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Decarbonising road freight

Future of Mobility: Evidence Review

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Decarbonising road freight

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The Centre for Sustainable Road Freight

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Executive Summary

Introduction

This report uses a robust and tested framework to consider the technical and operational trends which are the contributing factors to the amount of CO_2 emitted by road-freight activities.

It then considers the possible solutions, quantifying where possible the potential benefits, before using the investment attractiveness of each intervention to prioritise action.

The report concludes by presenting a road map for both technical and operational improvements for the decarbonisation of road freight.

Much of the work presented in this report has been carried out by the Centre of Sustainable Road Freight over the last five years and the centre would like to acknowledge the funding contribution made by the Engineering and Physical Sciences Research Council (EPSRC) in this respect.

The outcomes described in this report have been derived from a road-mapping model developed by the Centre for Sustainable Road Freight. This model uses a wide range of government-sourced data including vehicle information collected by the Department for Transport for the Continuing Survey of Road Goods Transport (CSRGT), forecasted fuel costs and km travelled, and future vehicle efficiency factors. The model contains a comprehensive list of emission and km reduction measures for vehicle and logistics operations, with predictions of likely take-up derived from a wide range of sources including literature, focus group meetings, discussions with experts and interactive stakeholder engagement sessions. The road-mapping model generates trajectories for UK emissions from the HGV fleet between 2010 and 2050, although the results presented in this report are limited to 2040. For this study four scenarios have been examined requiring varying levels of government support.

1. Maximum CO_2 – in this scenario it assumed that all vehicle and logistics measures will be adopted by companies according to the predicted take-up, irrespective of whether a measure is cost-effective. In this situation companies would be able to maximise the CO_2 reduction opportunity but would need significant government intervention to incentivise the adoption of some of these measures.
2. Positive net present value (NPV) – in this scenario a company would adopt a vehicle measure only if it were cost-effective for them to do so. In other words, any company investment in a measure would be paid back in terms of fuel savings. It would have to achieve a positive NPV within three years, with a discount rate of 10%. In this situation only a reduced number of measures would be adopted, but these would not require any government intervention.
3. Maximum CO_2 savings but without any electric vehicles – electric freight vehicles have a major role to play in reducing CO_2 emissions but, at present, there are limitations in terms of the high purchase cost, distance they can travel without being recharged and the extra weight of the batteries. This scenario examines the CO_2 reduction opportunity of using all measures available in Scenario 1 with the

exclusion of electric vehicles because they would require significant government intervention to encourage their take-up, and advances in technology to overcome the limitations. This option could therefore be considered as requiring less government intervention than Scenario 1.

4. Maximum CO_2 savings but no long-haul electric vehicles – as electric vehicles tend to show the most significant CO_2 reduction, this option allows them to be used in an urban and regional environment, but excludes the more problematic long-haul option. Improved battery technology, or the electrification of roads to enable freight vehicles to travel longer distances, are still being investigated and are some years away from reality.

Vehicle trends

There are a number of trends which can be used to support the business-as-usual trajectory. At vehicle level these include the adoption of the latest Euro standards, reductions in aerodynamic drag, reduced rolling resistance and the uptake of alternative fuels. At an operational level the logistics trends address vehicle-fill.

It is noteworthy that the latest Euro standards for HGVs prioritise air quality over carbon reduction and have therefore contributed little to the reduction of CO_2. In contrast, the uptake of some aerodynamic interventions has been significant (possibly, because reductions in aerodynamic resistance improve fuel consumption and reduce costs). However, there has been no equivalent increase in the adoption of measures to reduce rolling resistance (by switching to low resistance tyres) and light-weighting (by using novel materials) as these face some cost barriers.

The previously accelerating uptake of dual-fuelled vehicles through aftermarket modifications has been arrested because of clearer evidence of unburnt methane emissions. This contrasts with the uptake of grant-qualifying electric vans (the acceleration of all non-grant-qualifying electric vehicles has also abated, probably due to cost barriers).

Operational trends

Information and communication technologies (ICT) continue to play an important part in fuel-efficient routeing of vehicles and capturing driver behaviour to define more effective driver-training approaches. These continue to provide significant opportunities for improvement.

Although there is a strong logical argument to use higher capacity vehicles to reduce the overall amount of kms driven, the adoption rate for double-deck trailers has fallen. This may be a consequence of the special facilities required to accommodate these vehicles and the extension of the longer semi-trailer trial, which offers an alternative pathway for higher vehicle capacities. Compared to other countries the regulations on weights and dimensions continue to constrain potential improvements in logistics efficiency in the UK

As for higher capacity vehicles, it should be noted that empty-running remains stubbornly high, although vehicle-fill has marginally improved.

The need to improve air quality is resulting in the introduction of low-emission and ultra-low-emission zones. These use Euro standards to restrict the types of vehicles permitted to operate within the zones. Although the Euro standards for HGVs have challenging air quality thresholds they do nothing to reduce the CO_2 emissions.

Possible solutions

Although there are many interventions which can be economically adopted it is clear that, to establish an 80% reduction in CO_2 emissions by 2050, there will need to be a significant adoption of alternative fuels and, ultimately, the alignment of road freight with the broader efforts to decarbonise electricity supply. It is therefore not surprising to find that the electrification of freight features strongly in this report.

Electrification of freight presents significant challenges as freight transport is primarily concerned with the movement of heavy loads over long distances. Some of the solutions proposed for passenger transport do not work as well for freight.

The challenges of electrification highlight the importance of increasing the efficiency of freight operations, and the report identifies several approaches to increasing freight efficiency. These include the reorganisation of freight to embrace collaborative planning and operationalisation of freight operations. More specifically, efficient logistics will be enabled by urban consolidation centres, reconfiguring the supply chain and the development of collaborative ICT platforms.

Important interventions include:

- Electrification of road freight vehicles using a decarbonised electricity supply.
- Standardisation and sharing of logistics data to accelerate collaboration between organisations, thereby improving logistics efficiency and consequently reducing CO_2 emissions.
- Telematics-informed driver-training will continue to play an important role in reducing carbon emissions from road freight.
- ICT-based solutions such as dynamic vehicle routing and congestion predication will reduce the negative impact of congestion.
- The relaxation of time constraints may go against current trends in service-based competition, but have been shown to offer significant efficiency improvements.
- Changes to weights and dimensions regulations would permit the use of higher capacity vehicles and increase logistics efficiency.
- Despite the widespread adoption of over-cab fairings, aerodynamic improvements continue to offer significant opportunities to improve fuel efficiency.

Prioritising technical interventions

Scenarios were developed that reflected a number of assumptions.

Scenario 1: assumes investment will be made that prioritise CO_2 reduction over investment criteria. This scenario allows for the adoption of electric vehicles.

Scenario 2: assumes that only interventions which are financially acceptable (three-year positive NPV and payback) are adopted.

Scenario 3: assumes investment will be made that prioritise CO_2 reduction over investment criteria, but with no electric vehicles.

Scenario 4: assumes investment will be made that prioritise CO_2 reduction over investment criteria but excludes long-haul electric vehicles.

Only Scenarios 1 and 4 provided a pathway to achieving a reduction in CO_2 emissions by more than 60% by 2050 (Scenario 1: 62%; Scenario 2: 61%). In both these scenarios, alternative fuels made the most significant contribution to the CO_2 reductions. In this context, the electrification of road freight and, in particular, articulated trucks on long-haul journeys made the biggest contribution.

Roadmaps

Roadmaps for both logistics and technical interventions were developed through a process of focus groups and workshops. The roadmaps identify the research/policy activity required to enable/facilitate the technical or operational interventions specified in the report. The research and policy is then scheduled and sequenced to secure the required adoption rates.

Enabling/facilitating research included:

- making the case for LHVs;
- understanding how self-organising logistics systems using the Internet of Things (IoT) should be designed;
- specifying a Battery Electric Vehicle (BEV) charging infrastructure;
- understanding and ultimately specifying overhead electricity supply systems.

Enabling/facilitating changes to regulations included:

- regulations to facilitate increased urban access for off-peak deliveries;
- the re-prioritisation of land use to facilitate the development of urban consolidation centres;
- regulation to cover methane slip in dual-fuel vehicles.

