coasting before engine breaking, limit harsh breaking and acceleration), the emission of carbon dioxide and vehicles wear and tear.	Give drivers training in fuel efficiency
	• Fleet operation & maintenance	• Platooning. Refers to the practice of driving heavy-duty trucks (primarily tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations.	Platooning
		• Routing. Optimising delivery routes through the deployment of GPS and GIS to assist drivers in finding the shortest route or avoiding traffic congestion.	Use telematics to optimise vehicle routing
		• Retiming. Refers to shift to off-hour (or night-time) logistics operations and deliveries.	Reschedule deliveries to inter-peak periods and evening / night
		• Slow steaming. The practice of operating transoceanic cargo ships, especially container ships, at significantly less than their maximum speed.	Slow logistics
		• De-speeding. The practice of operating trucks, especially long-distance trucks, at significantly less than their maximum speed.	Set vehicle with slower speed
		• Planning of use. Reducing the non-productive operations of trucks, trains and ships (e.g. train coupling, truck maintenance, ship cleaning) through better planning.	
		• Maintenance. Moving from preventative to predictive maintenance that optimises the use of vehicles and vessels and improves planning of their use.	
	• Telematics/TMS	• Telematics is technology that combines telecommunications and global positioning system (GPS) information (i.e., time and location) to monitor driver and vehicle performance from the central authority or dispatching unit. Truck fleets can improve operational efficiency, boost driver safety, and reduce high-cost vehicle repairs by implementing these communication systems. Telematics is often combined with broader Transport Management Systems (TMS).	Use telematics to optimise vehicle routing, monitor and manage driver fuel performance
	• Logistics centres and warehouses	• Energy efficiency measures. Examples are renewal of equipment for material handling and yard logistics, LED lights, smart-sensors, high frequency battery chargers and lithium batteries, and thermal insulation. Additionally, to increase storage density by improving pallet stacking, automated systems and use of small(er) shuttles and redesign of roll cages	

alice - A framework and process for the development of a ROADMAP TOWARDS ZERO EMISSIONS LOGISTICS 2050, December 2019			SRF Roadmapping technologies
FLEETS AND ASSETS USE LOWEST EMISSIONS ENERGY SOURCE FEASIBLE	• Electric / hybrids	• Parallel hydraulic hybridisation may be the most cost-effective near-term technology option for municipal utility vehicles, while electric hybridisation tends to be the best hybridisation option for most other mission profiles. Electric road systems (ERS) consist of infrastructure (e.g. catenary) which supplies electrical energy to trucks while they move. Trucks maintain their operational flexibility as they can operate outside the ETS with a hybrid drive train or by	Increase use of electric vehicles, increase use of hybrid vehicles
	• Solar / Wind	• Logistics centres and warehouses	Increase use of biodiesel vehicles
	• Biofuels	• A range of biofuel options (biodiesel, HVO and biomethane) has the potential to partially replace petroleum product consumption in heavy-duty road transport, ocean vessels and barges, and airplanes.	
	• Hydrogen	• Trucks using fuel cells and hydrogen are essentially electric vehicles using hydrogen stored in a pressurised tank and equipped with a fuel cell for on-board power generation.	
	• CNG/bio-LNG	• By using positive ignition systems, medium and heavy-duty compression-ignition engines can be designed to run solely on methane, in form of compressed natural gas (CNG) for larger vehicles or liquefied natural gas (LNG) for smaller trucks.	Increase use of CNG vehicles, increase use of dual-fuel vehicles (Diesel + CNG), increase use of LNG vehicles, increase use of dual-fuel vehicles (Diesel + LNG)
	• Cleaner diesel/fuel management	• New cleaner diesel system that includes an efficient engine and optimised combustion system with the most advanced fuel-injection, turbocharging and engine management strategies. Usually coupled with advanced emissions controls and after-treatment technologies, including particulate filters and selective catalytic reduction (SCR) systems, all running on ultra-low sulphur diesel fuel.	

Appendix C – Analysis of source information

Source / Reference (significant literature in yellow)	Scale of 1 (minimal if any) to 5 (full information) - the level to which each element is considered in the literature											
	Freight measures considerd								Supporting policies & research identified	Cost information	CO2 savings identified	Timing of measures to 2050
	Freight demand	Transport modes	Physical logistics systems	Digitalisation	Fleet assets	Energy efficiency	Energy sources	Energy systems				
(ALICE-ETP, 2019)	4	4	3	2	4	4	4	1	4	1	2	4
(Ambel, 2017)	3	3	1	2	3	4	5	3	4	3	4	3
(Carnevale & Sachs, 2019)	3	4	1	2	2	3	4	5	4	1	2	3
(EC-DC R&I, 2018)	2	4	3	4	4	4	4	5	5	1	1	4
(McKinnon, 2018)	4	4	3	2	5	5	4	2	4	3	3	4
(Walsh, Mander, & Larkin, 2017)	2	2	1	1	1	2	2	1	1	1	2	3
(Murphy, 2018)	2	2	1	1	1	3	3	1	4	1	3	2
(Staffell, et al., 2019)	1	1	1	1	1	1	3	1	2	1	1	2
(Sense project, 2020)	3	4	4	2	3	2	2	1	4	1	3	4
(CEPI, 2018)	2	2	3	3	3	3	3	1	4	1	3	3
(EASAC, 2019)	4	2	3	4	3	4	4	4	4	1	3	4
(Advanced Propulsion Centre UK, 2018)	1	1	3	1	3	4	4	5	3	2	1	4
(DfT, 2018)	1	2	1	1	1	3	3	2	5	1	1	2
(APC, EPC, 2019)	2	1	1	1	1	4	5	2	3	4	3	4
(Gustavsson, Hacker, & Helms, 2019)	1	1	1	1	1	1	4	2	1	2	1	1
(ERTRAC, EPoSS and ETIP SNET, 2017)	1	1	1	1	1	1	4	1	4	2	1	3
(ERTRAC, 2019)	1	2	2	3	3	3	2	1	5	1	1	4
(Transport & Mobility Leuven, 2017)	1	1	3	2	4	4	3	1	3	1	5	3
(ITF, 2018)	4	3	3	3	4	4	4	1	4	2	5	5
(CE Delft; Eclareon; Wageningen Research, Dec 2016)	1	1	1	1	1	1	3	3	3	1	1	3
(TRL, 2018)	1	1	1	1	1	2	5	2	3	5	5	4
(Transport & Environment, 2020)	1	1	1	1	1	3	4	5	4	2	5	5
(Krause, et al., 2020)	1	2	1	1	3	3	2	1	2	1	3	3
(ACEA, 2019)	1	1	4	2	2	1	1	1	3	1	1	4
(ACEA, 2017)	1	1	4	1	1	1	1	1	3	1	2	4
(Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018) E	2	1	3	2	4	4	2	1	2	1	4	1
(International Energy Association, 2017)	2	4	3	3	4	4	3	1	4	1	2	3
CE Delft, 2017	1	1	1	3	1	1	4	3	4	1	1	2
Cambridge Economic Policy Associates LLP (CEPA) a	1	1	1	2	1	1	5	4	4	1	1	4
Committee on Climate Change, 2019	1	1	1	1	1	1	3	3	3	3	3	2