Enabling/facilitating infrastructure or other technical measures included:

- the development of a decarbonised electricity supply;
- the IoT/sensorisation of vehicles to enable the reorganisation of logistics.

Trends

Background

This section of the document outlines the trends for CO_2 emissions resulting from road freight. The analysis is based on the descriptions of the national fleet contained in the *Continuous Survey of Road Goods Transported for 2015* and provides a profile of the UK fleet of heavy goods vehicles by aggregated type and segmented by industry. The data contains three key descriptors:

1. tonne-km travelled;
2. km travelled;
3. the amount of fuel used.

This section also details the relationship between road freight and other factors such as GDP, empty-running, and vehicle-fill.

Fleet profile

In order to prioritise interventions it is first necessary to understand what types of vehicles are being used to carry out which functions. In broad terms the fleet can be divided into three categories of vehicles:

1. small rigids usually deployed in an urban delivery environment;
2. large rigids usually deployed on either regional or urban delivery tasks;
3. articulated trucks usually deployed on long-haul journeys.

The profile of the fleet, expressed as different vehicle types, is summarised in Figure 1.

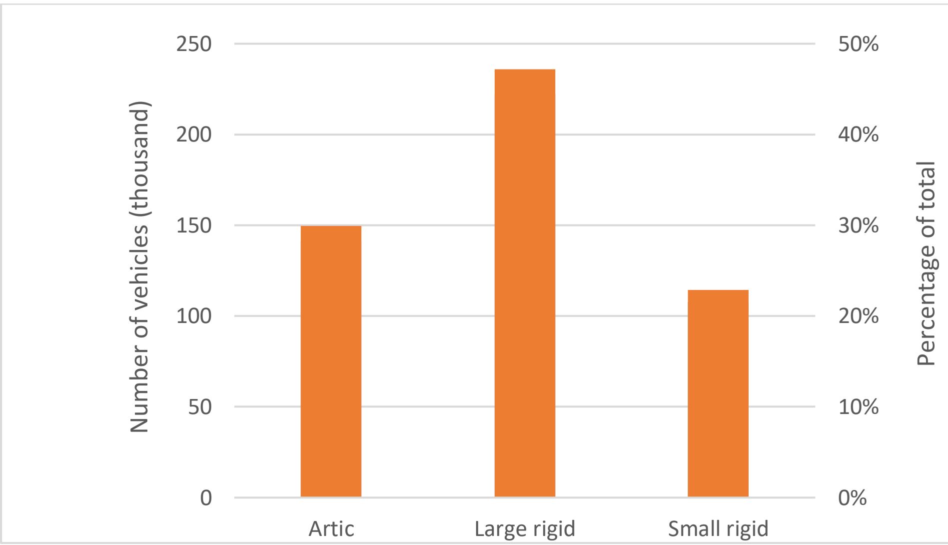


Figure 1: Fleet profile by vehicle type (DfT, 2017c)

It is not surprising to find that large rigids represent the biggest single proportion of the fleet, as this type of vehicle is deployed in all three logistics functions (long-haul, regional and urban distribution).

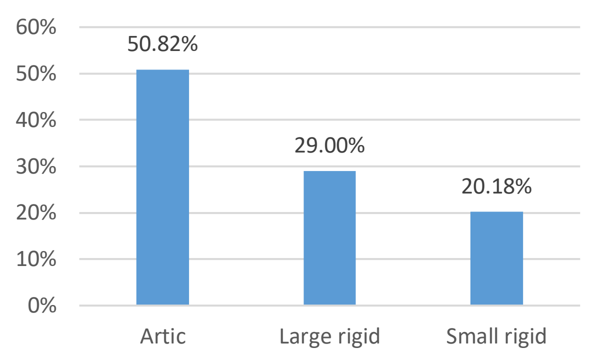


Figure 2: Proportion of kms travelled by vehicle type (Dft, 2017c)

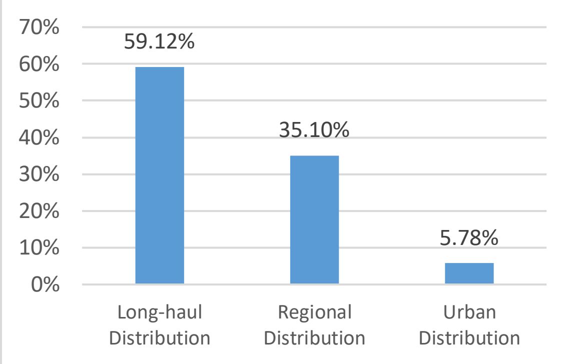


Figure 3: Proportion of kms travelled by logistics task (Dft, 2017c)

However, this does not mean that large rigids necessarily travel the most km. Figure 2 describes the breakdown of km travelled by type of vehicle whilst Figure 3 summarises the number of km travelled by each logistics task. Articulated trucks account for 50% of the km travelled in the UK and, as these trucks are less fuel-efficient than the smaller trucks, these vehicles account for 55% of CO_2 emissions. Although articulated trucks are largely deployed on long-haul journeys, similar journeys are also undertaken by some of the larger rigid vehicles, which explains why almost 60% of km travelled are on long-haul journeys.

In 2014 passenger traffic (car, taxis, vans and buses) amounted to 788 billion kms compared to just 24 billion kms for HGVs, and 67 billion kms for commercial vehicles and vans.

It is also useful to have a sectoral understanding of the tonne-km travelled (see Figure 4). The CSRGT data (at a high level) examines 5 sectors. The three largest sectors are ‘food products, including beverages and tobacco’, ‘metal, mineral and chemical products’, and ‘products of agriculture, forestry, raw materials’ (DfT, 2018). Between them, those 3 sectors amount to at least 63% of tonne-km moved (DfT,2018).

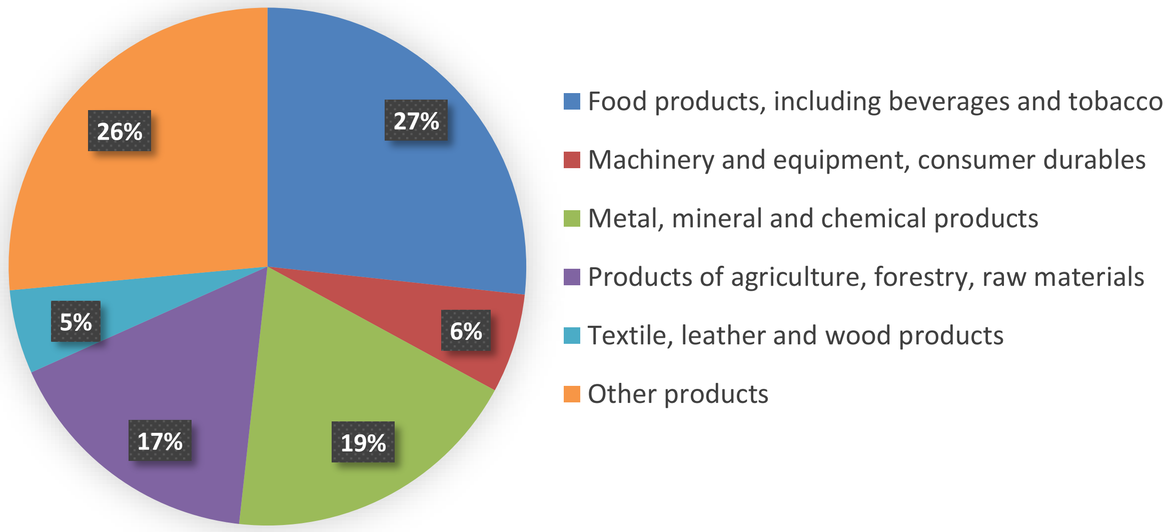


Figure 4: Tonne-Kms travelled by sector, (DfT, 2018)

Fleet profile key facts

For all the km travelled by domestic road freight in the UK:

- Articulated trucks account for 50%;
- Long-haul journeys account for 60%;
- The 3PL sector accounts for 50%.

Analytical framework

McKinnon et al. (2014) developed a framework (TIMBER) for the environmental appraisal of freight. This framework categorises the factors that affect freight's environmental efficiency. The TIMBER framework identifies six factors:

1. technology;
2. infrastructure;
3. market;
4. behaviour;
5. energy;
6. regulation.

These factors influence: modal split, utilisation, fuel efficiency, and available energy mix. This section will adopt the TIMBER framework to describe the current situation in terms of trends; the report then goes on to use the same framework to present various options which companies and governments can adopt to decrease CO_2 emissions.

Table 1: TIMBER framework*	
Technology	This includes advances in transport, warehousing and materials handling technology
Infrastructure	This is predominantly transport infrastructure comprising networks and terminals and covering all the main transport nodes, but can also include energy and communication infrastructures
Market	Changes in the structure of the logistics service market, the way logistics services are traded and the nature of the demand for those services
Behaviour	This applies industry and employee levels and includes driver-training and certification programmes
Energy	Comprising the nature of electricity generation, the availability of alternative fuels and the carbon intensity of the range fuels used
Regulation	At multinational, national and local levels. This can include construction and use regulations on trucks, regulatory controls on the road haulage industry and restrictions on vehicle access at particular times of day. It can also be extended to cover fiscal policy measures

*(McKinnon et al., 2014)

Trend analysis

Trend analysis gives a sense of the direction of travel and helps to identify potential barriers to progress. It also helps to identify trends of particular significance thereby directing policy and interventions designed to secure carbon-reduction objectives.

Technology

There are two aspects to the consideration of technology, the first focuses on vehicle technology while the second focuses on out-of-vehicle technology such as route-planning and congestion-avoidance.

Euro standards (power train)

The demographics of the UK fleet describe a steady increase in Euro VI vehicles at a pace determined by the vehicle replacement rate, which is approximately every seven years.

The Euro VI standard does little to reduce carbon emissions as the regulatory focus in HGVs across the Euro V and VI standards has been to reduce air quality pollutants and not CO_2.

Figure 5 summarises the profile of the fleet as described by Euro standards. It should be noted that the statistics do not allow disaggregation of rigid vehicles into large and small rigids as per the fleet profile presented in Section 2.1.1.

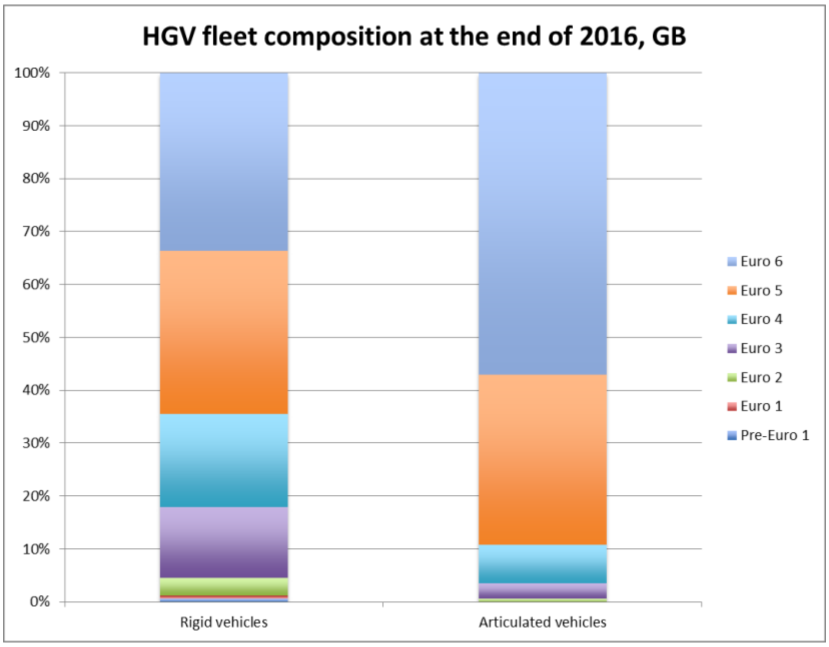
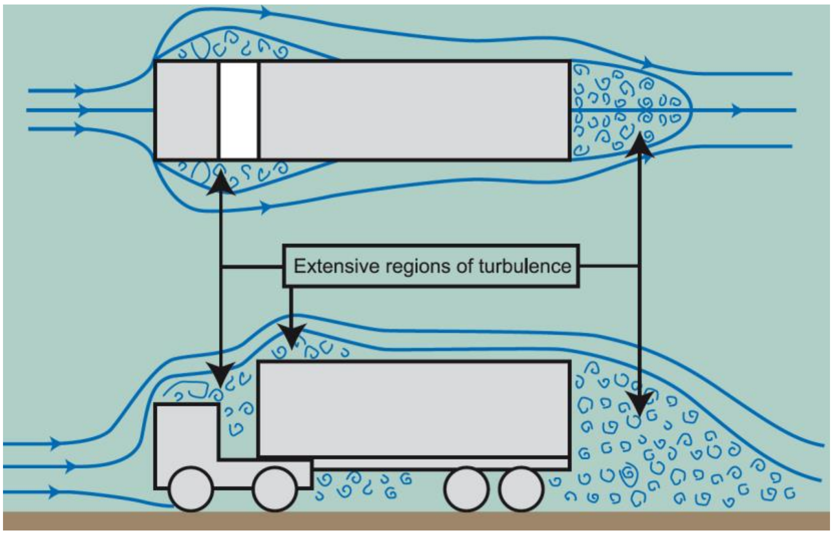


Figure 5: Fleet Composition by Euro standard (source: derived from TREMOVE[1] model)

Figure 5 clearly shows that the Euro VI standard has penetrated the articulated vehicle market more than the rigid vehicle market. This is of particular interest, as we already know there are more rigid vehicles than articulated vehicles in the overall UK fleet profile. However, the articulated vehicles travel approximately the same number of kms as the combined rigid fleet.

[1] More detail can be found out about the TREMOVE model at http://www.tremove.org/.

Aerodynamics
Some aerodynamic interventions can be specified at purchase. However, many organisations operate several trailer configurations to suit varying logistics demands; consequently many aerodynamic improvements are aftermarket interventions. The majority of aerodynamic improvements to HGVs have been delivered through the aftermarket. As long ago as 2006 the Freight Best Practice Survey[2] established that almost 90% of vehicles had cab roof deflectors and air dams. Figure 6 summarises the aerodynamic properties of a truck.



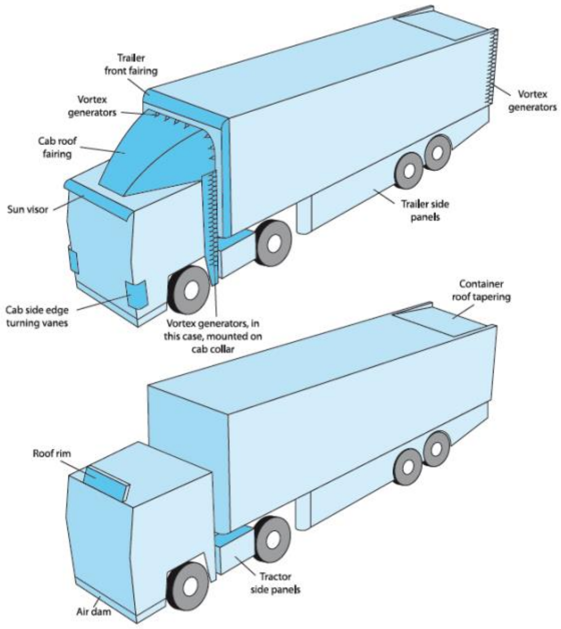
Source: DfT, (2010)

Figure 6: Aerodynamic properties of a truck

Although over-cab aerodynamic kits have been widely adopted by the sector, side skirts, boat tales and aerodynamic interventions between cab and trailer are less widespread (MJ Bradley and Associates, 2012).

Figure 7 summarises the types of aerodynamic improvements that can be incorporated into HGVs of all categories.