Source / Reference (significant literature in yellow)	Scale of 1 (minimal if any) to 5 (full information) - the level to which each element is considered in the literature											
	Freight measures considerd								Supporting policies & research identified	Cost information	CO2 savings identified	Timing of measures to 2050
	Freight demand	Transport modes	Physical logistics systems	Digitalisation	Fleet assets	Energy efficiency	Energy sources	Energy systems				
Electric Vehicle Energy Taskforce, 2020	1	1	1	1	1	1	3	4	3	1	1	1
Gross, 2020	1	1	1	1	1	2	3	2	1	1	1	1
Hamelincket al., 2019	2	1	1	1	1	2	3	2	3	1	1	1
ICCT, 2020	1	1	1	1	1	2	3	2	1	1	2	1
Institution of Mechanical Engineers, 2020	1	1	1	1	1	2	2	2	1	1	2	1
International Energy Agency, 2020	1	1	1	1	1	1	2	3	2	1	2	3
National Infrastructure Commission, 2019	1	1	1	1	1	1	1	2	1	1	1	1
SLoCaT - Partnership on Sustainable, Low Carbon Tra	1	1	1	1	1	1	1	1	4	1	1	1
Tricker et al., 2019 (Aldersgate Group)	1	1	1	1	1	1	1	1	3	1	1	1
Committee on Climate Change, 2020	1	1	2	1	2	2	2	1	3	3	3	4
Element Energy, 2020	1	1	1	1	1	1	4	1	3	4	3	5
Ricardo Energy & Environment, 2019	1	1	1	1	1	1	4	3	1	4	2	4
Greening et al., 2015	2	4	5	3	5	5	5	1	1	5	5	5
Greening et al., 2019	2	4	5	3	5	5	5	1	1	5	5	5
Department for Transport, 2020 (Decarbonising Trans	1	1	1	1	1	1	1	1	3	1	1	1
Lloyd's Register, 2019	1	1	1	1	1	1	3	1	1	1	1	4
Lloyd's Register, 2020	1	1	1	1	1	1	3	1	2	3	1	4
Department for Transport, 2019 (Clean Maritime Plan)	1	1	1	1	1	1	3	1	3	1	1	2
Department for Transport, 2018 (Aviation 2050)	1	1	1	1	1	2	2	1	3	1	2	3
Sustainable Aviation, 2020	1	1	1	1	1	1	3	1	1	1	1	1
Rail Industry Decarbonisation Taskforce, 2019	1	1	1	1	1	2	3	1	3	3	2	3
Network Rail, 2020	1	1	1	1	1	1	2	3	2	3	2	3
ITF, 2019	4	3	3	3	4	4	4	1	4	2	5	5
Number of papers with scale of 1	35	35	35	34	33	22	6	29	11	34	22	12
Number of papers with scale of 2	10	7	2	9	3	10	10	10	6	6	12	6
Number of papers with scale of 3	3	3	11	8	7	7	17	7	17	7	10	13
Number of papers with scale of 4	5	8	3	2	7	11	14	3	16	3	2	16
Number of papers with scale of 5	0	0	2	0	3	3	6	4	3	3	7	6
Average	1.58	1.70	1.77	1.58	1.94	2.30	3.08	1.92	2.89	1.77	2.25	2.96
Standard deviation	0.97	1.12	1.19	0.89	1.35	1.35	1.17	1.27	1.22	1.22	1.39	1.34

Appendix D – List of necessary activities to achieve a reduction on CO_2 emissions by 2050 (Transport & Mobility Leuven, 2017)

Decisions and preparations: 2020–2030

- Continued steady improvement of the diesel powertrain is expected, as is accelerated market uptake of new vehicles which have been type-approved in accordance with the VECTO methodology.
- Work towards decarbonising the (electric) power generation system will continue.
- Measures to prepare the electricity grid for increased usage by road transport vehicles, including commercial freight vehicles, should be taken.
- Hybrid vehicles are expected to contribute more to longhaul transport (including the use of on-demand hybrid systems to provide auxiliary power); a very high share of regional delivery, and especially urban delivery, should move to electric battery-powered operations.
- Advanced testing of electrified long-distance transport, including via the electricity grid, should be occurring. The nature of this measure does not allow for coexisting incompatible systems. Thus unanimous action by the Member States/road infrastructure authorities will be needed to ensure unified standards, perhaps considering a technology that can be used by different types of vehicles. An EU-level financing mechanism will have to be developed, and electric long-distance transport will have to be rolled out by the end of the decade to allow for sufficient infrastructure development in the long term.
- An incentive scheme for road freight transport operators should be created to encourage investments in alternative fuel vehicles.
- Continued steady improvement in the gas powertrain is expected, as is the development of biogas capacity for use in commercial road freight transport.
- Alternative-fuel infrastructure will have to be fully ready for use, as determined by the applicable Directive. The EU's Alternative Transport Fuel and Infrastructure legislation will have to be revised to enlarge the scope for alternative, renewable fuels for use in heavy commercial vehicles, including the use of electricity produced from renewable energy sources.
- Technological development of advanced biofuels is expected to speed up, aided by a long-term legislative framework which could include incentives, quotas or CO_2- based fuel taxes. Long-term electricity production plans should account for increases in power requirements. • Advanced driver assistance systems should be standard in new HDVs. The focus of driver training is expected to shift from taking action to properly reading and reacting to ADAS. ITS should ensure optimal routing.
- Implementation of the EU regulatory framework should allow regular truck platooning on all major European roads by 2025—a first step towards the use of fully autonomous vehicles. Further developments in EU and UN regulatory frameworks should enable progress in vehicle automation.
- A revision of EU weights and dimensions legislation and related EU and UN type-approvals and general safety rules should start by 2020. This will allow further flexibility in weights and dimensions on the grounds of environmental performance and road safety. Furthermore, this should create possibilities for increased carrying capacity provided that infrastructure-related performance standards are met, including turning-circle, vehicle width and axle (weight, number and type) requirements.
- Aerodynamic cabs should become the norm. Further steps in weights and dimensions regulation should improve vehicle design and the aerodynamics of complete vehicle combinations.
- A complete removal of restrictions on the cross-border use of LHV combinations is expected, provided that infrastructure can accommodate them. There may be increases in the maximum authorised weights of all crossborder road freight transport vehicles above 3.5 t provided they comply with a set of environmental performance, operational performance and road safety-related rules.
- A move towards the integration of toxic and nontoxic emissions norms is expected, as is the gradual introduction of global rather than regional norms.
- Taxation based on vehicle ownership or the type of energy used is expected to gradually move to taxation based on environmental performance and the type of vehicle use. This principle should apply to all road vehicles, not only commercial road freight transport vehicles. The environmental performance of a road freight transport vehicle should be calculated based on the entire vehicle or vehicle combination, not just its engine/gearbox.

• An evaluation of the achievements of emission certification tools should be carried out, as should ananalysis of the performance of CO_2 reduction and fuel consumption standards in heavy commercial vehicles.
• The testing of collaborative logistics platforms should be expanded, with harmonisation coming towards the end of the decade. Integration should be fully multi-modal.
• Fully interoperable, compatible, cross-border ITS applications should be helping infrastructure managers, road transport users and enforcement authorities.
• Road pavement renewal should focus on reducing rolling resistance while improving grip.

Time for major action: 2030–2040

• Alternative-fuel infrastructure for road transport should be widely available throughout the European Union.
• The conditions should have been met to allow alternative propulsion and energy sources to reach a significant share of the road transport energy market.
• An advanced biofuel production breakthrough will be needed to power long-haul operations off the grid and regional deliveries when battery operation is impossible. Gas vehicles should be switching mostly to biomethane.
• Diesel engines are expected to be fully ready for high proportions of biofuel.
• Single wide, latest generation, low rolling resistances tyres are expected to be standard.
• Logistics harmonisation should be moving ahead at full steam, resulting in increasing load factors and even in longer, heavier vehicles (which are also used in regional delivery cycles).
• Weights and dimensions regulation should be based on standards of operational performance. Modularity should move towards the “physical internet.”
• Legislative processes authorising fully autonomous vehicles should be complete (including provisions for driving/resting times).

Rolling towards the goal: 2040–2050

• Autonomous vehicles are expected to be in common use, 24 h per day, 7 days per week. The driver’s role will have changed to that of a cargo manager. Fundamental vehicle redesigns are to be expected, taking into account the changed role of the human being.
• Investment renewable energy sources for all types of road freight transport operations will continue in. At least 30% of the average blend should be advanced biofuels; 40%–45% of long-haul road transport should be powered through road network charging infrastructure. Preparations are expected to be underway for a complete phasing-out of fossil fuels as an energy source.

Appendix E – Policy measures provided by the International Energy Authority (International Energy Association, 2017)

Table E1: Policy measures that address market barriers to truck fuel economy investments (International Energy Association, 2017)

Market barrier	Policy types	Examples
Payback gap	Regulations and fuel economy standards compel firms to prioritise spending on fuel economy measures, usually with positive net present value (NPV)	Fuel economy standards in Canada, China, Japan and the United States; Hong Kong, China's 2010 anti-idling bill; California and other US states' anti-idling bills
	Grants, tax breaks and other fiscal measures targeted at measures with longer paybacks	California Clean Air Action Plan for the Ports of Los Angeles and Long Beach
	Scrappage schemes reduce transaction costs associated with the replacement of the existing fleet	China's "old swap new" programme (2010)
		India's vehicle fleet modernisation programme (under development)
Imperfect information	Set up forums for knowledge exchange	SmartWay Transport Partnership; Green Freight Asia; Transport Limpio (Mexico); Ecostation (Australia); EcoStars (United Kingdom); Lean & Green (Netherlands and other European countries); Global Green Freight Alliance; and many others
	Disseminate experience with the reliability of new technologies and prioritise ensuring reliability in research programmes Independent accreditation schemes	Smartway Transport Partnership provides accreditation for manufacturers of low-carbon vehicles
Split incentives	Standardise use of technologies that reduce the influence of driver behaviour	Mandatory speed limiters in the European Union
	Information provision about the benefits of performance feedback for drivers	Royal Dutch Shell's FuelSave Challenge Partner system; GreenRoad's real-time fuel consumption feedback system, as used, for instance, by the Dutch carrier Emons
	Provide eco-driving training or incentivise eco-driving through monetary and other rewards	FleetSmart, Canada, and many documented examples among Finnish, German, United States and other carriers
	Fuel economy standards ensure that truck leasing companies adopt technologies that will benefit their clients	Fuel economy standards in Canada, China, Japan and the United States
Network and learning externalities	Support to the innovation ecosystem for developing and piloting new technologies	Innovate UK; California Air Resources Board's Low Carbon Transportation and Fuels Investments and Air Quality Improvement Program; Swedish Strategic Vehicle Research and Innovation Program; European Union mandates on alternative fuelling infrastructure (EC, 2016a); European Truck Platooning Challenge
Liquidity and scale constraints	Grants, tax breaks and other fiscal measures	Japanese HDV purchase subsidies. Texas Natural Gas Vehicle Grant Program
	International co-operation on vehicle standards to harmonise new and used vehicle standards	Mexico emissions standards for used equipment and scrappage scheme.
Trade-offs	Align maximum truck weight limits and fuel economy objectives.	Australia's Performance-Based Standards (PBS) and Intelligent Access Program (IAP) (see the discussion of 'High-capacity vehicles' in Chapter 2).
	Facilitate accreditation for efficiency retrofits	Smartway Transport Partnership provides accreditation for "Upgrade" packs for retrofitting