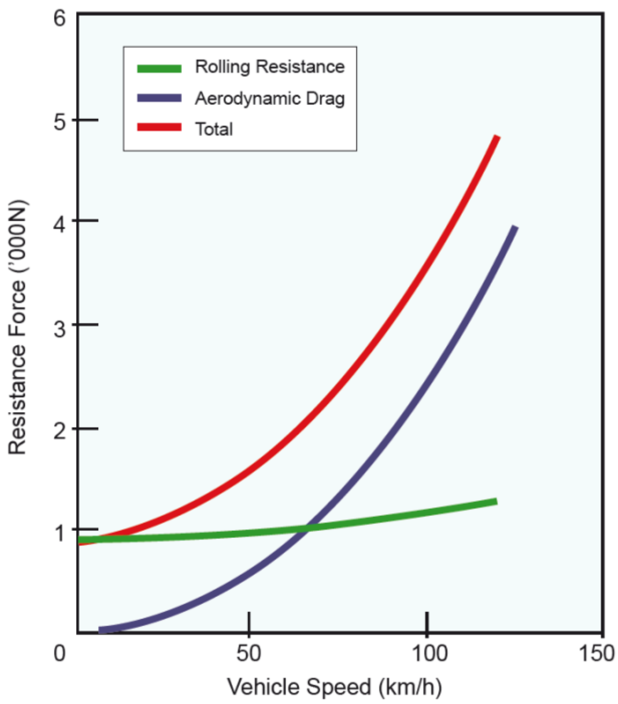
[2] http://www.freightbestpractice.org.uk/index.html



Source: DfT, 2010

Figure 7: Aerodynamic improvements

While it is possible to fit aerodynamic improvements to all vehicles it should be noted that not all vehicle functions are suited to aerodynamic improvements. Aerodynamic improvements are only of benefit if speeds of over 50 km an hour are commonplace. This constraint tends to rule out the application of aerodynamic improvements in urban logistics environments, but they remain suitable for long-haul and regional distribution activities. Figure 8 summarises the resistance force experienced by the vehicle for various speeds and clearly illustrates how aerodynamic resistance increases with speed, whereas rolling resistance varies little with speed. Aerodynamic improvements continue to be significant in contributing to the reduction of carbon emissions at speeds in excess of 50 km/h.



Source: MJ Bradley and Associates, 2012

Figure 8: Variation of resistance forces with speed

Dual-fuelled vehicles

Dual-fuel vehicles utilise both diesel and methane fuels. The methane component of this fuel mixture produces less CO_2 per unit of energy generated (Cluzel and Hope-Morley, 2015). However, methane has a global warming potential 237 times greater than CO_2 and any unburnt methane emitted from the tailpipe will significantly reduce the benefit of combining these fuels. Work carried out by the Centre for Sustainable Road Freight (CSRF)[3] showed that aftermarket catalytic abatement methods for dual-fuel vehicles failed to remove all unburnt methane and meant that, in all cases, dual-fuel vehicles emitted more CO_2 equivalent exhaust gases than did pure diesel engine vehicles.

Recent surveys have shown that there is no acceleration of uptake from the industry of dual-fuel vehicles (Cluzel and Hope-Morley, 2015). However, it should be noted that pure methane-fuelled spark ignition engines are unlikely to produce the same proportion of unburnt methane and may present a pathway to reducing CO_2 and CO_2 equivalent emissions.

Other technologies

Fleet management software is primarily designed to demonstrate compliance with maintenance and driver hours regulations (Perego et al., 2011). However, these technologies have been used to increase the impact of driver-training through driver-monitoring. The collected data is used to identify driver behaviours that can be improved

[3] http://www.csrf.ac.uk/

through training, as well as providing evidence-based feedback to the drivers in debriefing sessions.

Fleet management software packages are commonly used by medium and large operators to track compliance and provide feedback for driver-training.

Transport management systems and routing software provide planning platforms for the most efficient utilisation of vehicle capacity for the longest period of the journey (Mason et al., 2003). These systems are designed to identify the most efficient combination of load and route within logistical constraints such as delivery times and restricted access.

These packages are typically deployed within a company's Enterprise Resource Planning (ERP) business systems management suite and do not normally accept resource availability from other organisations (Marchet et al., 2009; Perego et al., 2011). Recently there has been a spate of research activity to identify the potential benefits of organisations sharing data and platforms for the purpose of planning loads and journeys.

Freight exchanges are third-party platforms that provide spot markets for operators to advertise surplus capacity and backhaul opportunities (Föhring and Zelewski, 2015). These platforms provide a useful service to small operators by enabling more efficient vehicle utilisation than would otherwise be possible.

The range of ICT platforms for logistics planning and execution continue to play an important role in reducing kms travelled and therefore CO_2.

Rolling resistance

The adoption of super singles[4]/low resistance tyres to reduce the rolling resistance of the vehicle has been inhibited by cost and concerns over increased tyre wear and pavement erosion (MJ Bradley and Associates, 2012). Super-single tyres can be used to replace dual tyres thereby reducing rolling resistance and weight.

The trade-off between the benefits of reducing the rolling resistance of the vehicle and the increased costs associated with the operation of modified vehicles (e.g. tyre failure will immobilise the vehicle) suggest that, in the current regulatory environment, the uptake of this technology will continue to be limited.

Light-weighting

The Centre for Sustainable Road Freight considered two case studies for the implementation of light-weighting strategies.

The first found that weight proved to be the limiting load constraint for double-deck trailers. By replacing subcomponents with lightweight replacements the study showed that an additional one tonne of payload could be carried. Despite the increase in payload, the

[4] Super singles are 17-inch wide tires that have a load rating equal to or greater than a pair of conventional 22.5. Compared to traditional tyres, super singles free up 200 pounds per axle (Lyseng, 2010).

vehicle would still have significant spare volume capacity, and the study noted that changes to the axle configuration would increase the payload further.

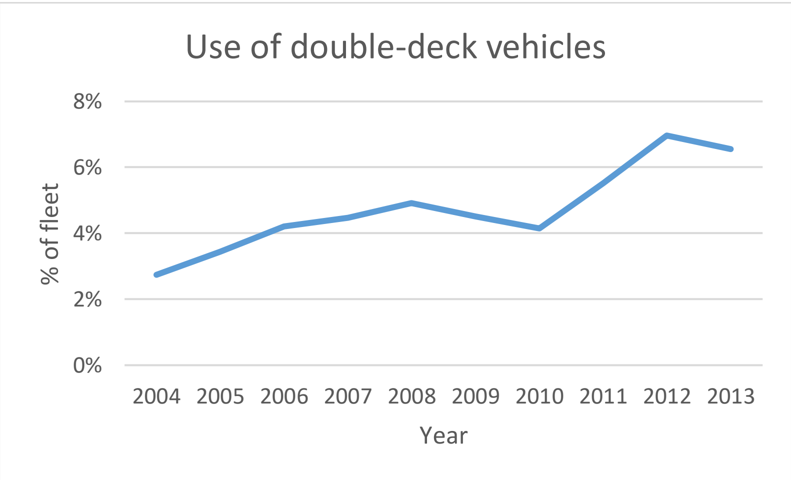
The second case considered the light-weighting of a single-deck trailer. In this case the study found that volume was the prime loading constraint. Inevitably, any light-weighting did nothing to increase the volumetric capacity of the vehicle and therefore no extra cages could be carried.

Light-weighting will therefore be of most benefit for commodities that are typically weight constrained, whether they be in single or double-deck trailers. However, weight constraints are likely to be more significant in the loading of double-deck trailers given their increased volumetric capacity.

Double-deck trailers

Double-deck trailers provide a useful way of increasing the volume capacity of articulated vehicles. There are two types of double-deck trailers, the first externalises the material-handling equipment; using lifts within the warehouse to raise pallets to the upper deck. The second deck management approach uses mechanically movable decks within the trailer to raise and lower the upper deck.

Figure 9 records the uptake of double-deck vehicles between 2004 and 2013 and shows an increasing appetite for this innovation (Dft, 2014). However, it should be noted that there was a small downturn in the adoption of double-deck trailers in 2013 and that there is no data available to describe the uptake between 2013 and 2018.