Table E2: Decarbonising policies required by authority level (International Energy Association, 2017)

Policy measure	Actors	Authority level	Vehicle efficiency	Systemic improvements	Alternative fuels
Heavy-duty fuel economy standards: geographical expansion and gradual tightening	Government	National and supranational	XX		X
Differentiated vehicle taxes	Government	National and supranational	XX	X	XX
Low interest loans for energy efficient trucks	Commercial banks	–	X		
RD&D support to accelerate the development of technologies enabling energy efficiency improvements	Government	Local and municipal	X		X
Green financing to mobilise investment for the deployment and market uptake of energy efficient technologies	MDBs, commercial and national banks	–	XX	X	X
Accelerated vehicle replacement schemes to remove only older vehicles that are still being driven	Government	National, local and municipal	X		X
Green freight programmes: expansion of the regional and sectoral scope, and corporate membership	GFPs	–	XX	XX	
Voluntary annual reporting of road freight operations (e.g. aggregate vkm, tkm and fuel consumption)	Government, GFPs	National and supranational		XX	
Mandatory CO_2 emissions reporting	Government; GFPs	National and supranational	XX	XX	XX
Rules and regulations to promote external collaboration	Government	National and supranational	XX	XX	XX
Standardisation of truck sizes and regulation of operations of high-capacity vehicles	Government	National and supranational Ideally global	XX	XX	
Standards for ultra-low and zero-emissions infrastructure	Government	National and supranational	X		XX
Support for the deployment and use of alternative fuels infrastructure	Government, PPPs	National and supranational	X		XX
Biofuel mandates and low-carbon fuel standards	Government	Regional, national and supranational	X		XX
Differentiated distance-based pricing based on GHG emissions	Government	National and supranational	XX	X	XX
Tax transport fuels based on life-cycle GHG emissions	Government	Regional, national and supranational	XX	XX	XX
Stringent standards for pollutant emission and fuel quality *	Government	Regional, national and supranational	X	XX	XX
Access restrictions in urban areas based on vehicles' environmental performance (with a focus on air quality) and/or regulations that affect the cost or limit the availability of license plates for conventional vehicles	Government	Local and municipal	X	XX	XX
Measures to increase the cost of access to urban areas (e.g. usage fees for specific portions of the road network), differentiated on the basis of vehicles' environmental performance (focusing on air quality)	Government	Local and municipal	X	XX	X

Appendix F – Policy measures provided by Transport and Environment (Transport & Environment, 2017)

- CO_2 standards for trucks and trailers. A CO_2 vehicle standard, if accompanied by reliable emission testing, has proven to be a very strong driver in bringing fuel efficient technologies to the market for cars and vans in Europe but also for trucks in other regions in the world.
- A zero emission vehicle (ZEV) mandate/quota for delivery trucks
- Road charges, tolls and fuel taxes are key drivers of lower carbon trucking. The operational cost of a truck is artificially low if vehicle externalities are included. Increasing the price of road transport is a way to improve the efficiency of road haulage
- Zero-emission freight strategies for cities need to be adopted across Europe
- Building the right infrastructure
- Boost the supply of sustainable and advanced fuels

The report also provides a set of policies *"to unlock the potential*", as follows:

- Implement an ambitious CO_2 standard for trucks
- Invest in infrastructure so trains can cross borders easily and transhipments can be faster and cheaper.

Increased electrified rail freight

- Open national/international EU markets to competition, including separating the financial accounts of infrastructure manager and railway undertaking and creating an independent regulator to ensure fair competition in the European railway market.
- Improve management of tracks to allocate more capacity to freight trains, while maintaining passenger kilometres).

Improve logistics efficiency

- Implement a distance-based road charge for trucks across Europe.
- Ensure that fuel taxes reflect the external costs of trucks.
- Invest in smart infrastructure to allow for ITS and advanced road tolling, while possible obliging data sharing (with strong data protections in place) so that internet applications can optimally improve the efficiency of freight transport.

Clean electricity

- Establish high renewable energy targets.
- Ensure that carbon has a high price, either through the ETS or other tools

E-highways for HHGVs

- Take a decision to push this alternative as soon as possible to start developing the infrastructure.
- Use road charging revenues to finance infrastructure and vehicle costs and other pilot projects (eg LKW Maut in Germany). It can be complemented with EU funding.
- Develop a common EU strategy to avoid bottlenecks, reduce prices and incentivise investments in catenary truck technologies.

Fully electric MHGVs

- Establish an e-vehicle mandate for trucks below 16 tonnes, helping to decrease price.
- Invest in infrastructure and R&D for battery technologies.
- Guarantee that green public procurement schemes, such as the currently ongoing revision of the Clean Vehicles Directive, promote the uptake of these technologies

Advanced sustainable fuels

- Establish stable policy to promote industry confidence, ensuring proper sustainability from the beginning.
- Focus on efficiency measures in the EU. The biomass available for the transport sector is dependant significantly on the heating and electricity sector.

Appendix G – Policy measures provided by EASAC (EASAC, 2019)

1. Avoid and contain the demand for conventional motorised transport.
(a) Policies to contain growth of freight transport (sustainable urban logistics plans) and of aviation for both passengers and freight while supporting economic development, cohesion, consumer services and competitiveness.
2. Shift more freight off the road and onto railways or waterways.
(a) Public and private sectors should jointly invest urgently in more and better access points for intermodal containers to transport freight by rail, inland waterways or maritime services.
(b) Substantially bigger investments should be made for the long term to expand routes and capacities for transporting freight by rail, inland waterways and maritime services.
3. Improve/reduce the average emissions of all light duty vehicles during the next 10 to 15 years – a crucial transition period.
(a) Binding target dates for phasing out fossil fuels and subsidised scrapping schemes to accelerate renewal of the fleet should be implemented as soon as possible.
(b) Hybridisation and optimisation of internal combustion engine vehicle (ICEV) and powertrain design should continue to be promoted using legislation, standards and high-visibility vehicle labelling campaigns.
4. Improve/increase the rate of market penetration of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).
(a) Incentivise purchase of BEVs and PHEVs (including buses), limit use of fossil fuels in urban areas, install public charging points, and provide recycling facilities for batteries.
(b) Certify and label BEVs and PHEVs for embedded emissions on a life cycle basis to limit carbon leakage through overseas battery manufacture. Support battery manufacture in the EU.
(c) Regulate the sizing of PHEV batteries and ICEs, so that PHEVs can be excluded from incentive schemes and credits unless they provide electric driving for at least 50–70 km.
5. Improve/increase the penetration rate of low carbon electricity generation into the grid urgently.
(a) Growth of low-carbon electricity generation must be higher than the total growth in electricity demand from transport, hydrogen/ synthetic fuel production, industry and buildings sectors.
6. Improve and adapt the design and regulation of electricity markets and tariffs that apply to electric vehicles, so that costs are minimized for all consumers.
(a) Promote synergies between grid flexibility management and BEV storage, sharing the costs and benefits between BEV users and others by using time-of-day and power-related tariffs.
(b) Permit aggregators and innovative ICT solutions to benefit grid operators and all electricity consumers including industry, buildings, BEV owners and hydrogen/synthetic fuel producers.
7. Improve and simplify guidance on use of biofuels, biogas, natural gas and methane for transport.
(a) Sustainability criteria should continue, with a cap on conventional biofuels. Biofuels should not be zero-rated if produced from forest biomass with long carbon-payback times.
(b) Natural gas can reduce ICEV emissions but should only be used for transport if all upstream ‘fugitive‘ leakages of methane are monitored, certified and limited to less than about 1%.
8. Improve/increase resources for the development of technologies for producing synthetic fuels.
(a) Facilitate deployment for the long-term needs of long-haul transport (marine, aviation, heavy-duty vehicles (HDVs)) and the short/medium-term demand for ‘drop-in‘ substitute fuels for conventional ICEs.

9. Improve/increase the levels of investments in information and communication technologies and autonomous vehicles.

(a) Promote ICT for freight sharing, traffic management, road pricing, electric vehicle charging, automatic driving and interconnected vehicles, to reduce GHG emissions.

(b) Monitor progress with ICT and autonomous vehicle incentives, regulations, codes and standards to check and if necessary correct for possible rebound effects.

10. Improve/strengthen preparations for long-term emission reductions by making long-term policy commitments to invest in innovation, jobs, skills and interdisciplinary research.

(a) Support the transition of the EU automotive industry to a decarbonised future by investing in low-carbon footprint battery manufacturing within the EU.

(b) Support collaborative research and innovation activities to build skills in ICT, life cycle analysis, electrical system management, and low carbon vehicle manufacture, maintenance and repair.

(c) Promote market uptake of BEVs, fuel cell electric vehicles (FCEVs), electric road systems (ERS) and synthetic fuels through collaborative actions on behaviour change, socio-economics, business models and standards.

(d) Strengthen international cooperation on producing, certifying, labelling and using synthetic fuels in aviation and shipping, and on synthetic fuels for seasonal storage of electricity.

Appendix H – Future research requirements provided by the European Commission (EC, 2018)

- R&I is needed not only related to the electrification of common land-based transportation systems (e.g. passenger cars) but also for the segments that receive less attention, for example the decarbonisation of industrial vehicles (yellow machines), trucks (e.g. overhead lines) and the electrification of ports & short distance water-based transport (e.g. ferries). For electric vehicles, R&I should also address the standardisation of charging systems to overcome adaptation barriers on the consumer side.
- New battery chemistries as well as the re-use and recycling of batteries should be explored to improve their life cycle sustainability, reliability, safety and cost performance. An aim could be to lift batteries from TRL 4 (all-solid-state lithium technologies) to TRL 7 within the next decade.
- Assuming battery electric vehicles will be largely rolled out for individual passenger road transport, R&I is needed to identify efficient hydrogen carriers (e.g. liquid hydrogen organic compounds) to enable hydrogen in other mobility market segments that are difficult to electrify such as rail, road freight, emergency vehicles and shipping. What would the corresponding business cases look like, and what is the trade-off of in using hydrogen in vehicles directly versus producing synthetic fuels based on hydrogen?
- R&I on new ships and airplanes is needed to further reduce the specific fuel consumption per transport unit. This comprises development of new airplane and ship designs to increase transport capacities as well as new materials (e.g. composite materials) and improved aerodynamic designs. Furthermore, R&I should focus on the sustainable production of biofuels and synthetic fuels as equivalent substitutes for fuel oil and jet fuel. In particular, R&I is needed to ensure and enhance the EU production of lignocellulosic
- feedstock through investment in new crops, the identification of efficient agriculture, waste and forestry management techniques, optimised harvesting and supply chain logistics.
- Analysis is needed of international and transcontinental transport infrastructure requirements and new technologies to substitute short-distance EU air traffic with high-speed rail as well as to shift long-distance freight transport based on road or ship to rail freight transport.
- R&I should be developed on sustainable hydrogen supply, comprising production, storage and transport to address the specific question on how the conversion efficiency (over the entire conversion pathway) can be improved to use as little energy as possible to produce H_2/synthetic fuels, including new materials such as MOFs as catalysts, for instance. It is relevant in this R&I field to gain knowledge and experience on the realisation of sector coupling projects along with H_2 and CH_4 network design and operation, i.e. to build new hydrogen networks versus using the existing gas network versus decentralised production. A spatially detailed analysis would allow consideration of different consumer groups (e.g. industries) and their requirements in terms of gas supply and gas quality.