Source: Dft, 2014

Figure 9: Use of double-deck vehicles

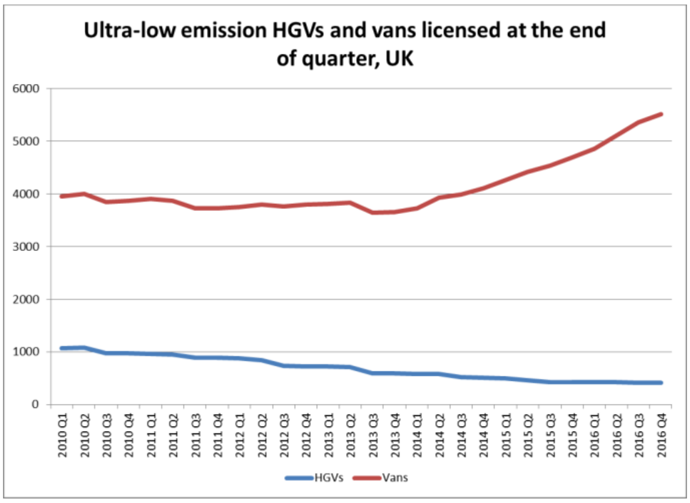
Fuels

Emergence of gas

Biomethane for transport can be produced from landfill and anaerobic digestion (AD) of wastes (Patterson et al., 2011). The AD plants can use a variety of wastes such as food wastes, commercial and industrial waste, crops, agricultural materials and sewage sludge digestion. Utilisation of biomethane can reduce well-to-wheel greenhouse gas (GHG) emissions significantly if sourced from waste products (Patterson et al., 2011). The biomethane produced can be injected into the gas grid and the plants can benefit from fixed income per kWh under the Renewable Heat Incentive (RHI) in the UK (Patterson et al., 2011). At the moment, the Renewable Transport Fuels Obligation (RTFO) provides Renewable Transport Fuel Certificates (RTFCs) to incentivise suppliers producing renewable fuels in the transport sector (DfT, 2017b). The suppliers of renewable fuel can claim RTFCs for every kilogram of biomethane supplied (DfT, 2017b). However, there is little incentive for this in the transport sector as the reward offered by RTFO is lower than the RHI (DfT, 2017b). Therefore, suppliers are better off supplying biomethane to other sectors in the UK.

Electric

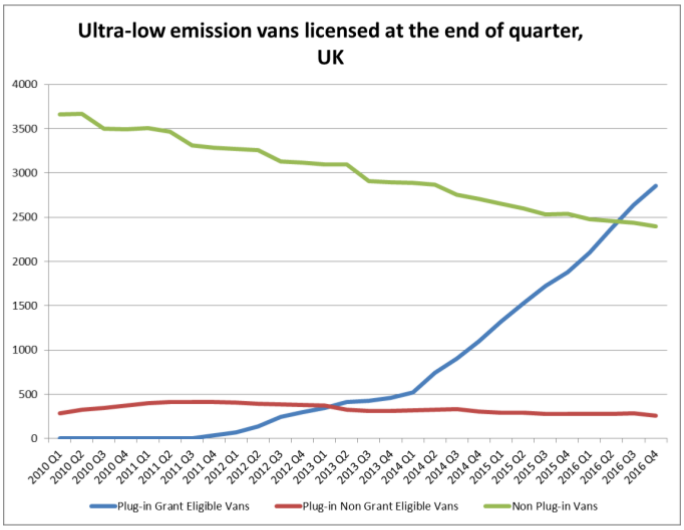
The uptake of electric commercial vehicles has been dominated by the increased adoption of ultra-low emission vans in contrast to the marked decrease in the adoption of ultra-low emission HGVs. These trends are summarised in Figure 10.



Source: DfT, 2017d

Figure 10: Ultra low emission registered vans and HGVs

One potential explanation for this observation is the marked increase in vans being licensed that are eligible for the plug-in grant subsidy. Figure 11 shows how this increase contrasts with the decrease in other ultra-low-emission vans, which include gas fuelled, and non-grant eligible electric vans.



Source: DfT, 2017d

Figure 11: Ultra low emission van registrations by type

Battery and hydrogen technologies

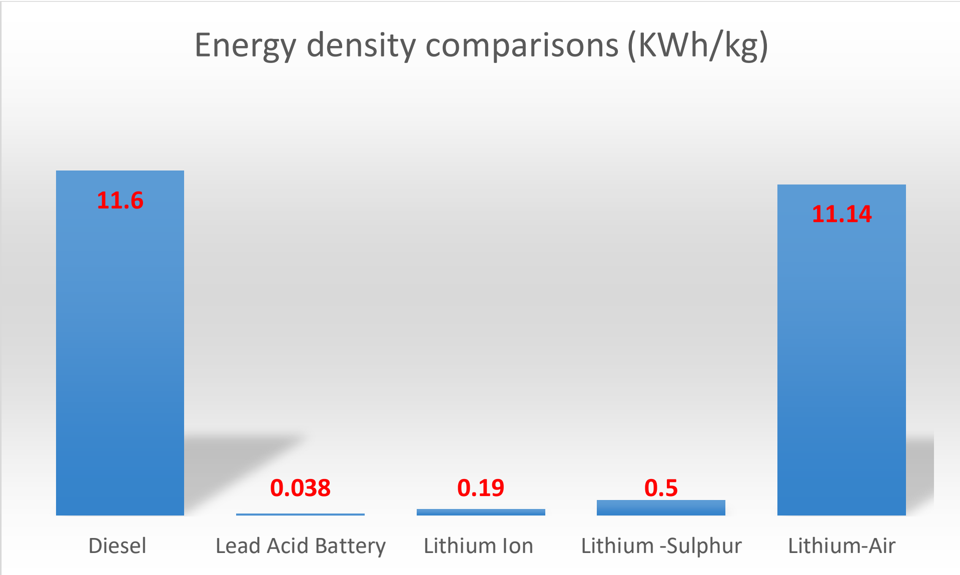
Battery technology

The main trend in battery technology is the improvement usefully measured as the increase in energy density (Nykvist and Nilsson, 2015).

A major barrier to battery technologies and their application to freight tasks is the extra weight necessary to deliver equivalent performance to diesel fuel vehicles (Herron, 2017). The increased weight of batteries using the most current battery technology will mean that the payload of a typical articulated truck would be significantly reduced. This implies an increase in vehicles and km travelled, with obvious impacts on congestion.

> ‘Based on the figures recently presented by Tesla for their electric truck, a range of 800kms will have an energy consumption of 1.25kWh/km requiring 1000 kWh of energy: in practice a 1300 kWh battery. Suitable lithium-ion batteries for electric vehicles cost £107/kWh today and are expected to fall to £70/kWh by 2021. This suggests a 2021 battery cost of £93,000.
>
> The specific energy of lithium-ion batteries is 0.1 kWh/kg – 0.25 kWh/kg. So the weight of a 1300 kWh battery will be between 5.2 and 13 tonnes which will significantly reduce the available payload of a typical truck.’
>
> Professor David Cebon (Director of the Centre for Sustainable Road Freight)

However, recent research has shown that the energy densities of batteries is increasing, thereby reducing the weight of batteries needed. Furthermore, recent research has identified new battery technologies such as lithium-air (Pan et al., 2018) that have similar energy densities to diesel (see Figure 2). Moreover, a recent study has also suggested that the cost of batteries for electric vehicles has been dropping rapidly (Nykvist and Nilsson, 2015), which could potentially increase the uptake rate of electric vehicles on road.



Source: Herron, 2017; May et al., 2018

Figure 12: Battery energy densities

Despite the advances in technology, the most likely application of batteries in road freight is likely to be in the urban environment (TfL, 2017a), which is currently dominated by electric vans for reasons previously discussed.

One of the advantages in using battery-driven vehicles is their inherent ability to act as a buffer or storage medium for the grid. This can then be used to manage peak demand as opposed to contributing to it.

Hydrogen technology

Hydrogen can be produced for use in hydrogen fuel cells in multiple ways. The most accepted method is methane reforming which can be achieved using steam methane reforming (SMR) technology or autothermal reforming (ATR) technology. These technologies can produce hydrogen by reforming natural gas. However, low-carbon hydrogen production may potentially need carbon capture and storage unless there is a plentiful supply of decarbonised electricity. Just by way of an example, the efficiency of generating hydrogen through ATR (80% efficient), transporting it (98% efficient), storing it in salt caverns (99% efficient) and then using it in a hydrogen fuel cell (60% efficient) to produce electricity has an overall efficiency of approximately 47% (Element Energy, 2018; Roland Berger, 2015).

Another way in which hydrogen can be produced is through electrolysis (Energy Research Partnership, 2016). The cost and feasibility of these technologies will determine their future usage.