Appendix I – Future research requirements provided by the APC and EPC (APC, EPC, 2019)

Table I1: Future research topics (APC, EPC, 2019)

Research area	Details
Net zero emissions by 2050 targets	As net zero targets were set while the project was ongoing, the ESME model was set up with an 80% emission reduction target. Reflecting the current political climate, it is proposed that the models and scenarios developed within the project are run in a net zero emission context.
Charging and refuelling infrastructure	Refuelling stations were split between private and public ownership and different costs were used. As infrastructure is seen as one of the defining factors for the vehicle choice, more detailed representation of infrastructure requirements and costs per segment would provide more granularity to the results. For example, based on the energy consumption different types of chargers can be used for each segment. Furthermore, the model can be expanded to show different pathways for hydrogen and electricity generation. For example, in the current model hydrogen is assumed to be generated on site with an average value used for the cost of the generation. The model can be further developed to include different methods for generation, transmission and delivery to the stations.
Vehicle powertrains	Certain vehicle powertrains were excluded from the scope of this work due to lack of data. It is recommended that these powertrains should be included in the model when data becomes available as these could be used as transition vehicles in reducing emissions from the HGV sector. Some examples include gas/electric hybrid and diesel/electric hybrid powertrains.
Scenarios	The workshops resulted in the formulation of various scenarios describing pathways for the decarbonisation of the freight sector but not all the scenarios were modelled within this project. A few examples include the implementation of taxation or incentives to promote zero emission powertrains and shifting demand from road to rail transport. It is therefore proposed that these scenarios will be modelled in the future to answer more of the industry questions around the potential routes to reduce emissions from HGVs.
Infrastructure synergies	The Freight model currently does not include infrastructure built for MGVs and passenger vehicles (where appropriate). This could reduce the TCO calculated by the model where new infrastructure is benefiting not only HGVs in the transport sector and consequently could potentially improve the uptake of the relevant powertrain options.
Lifecycle emissions approach	The model does not include emissions associated with the manufacturing of vehicles and vehicle components like the batteries used in electric powertrains. It is proposed that as net zero emission targets are set; the Freight model is updated with lifecycle emissions capabilities.

Research area	Details
Validating / evaluating assumptions Sensitivities on assumptions	The lack of data was listed as one of the limitations the project encountered. It is therefore proposed that assumptions made are validated either by further research or by sensitivity analysis.
Air quality	Air quality related emissions should also be considered in future work. As ESME capabilities expand and air quality modules are introduced within the tool the scenarios modelled can be updated with further optimisation objectives to meet air quality constraints. This could potentially affect the vehicle parc composition.
Well-to-motion pathways	For the purposes of this project, the well to motion pathways for gas in the WtM model were simplified. Having the capability to evaluate the entire well-to-motion pathways for gas, electricity and hydrogen would add further value to the Freight model. In addition to re-introducing the gas well-to-motion emissions calculation, well-to-motion emission calculations could be developed for the other energy vectors used. This would allow emissions to be calculated for each station category separately.
Penalty value and penalty end year for gas, hydrogen and electric vehicles	A penalty on sales was introduced to reflect operator's hesitation towards new technologies. The same value was used across all vehicle segments and powertrain options. Future work around identifying in which segments operators are more hesitant to adopt certain technologies would better refine these assumptions and would provide a more accurate representation of operator's behaviour within the model.
Motorway catenary charging	Motorway catenary charging was included in the ESME model but not in the Freight model. Future work is needed on how the operators' behaviour changes and which powertrains are selected when catenary powertrains are added to the fleet.
Development of an integrated toolset	In this project the Freight model was developed to reflect the operator's choice on HGVs and the modelling outputs was used to assess the impact these choices have on the energy system in ESME. The data were transferred manually and not iterated. Automating the data transfer and introducing a feedback loop to inform the choice model with energy system implications and constraints, would add value to both models and would offer a more holistic view.
Competitiveness of powertrains	Investigate the parameters which need to be influenced and by how much for the hydrogen powertrains to be more competitive, e.g. subsidies on hydrogen infrastructure. Investigate the parameters which need to be influenced and by how much for the diesel and gas powertrains to be less competitive compared to battery in the long run, e.g. tax on fuel.
Distribution hubs around cities	The modelling results showed that in the scenario where demand is shifted from HGVs to smaller vehicles emissions from the HGV sector are reduced. This scenario would benefit from further investigation to better understand the infrastructure and additional energy requirements and the impact on traffic and land use.
Transition to a zero-emission fleet	The transition to zero emission vehicles and the infrastructure required to support zero emission vehicles will need to be further explored. The Freight model with the added modules on detailed infrastructure options and well to motion emissions will be able to provide recommendations on what steps would need to be taken for a optimised transition to a zero emission fleet.

Appendix J – Future research requirements into battery technologies provided by APC (Advanced Propulsion Centre UK, 2018)

Table J1: Identification of key research and pre-competitive development challenges to help facilitate academic / industrial collaboration on longer term product and manufacturing research and development (Advanced Propulsion Centre UK, 2018)

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
1 Cost effective battery packs	All research challenges listed below imply efforts to reduce cost wherever possible, or, demonstrate an improvement in performance that mitigates the increase in cost		
2 Improve safety	• Safer cells and packs, with improved cell-level fault containment	• Cell level solutions to make fault conditions benign, including thermal shut-down separators and sensors integrated into the cell	• Eliminating thermal runaway at a pack level by using electro-chemistries that are inherently stable
3 Fast charging capability for BEV's	• Pack charge rate capability to 1.5-2C	• Pack and cell charge rate capability to 2.5-5C	• Pack and cell charge rate capability to 5+ C
4 Increase power density for high power applications	• Combining hybrid Li-Ion and/or ultracap cells in a pack • Utilise current materials and approaches to create cells tolerant to high power densities (i.e. carbon anodes)	• Reducing interconnect resistance • Mixed lithium ion cells that mix high power and high energy performance • Advanced cooling strategies in operation to achieve high power densities	• New materials (including graphene morphologies) for higher power and higher energy density capacitors (i.e. supercapacitors, pseudo capacitors)
5 Increase energy density in existing lithium-ion chemistry	• Improving existing electrolytes, electrode structure and cell packaging in known chemistries • Introducing elements into lithium based cathodes that enhance energy density	• Higher voltage (5V) electrolytes • Developing safety concepts for high voltage modules and packs	

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
6 Better battery pack design through improved predictability of performance, durability and ageing via modelling, simulation and testing	• Predictive modelling tools with greater accuracy <5% margin of error (e.g. prediction of life models) • System engineering solutions to improve pack robustness to >8 years (1st life) • Better understand response of cell structures to mechanical stimuli (bending, impact, vibration, crush) and the effect on health • Better modelling of battery lifetime requirements of applications with heavier duty cycles (e.g. trucks, off- highway machinery)	• Testing techniques for accurately predicting life and performance degradation in 1st and 2nd life applications • Better modelling and understanding of battery lifetime requirements for CAVs	• Holistic predictive modelling tools with <1% margin of error • In-situ electrochemical analysis techniques leading to improved fundamental understanding and predictive modelling capabilities encompassing electrochemical, electrical, mechanical and thermal properties • Improved understanding of degradation mechanisms to enable more radical materials and engineering solutions to increase pack durability to 15 years (1st life), including self-healing binders, separators and electrolyte
7 Reduce mass and volumes overheads at vehicle level	• Utilising multi-material solutions, plus integrating structures to increase the % of active materials in battery packs (45% active material)	• New multi-material approaches to increase the % of active materials in battery packs (55% active materials)	• Structural batteries with novel structure and form • New concepts for integration of the cell, module and pack to increase the % of active materials in battery packs (65% active materials)
8 Increase operating temperature range and efficiency of thermal management systems	• Battery packs with -30°C / +70°C capability • Higher temperature capable electrolyte • Reducing the power consumption of thermal management systems	• Thermal management systems fully integrated with vehicle thermal management systems that leverage new technologies (such as phase change materials) to improve efficiency and reduce parasitic loss	• Battery packs with -40°C / +80°C capability • Cells with passive cooling capability

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
9 Improve BMS systems	• Embedding accurate real time cell models into BMS • In-situ diagnostic techniques	• Cell level monitoring systems • Real-time prognosis and active SOH management	• Predict failures with >95% reliability • On board machine learning to self-parameterise and self mitigate in event of degradation and failure
10 Increase the speed, improve the quality, reduce the cost and improve the sustainability of manufacturing	• High volume automotive standard production and quality assurance processes • Improved cell to busbar joining technology • Production variability and process control • Improved electrode processing methods and structures at higher volumes • Develop low cost high speed deposition processes and evaluate in larger footprint and alternative cell formats • Understand and validate life cycle impact analysis	• More consistent processes to improve the homogeneity of cells • Lower cost formation processes • Actively reduce lifecycle impact of manufacturing • Mass manufacturing processes for new chemistries • New production process and equipment reducing cell manufacturing times • Material solutions to increase cell durability and improved cell joining technologies	• Developing chemistries and processes to reduce formation time and speed up conditioning • Standardisation of formats for vehicle applications • Better integration of pack and vehicle manufacturing • Creating a circular economy for automotive battery packs
11 Identifying the next-generation chemistry to displace existing Li-Ion		• Example: Lithium-Sulfur (Li-S) as an automotive technology capable of delivering > 25% improvement in energy density at equivalent cost relative to contemporary lithium ion • Example: Sodium-ion (Na-ion) as an automotive technology capable of delivering similar performance levels at >25% cost reduction relative to contemporary lithium ion • Developing room temperature solid state electrolytes with high ionic conductivity	• Breakthrough concepts such as: lithium-air and alternation metal-ion chemistries, higher energy capacitors and more sustainable cells • Anodes for higher energy density (e.g. lithium metal) and higher power density (e.g. graphene) • Exploring whether multi-valent chemistries such as Zn, Al and Mg can tolerate higher voltage levels (5V+)

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
12 Mobilising a UK supply chain that demonstrates cost competitiveness and higher productivity	• Develop flexible pilot and high volume manufacturing capability to capitalise on future cell technologies • Leveraging and adapting manufacturing processes and materials used in adjacent sectors (e.g. chemicals industry) to improve UK battery manufacturing capability	• Manufacturing capabilities that are automated and flexible enough to capitalise upon different potential technology paths (e.g. cylinder vs. pouch vs. prismatic, liquid vs. solid electrolyte etc.) • Aligning manufacturing processes with next generation chemistries (see medium term challenge 11) • Flexible rapid prototyping / proof-of-concept capabilities for new module & pack concepts • Flexible rapid digital prototyping / proof-of-concept capabilities for new materials and cell concepts • Large volume (i.e GWh) manufacturing capability and capacity	• 3D printed, multipolar formats, conformable cells, electrochemically functionalised materials • Aligning manufacturing processes with next generation +1 chemistries (see long term challenge 11)
13 Develop an economically viable value chain for 2nd life reuse	• 1st life design systems that meet 2nd life End-of-life diagnostic tools • Model and test aggregation of aged batteries for energy storage applications	• Scaling up of repurposing facilities to enable roll-out • Design packs for 2nd life to enable easy interoperability • Predictive performance and life models for 2nd life applications	• Understanding the economic case of using 2nd life batteries compared to virgin materials • Techniques for post-crash health diagnostics, remanufacturing cell components and processed materials (e.g. cathode powder) into new cells
14 Develop and scale up of cell and pack recycling processes	• Define and develop processes for material recovery from cells (including value modelling) • Design methodologies and cost models for design for disassembly of modules and packs • Understanding the logistical and economics implications of recycling	• Interconnects that enable removal of individual cells • High throughput end of life testing and recycling processes (including automation) • Increased use of recycled materials in battery packs	• Methods to recycle 100% of a cell and pull materials back into new material streams • Develop a circular economy for battery packs

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
1 Reduced air quality impact	**The implications of improving air quality both in cylinder and post-combustion need to be considered together and not taken in isolation**		
	In-cylinder approaches • Novel ignition systems for dilute operation • Multiple/split injection strategies to overcome the NOx/soot trade-off (inc. including understanding problems such as cavitation associated with new injection methods) • Fast cycle – cycle control of homogenous compression ignition • On board water recovery for water injection • Dilute homogenous combustion (both CI and SI) **After treatment approaches** • Develop more efficient approaches for reducing NOx, and oxidizing PM, HC, and CO in low temperature exhaust (150°C). • Portable emissions measurement systems (PEMS) for future requirements (e.g. particulate numbers, future EU-7 and gaseous vehicles) • Improved DPF and GPF efficiency for smaller particles (below >23nm) • Low temperature (below 350°C) oxidation catalysts for CH4	**Technologies that achieve zero emission impact thermal propulsion systems** • Zero emission combustion systems / architectures compatible with carbon neutral fuels (e.g. nitrogen scrubbing, full cycle HCCI, catalytic combustion) • Radical near 100% efficient after treatment systems that convert over the whole operating cycle • Low cost, mass manufacturable and recyclable fuel cells (both high and low temperature) • Cost effective technology for on vehicle hydrogen storage	