Infrastructure

Congestion

Congestion is typically measured as the increase in travel time resulting from increased traffic. While this measurement is useful (TfL, 2016), it does not give any insights into how much more CO_2 is emitted because of longer journeys. The main insight into the impact of congestion comes from analysis of drive-cycle data comparing free-flowing traffic with congested traffic, which incorporates many more stops, starts accelerations and decelerations (TfL, 2016).

The drive cycles in congested traffic, without any interventions on the vehicles to capture and store kinetic energy, can be estimated to result in a 54% increase in CO_2 emissions (TfL, 2016). However, the stop-start nature of these journeys also yield opportunities to mitigate the negative effects by harvesting energy through kinetic energy storage systems (such as hydraulics, flywheel).

Carbon emissions from a small rigid vehicle have been shown to be 54% higher when operating under a congested drive cycle compared to the same vehicle operating under a non-congested drive cycle.

The impact of congestion can be contextualised by considering some of the descriptors of freight traffic in the London area. *Travel in London Report 9* (TfL, 2016) describes London traffic using some significant trends:

- **LGV traffic**: up 22% in Outer London[5] 2000 to 2015, 5% in Inner[6], 1% in Central[7] (16% overall in Greater London[8]).
- **HGV traffic**: fallen across Greater London 2000 to 2015, by 22% Central, 19% Inner, 1% Outer, and 7% Greater.
- **Number of licensed Public Hire Vehicles** has gone from 49K to 78K between 2008/9 and 2015/16.

This analysis broadly supports the congestion predictions produced by DfT and summarised in Figure 13. According to the DfT (2015), their scenarios 1, 4 and 5 estimate a positive and declining relationship between income and travel. Further, scenario 1 assumes average fuel costs, scenario 4 assumes high fuel cost and scenario 5 assumes

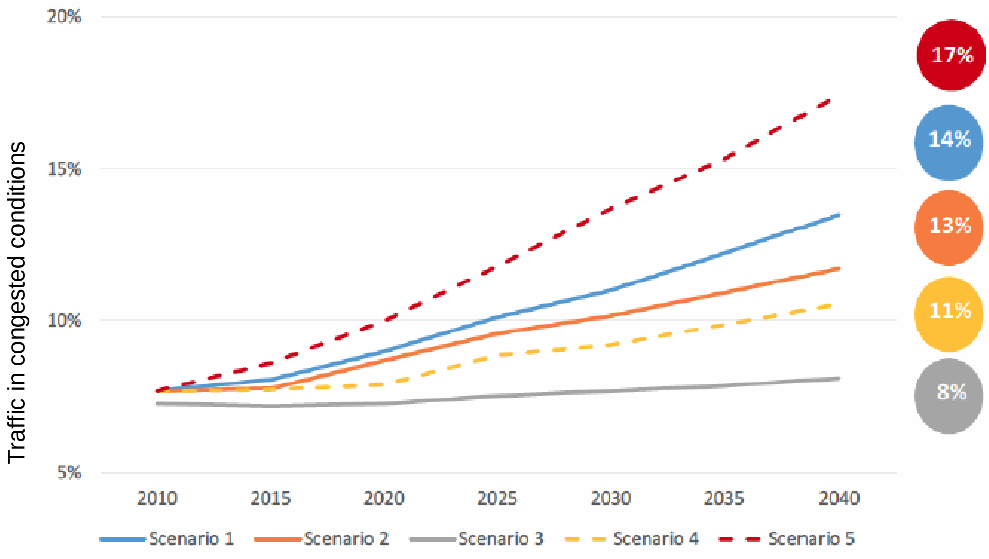
[5] Outer London is the group of boroughs that form a ring around Inner London. It contains the following boroughs: Barking and Dagenham, Barnet, Bexley, Brent, Bromley, Croydon, Ealing, Enfield, Haringey, Harrow, Havering, Hillingdon, Hounslow, Kingston upon Thames, Merton, Newham, Redbridge, Richmond upon Thames, Sutton and Waltham Forest.

[6] Inner London is the group of boroughs which form the interior part of Greater London and are surrounded by Outer London. It contains City of London and the following boroughs: Camden, Greenwich, Hackney, Hammersmith and Fulham, Islington, Royal Borough of Kensington and Chelsea, Lambeth, Lewisham, Southwark, Tower Hamlets, Wandsworth, Westminster.

[7] Central London is the innermost part of London comprising the boroughs of Camden, Islington, Kensington and Chelsea, Lambeth, Southwark, Westminster and the City of London.

[8] Greater London is the area made up of Inner London and Outer London.

low fuel cost. Scenario 2 removes the link between income growth and travel while assuming average fuel costs, and scenario 3 explores the impact of alternative assumptions for future trip rate.



Source: DfT, 2015

Figure 13: Proportion of traffic in congested conditions

Market

Relationship between GDP and freight activity

There is an established relationship between GDP growth and the freight activity (normally expressed as tonne-kms) (McKinnon, 1989). This relationship means that, as GDP grows, there will be a proportionate growth in freight activity.

More recent research has identified a potential de-coupling of this relationship (McKinnon, 2007) although others have drawn the relationship between the potential de-coupling and the economic downturn in 2010.

The obvious extension of an analysis of the relationship between GDP and logistics activity suggests that, as long as GDP grows, logistics activity will increase.

Behaviour

Empty running

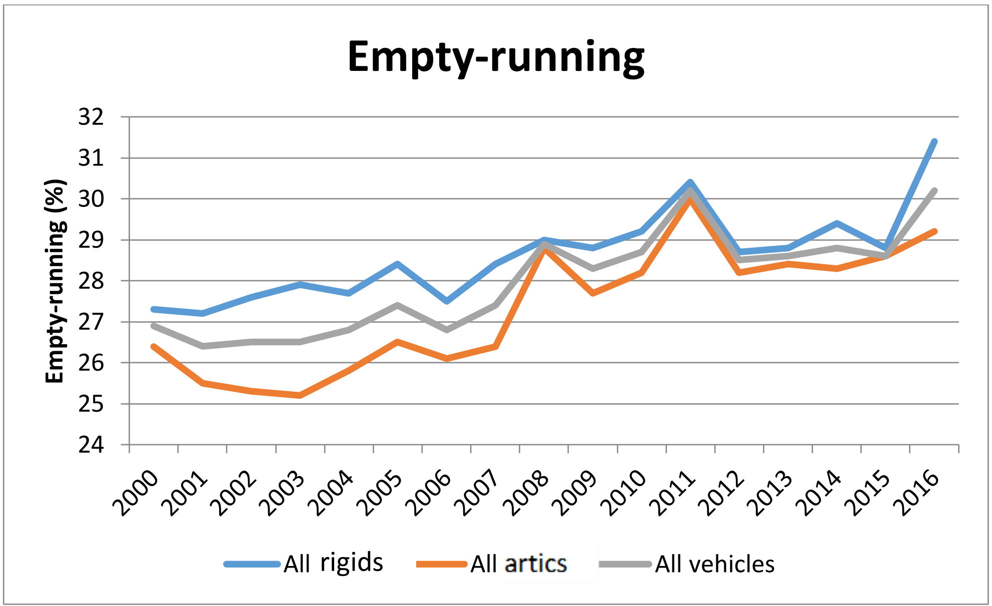
There are many factors (McKinnon and Ge, 2006) that explain the persistence of empty-running, these include:

1. trade imbalances;
2. organisational constraints (firm-centric organisation of logistics).

Trade imbalances are a reflection of the spatial distribution of economic activity, which is generally centred on either concentrations of population or the availability of raw material. The spatial distribution of activity is coloured by the import and export flows into and out of ports. An example of the imbalances in economic activity can be found in the flow of materials to and from Scotland. Scotland imports many of its materials and products from England, but exports most of its finished products through Scottish ports. This means that the road vehicles that are generally used for the movement of goods from England to Scotland have to return from Scotland empty.

It should also be noted that last-mile deliveries have a limited opportunity for backhaul (apart from the return of waste materials) as a result of domestic residences being located in areas remote from economic activity and, in particular, production (i.e. factories and warehouses).

Understanding the drivers of empty-running however, has not led to a decrease in empty-running. In fact, empty-running has increased recently, as summarised in Figure 14.



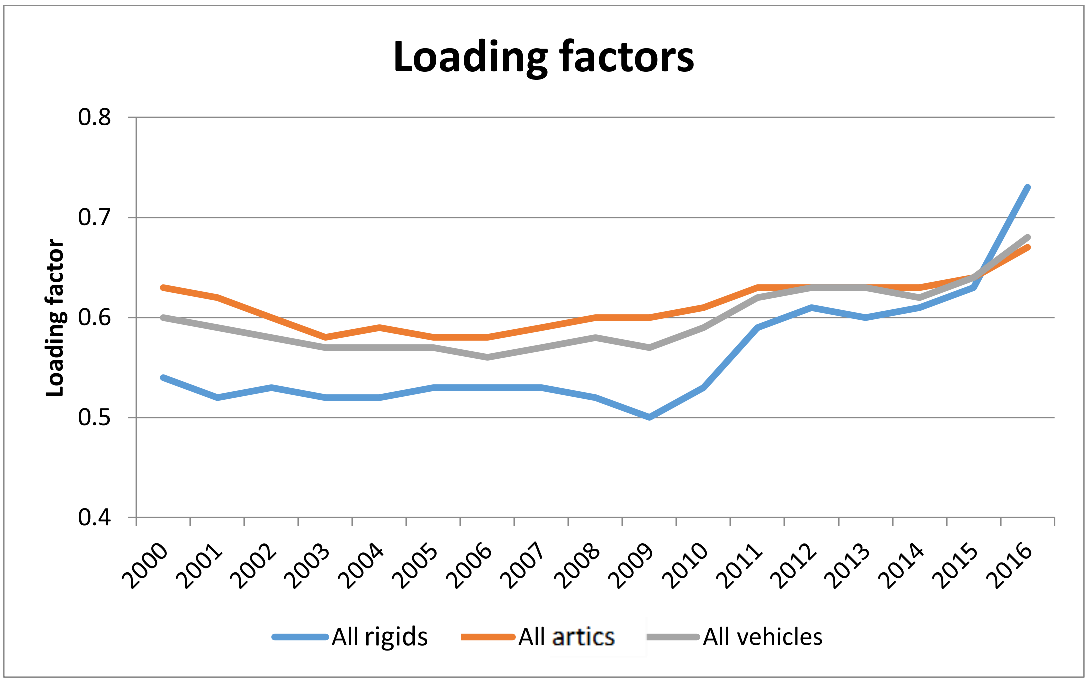
Source: DfT, 2016

Figure 14: Empty-running

Fill efficiency

Unfortunately the vast wealth of data used by companies for the organisation of logistics operations is not generally available and this has limited any research activity aimed at developing an understanding of poor fill factors (Morabito et al., 2000).

Indeed the lack of volumetric and weight data in transport and warehousing ICT systems inevitably drives inefficient packing and fill of vehicles (ACEA, 2010). Time constraints have also been shown to limit the company's ability to fill vehicles (Bushuev and Guiffrida, 2012). Restricted time delivery windows result in some vehicles not being filled to include other orders, as this would mean delivery time constraints could not be met. Despite this, the loading factor[9] on vehicles that are not empty has started to improve, as shown in Figure 15.



Source: DfT, 2016

Figure 15: Loading factors

The statistics in the UK show that 28.6% of vehicle-km are running empty and vehicles are utilised to only 63% of their weight capacity (DfT, 2016). In the last 10 years, the loading factor of vehicles has remained at an average of around 60% in the UK (DfT, 2016). At the same time, there are increasing efforts to lower carbon emissions and improve efficiency from logistics operations worldwide. Based on such circumstances, organisations have realised that collaboration - joint-planning, sharing of risks and access, complementary resources - has the potential to deliver long-term benefits such as reduced transaction cost and enhanced efficiency of their supply chain (Daugherty et al., 2006; Sandberg, 2007).

Horizontal collaboration is less common and defined as "*bundling transport of companies operating on the same level of the supply chain, who have similar or complementary transportation needs*" (Vanovermeire et al., 2014, p. 339). Potential benefits of this collaboration include cost and productivity benefits, asset-utilisation and better resource management. There is some evidence to suggest that horizontal collaboration is becoming more commonplace. For example, Kimberley Clark and Kellogg's have combined a number of transport operations and saved 430,000 vehicle-kms in a year (*Logistics Manager*, 2008). Similarly, the collaborative partnership between Brakes and Nestlé aims to improve vehicle utilisation, eliminate road miles and enhance efficiency of the transport network (IGD, 2015). The Institute of Grocery Distribution (IGD) and Efficient Consumer Response (ECR) have

[9] The amount of goods that were moved, as a proportion of the total amount of goods that the vehicle can move.

published some guides, case studies and best practices to support road freight collaboration in the UK (IGD, 2011).

More recently, advancements in ICT have enabled companies to develop collaboration opportunities. The online freight exchange platform and web-based electronic logistics marketplaces (ELMs) are supporting collaboration by analysing potential synergies among participating companies. The freight exchange platform is more popular among 3PLs due to the spot-trading nature of this system (Wang et al., 2015).

Driver-Training

Driver-training has been widely implemented across the sector and there are now fresh insights into best practice implementations. Research undertaken by CfSRF showed that refined driver-training could improve the CO_2 reducing benefits of eco-driver-training by as much as 20% (Greening et al., 2015).

This research found that the most successful elements of the eco-driver-training were regular eco-performance appraisals, carrying the trainings on the road and under supervision, giving de-briefs immediately and in cab, and regular refresher trainings.

Effective driver-training is closely linked to telematics and fleet management software, which is not widely implemented in the large proportion of the fleet that is run by is small owner-operators.

Regulation

Weights and dimensions

The DfT initiated a longer semi-trailer trial in 2012 (DfT, 2017a). This was designed to evaluate the impact of increasing the permissible semi-trailer length from 13.6m to 15.65m thereby increasing the footprint capacity from 26 UK pallets to 30. The trial addressed questions of safety, emissions, cost savings, externalised costs (more damage to roads) and how these trailers were deployed.

The trial has shown that, when operators used the vehicles predominately on routes where they could fill the vehicle in both directions, only 18% of journeys were empty, and saved between 15 and 18 million kms (representing 125,000–150,000 journeys).

Whatever the nuances of the operations considered, the trial has shown significant environmental benefits through the reduction of kms travelled and increased utilisation.

Emissions zones

Low-emission zones were first introduced in 2008 (TfL, 2017b). They are designed primarily to address air quality challenges, although they undoubtedly have resulted in pressures to upgrade the fleet as vehicles not reaching Euro IV are fined if they enter the low-emission zone (LEZ) (TfL, 2017b).

The introduction of ultra-low-emissions zones (ULEZs) has been accelerated because of a legal case prosecuted by ClientEarth (Morton et al., 2017). The ULEZs raise the threshold of vehicle Euro standards permitted to enter the ULEZ from IV to VI (Morton et al., 2017), and include vans in the regulation.

As noted in previous sections, the Euro standards for HGVs are primarily designed to improve air quality. Consequently, the impact of emissions zones on reductions of carbon emissions is minimal. However, there appears to be some second-order effects from LEZs and ULEZs. Specifically, LEZs encouraged faster investment in newer vehicles and the reorganisation of their activities for greater efficiency (Dablanc and Montenon, 2015; Allen et al., 2017).

The main climate change impact of ULEZs will be:

1. the reduction of traffic, in turn reducing congestion;
2. the accelerated uptake of ULEVs (such as electric vehicles);
3. the reduction of unregulated van based freight (if enforced).

The ULEZ *Consultation Report to the Mayor – Impact Assessments* estimates that this will result in a 15% reduction in CO_2 emissions (TfL, 2017b).

Possible solutions

There are a range of ways to reduce CO_2 emissions from road freight. These include increasing vehicle-fill, increasing fuel efficiencies, and the use of alternative fuels.

The report will present several options that could have a positive impact on CO_2 emissions. Going through the report, we discuss some of the key options and their impacts. At the end of the report, these are drawn together into scenarios, showing the impact that the combination of these options will have on CO_2 emissions.