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
2 Improved thermal propulsion system efficiency and real world fuel consumption/GHG reduction	**Challenges in improving real world fuel consumption / reducing GHG emissions occur during combustion and systems that operate around the TPS**		
	Optimising current combustion cycles • Improving conventional combustion cycles (i.e. through better valve control, deeper Miller/Atkinson cycles, altering combustion cycles depending on load) to improve thermal efficiency • Cascading technologies and principles from lighter duty (i.e. cylinder deactivation and downsizing) into heavier duty cycles **Improving existing techniques for thermal management and friction loss** • Cost effective surface treatments for friction and heat loss (e.g. thermal barrier coatings and new lubricant formulas) • Lower cost WHR systems and components (i.e. turbo-compound, thermoelectric, thermo-acoustic) **Optimising current air handling strategies** • Improved turbocharger efficiency over wide map, including down speeding (e.g. better twin scroll, e-boost)	**Advanced combustion strategies to achieve higher engine efficiencies** • Advanced efficient combustion systems such as ultra lean and SACI • Geometric variable compression ratio concepts **New concepts for thermal management and friction loss** • Novel thermal barrier coatings (e.g. temperature swing) • Fast warm up systems (e.g. on board thermal storage, low thermal inertia systems) • WHR combining high grade and low grade heat, including direct powertrain cooling • High efficiency expander that can operate over a wide turn-down ratio • Novel fluids for high efficiency WHR **Advanced air handling strategies integrated with other systems** • Integrated WHR (thermoelectric) and electric turbocharger (e-boost, e-turbine) and integration (e.g. water recovery) **Fuel injection systems** • High flexibility FIE (including injection rate and nozzle geometry	**Technologies that achieve carbon neutral thermal propulsion systems** • Thermodynamic cycles with integrated waste heat recovery (e.g. split cycles, on board fuel reformation) • Multi fuel combustion systems that deliver ultra-low life cycle CO_2 • On board CO_2 capture (pre and post combustion) • Low cost, mass manufacture fuel cells (high and low temperature) with advanced WHR systems

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
3 Reducing the cost and complexity / attribute trade-off of electrified thermal propulsion systems	• Modifying current engine architectures and platforms to operate as part of a hybrid system	• New, flexible and modular thermal propulsion system for hybrid applications applicable across vehicle platforms	• New architectures for low cost and complexity PHEV / REEV thermal propulsion systems
4 Improved powertrain control and operation using approaches such as machine learning or connected data	• Utilising connected vehicle data for improved powertrain control • Advanced model based control with reduced reliance on base maps • Improved sensor technologies (e.g. better accuracy, more parameters, lower cost)	• Design systems for cyber security • Prognostics – improved software capability to better sustain health of engine and powertrain • E-horizon enabled powertrain control considering V2V interactions, geo-fencing and optimising vehicle level energy management. • Application of machine learning to powertrain control, calibration, validation and OBD	• AI led, adaptive and collaborative control schemes, fully connected with city infrastructure • Low power consumption control, sensing and processing • Human-like autonomous control focussed on customer experience
5 Decarbonising thermal propulsion systems via co-developed engines and de-carbonised fuels	**Two possible research pathways: TPS fully optimised with fuels or TPS that is flexible and accepts a wide range of alternative fuels**		
	• Higher efficiency engines for lower GHG-intensity fuels (i.e. bi and duel fuel concepts, lean burn DI CNG/LNG combustion systems with negligible methane slip) • Novel concepts to extend the utility of low grade or renewable fuels and/or reduce the need for high grade fuels • Global energy system analysis tools to inform fuel pathway choices and engine development	• Mass production of fuels tailored for clean, efficient TPS e.g. on vehicle fuel reforming, lean homogenous combustion, high temperature fuel cells • TPS tolerant to wider fuel specification (higher bio content, fuels from recycled waste) • Drop-in low carbon fuels to decarbonise existing fuel content • Mass production of paraffinic fuels (e.g. Fischer–Tropsch, HVO) • On board fuel conversion from a low cost liquid source	• Alternative thermodynamic cycles for ultra high efficiency (inc. fuel cells) using sustainable, low cost drop in 'sun-to-liquid' fuels and /or tailored bio-fuels • Co-developed engines and tailored 'sun-to-liquid' fuels for near zero emissions • Sustainable fuel production processes from recycled waste with zero emissions TPS tolerant to variable fuel specifications • Offering electrical network system resilience via TPS in V2G mode

Research Challenge	SHORT TERM (5-7 years to mass market)	MEDIUM TERM (7-15 years to mass market)	LONG TERM (10-20 years to mass market)
6 Manufacturing and materials for improved attributes, recyclability or life cycle impact	• Engines designed for serviceability and manufacture • In-engine lightweight technology with mid and end of life in mind • Additive manufacturing for niche applications • Low cost thermoelectric materials • Develop deeper LCA insights into powertrain materials, their manufacture and end of life	• Cost effective next generation surface treatments such as temperature swing coatings or ceramics for exhaust • Mass production additive manufacturing techniques and associated evolution in component design • Greater use of bio materials and recycled materials in TPS components	• Chemical heat storage materials • Lubricant free materials • Low cost, volume production using additive layer manufacturing (i.e. fully printed powertrains) • Fully automated manufacturing tools that auto optimise and self regulate • Low LCA and environmental impact of TPS materials and manufacturing processes
7 Minimising time to market, efficiency of development and product attributes via improved methods and toolchains	• Virtual calibration based on improved representation of physics in engine models • Use of big data for harnessing in-service data to inform engine design, control and OBD • Models that can effectively simulate engine combustion and in-cylinder emission formation processes through to the performance degradation of after treatment systems for existing and new combustion cycles	• Multi-physics system level modelling to understand powertrain level trade-offs and optimise powertrain architectures • Predictive simulation tools for industry to design advanced thermal propulsion systems • 70% virtual testing and verification for thermal propulsion systems	• AI led deign and optimisation techniques • 95% virtual testing and verification for thermal propulsion systems