Operational interventions

Backhaul, load consolidation, and collaboration

It has been argued that there are two fundamental reasons why empty-running is not decreasing, despite the obvious focus of organisations on increasing their logistics efficiency. Firstly, there are fundamental trade imbalances within the UK, which mean that trucks travelling from the south (the source of most freight) to the north are full. However, there is little trade in the opposite direction, meaning that those vehicles returning from the north travel empty. Secondly, organisational constraints work against the sharing of information and assets, which would otherwise facilitate collaboration.

The trends in loading factors show that journeys which are not empty still have significant spare weight or volume capacity. Again, one reason for this is the constrained pooling of information on the planning and organisation of logistics. This is due to the many different private companies working in different bits of the supply chain.

Improvements in backhaul and loading factors could be achieved if data and journey information were pooled across multiple organisational boundaries. The availability of information could be confined to collaboration between organisations or, alternatively, improvements could also be achieved through a more widespread adoption of freight exchanges.

In the medium-to-long term, the increased connectivity and sensorisation of vehicles could move the default logistics planning position from being company confined to being sector confined. Such a move would require the standardisation of data and the development of electronic automatic transaction recording, similar to that used in many distributed ledger protocols.

Driver-training and telematics

Driver-training is widely acknowledged to be one of the most cost-effective means of reducing fuel consumption and CO_2 emissions in the road freight sector. Drivers undergoing training as part of the government-sponsored SAFED programme have, on average, managed to improve the fuel efficiency of their driving by around 7%. The percentage saving that an individual company can achieve will depend on factors such as the calibre of the drivers, the nature of the delivery operation and age of the fleet; and so generalisation is difficult. There is, nevertheless, general agreement that driver-training must be accompanied by monitoring, debriefing, publicity and incentive schemes to ensure that the ‘eco-driving’ practices get embedded after the training period.

Telematics provide an important source of driver performance data and should be used to identify conditions under which performance is lower than expected, as well as driver-training requirements.

It is estimated that engine idling while the lorry is stationary typically wastes 3-5% of fuel. The experience of four companies that have run anti-idling campaigns, including monitoring and driver advice / training specifically on idling, was outlined by the Freight Best Practice programme (Freight Best Practice and DfT, 2008).

Real-time driver feedback systems provide dynamic feedback to drivers on current operating conditions. This can include systems such as acceleration/deceleration feedback, active accelerator pedals, shift advisors and miles-per-gallon gauges.

Driver-training can deliver between 5-13% reductions in CO_2 emissions (Greening et al., 2015).

Congestion prediction and avoidance

The ability to use big data analytics, which draw on new data sources to predict congestion, permits the possibility of dynamically re-routing vehicles, avoiding congestion and significantly reducing carbon emissions.

Such approaches are in the early stages of development but will be dependent on new data sources and the development of new ICT platforms. However, this development trajectory is aligned to the development of autonomous vehicles and, as such, is likely to attract significant research resources.

Relaxation of time constraints

Recent research by CfSRF, enabled by the availability of large granular data sets, have enabled sophisticated high fidelity computer experiments to evaluate the effect of relaxing time constraints.

These experiments have shown that, as time constraints are relaxed, planning becomes more flexible and a one-hour relaxation can result in a 7% reduction in kms travelled, while a three-hour relaxation can yield of reduction of up to 22%.

Higher capacity vehicles

Double-deck trailers

A double-deck trailer has one deck above the other. Upgrading to double decks from a 33-tonne articulated lorry can increase its capacity from 85m^3 to 125 m^3, yielding a carbon reduction of between 18–22%. Despite this, the penetration of double-deck trailers in the trailer market remains less than 7%.

A more widespread adoption of double-deck trailers would in principle yield significant carbon benefits – although it should be noted that the 18-22% reduction would, at best, apply only to a restricted set of journeys. Journeys would have to begin and end at facilities that could accept these specialised vehicles and this might result in a reduced opportunity to backhaul.

Most double-deck box trailers in the UK have powered-decks which allow operators to lower and offload the top deck. The hydraulic system for the powered deck adds extra weight (3–4 tonnes approximately) to the trailer reducing its fuel efficiency. It is estimated that a trailer with a fixed second deck is around 3-4% more fuel-efficient than one with a powered deck, other things being equal. Double-deck box trailers with a fixed deck require external lifting gear at factories, warehouses and shops. Where space permits these can be installed quite quickly and, for some types of logistics operation, offer a good rate of return. Allowance must be made for the electricity used by the external lifting equipment and related CO_2 emissions.

Longer heavier vehicle trials

Since 2012, the Department for Transport has been running a longer semi-trailer (LST) trial (DfT, 2017a), which enables the use of semi-trailers two metres longer than the current standard. Monitoring of the trial is showing some encouraging initial results. Between 2012 and 2017, 1,775 LSTs have been used by 161 operators, with another 1,000 to be added in the next five years. By the end of 2016, the LSTs had travelled 319 million km. For 34% of that distance, the additional capacity was fully utilised and, for a further 50%, it was partially utilised. As a result, the LST trial has saved an estimated 15 to 18 million km of freight travel. Empty running, at 18%, was found to be lower than the national average. Accident rates were also lower, potentially due to the additional training given to drivers of LSTs. The reduction in distance travelled as a result of LST use varied between operators however, the highest savings were around 11.5%, which equates to one in nine journeys. The next stage of the trial will include specific estimates of carbon emissions reductions resulting from LST use. However, it is clear from the trial so far that LSTs can reduce vehicle km travelled and therefore save carbon emissions.

Increasing capacity across categories

The benefits of higher capacity vehicles is not constrained to the larger categories of vehicle. Increasing the capacity of all categories of vehicles will yield the opportunity of reducing the number of journeys and therefore the number of kms travelled. Table 2 summarises the benefits from increasing the capacity of smaller vehicle categories.

Table 2: Impact of increasing vehicle capacity*		
Measure	**Description**	**CO_2 reduction benefit**
From 3.5 to 7.5 tonne rigid	can increase the carrying capacity of vehicle from 1.6 to 3.1 tonnes	11-19%
From 7.5 to 17 tonne rigid	increase the carrying capacity of vehicle from 3.1 to 10 tonnes	11-14%
From 17 to 25 tonne rigid	can increase the carrying capacity of vehicle from 10 to 15.5 tonnes	8-12%
From 25 tonne rigid to 33 tonne artics	can increase the carrying capacity of vehicle from 15.5 to 25.5 tonnes	15-20%
From 33 tonne to 44 tonne artic	can increase the carrying capacity of vehicle from 25.5 to 29 tonnes	4-8%
From 33 tonne artic to European Modular System	can increase volume from $85m^3$ to $158m^3$	12-17%
From 33 tonne artic to double-deck trailers	Double-deck trailers allows combination of two identical standard semi-trailers, a tractor and a converter dolly; can increase in volume from $85m^3$ to $180m^3$	18-22%

*Source: Authors' calculation

Technical interventions

Rolling resistance

Low rolling resistance tyres

Low rolling resistance tyres reduce fuel consumption without reducing road grip. The carbon reduction benefit of these tyres is estimated to be between 1 and 5%.

Super-single tyres, which replace two narrower tyres on HGVs, have been available for over 40 years and are widely used. It is estimated that, because of their lower rolling resistance and lighter weight, they improve fuel efficiency by an average of 4–6%. Fitting super-single tyres to steering axles, however, tends to reduce fuel efficiency.

Tyre inflation

Research suggests that, if a tyre is 20% under-inflated, fuel efficiency drops by around 2%. Increasing the frequency of tyre pressure checks by drivers, preferably to a daily inspection, can yield significant fuel savings as well as extending tyre life and alerting drivers to other tyre problems (10% under-inflation can reduce tread life by 9–16%, while tyre problems are responsible for around a quarter of commercial vehicle breakdowns). Literature suggests that pressure of HGV tyres should be checked weekly and before any long deliveries.

Unsurprisingly devices for adjusting tyre pressure automatically have been found to yield fuel savings. These systems monitor the tyre pressure automatically keeping the tyres at optimal inflation.

Aerodynamic resistance

Aerodynamic interventions only apply to vehicles travelling in excess of 50 km/h, and as such they are not widely used for regional and urban logistics functions (Kopp, 2012). The biggest impact of these interventions is found on articulated lorries which are generally used on longer journeys involving substantial distances on motorways, dual carriageways or A roads.

Over-cab fairings are now the most widely adopted aerodynamic intervention for HGV freight vehicles. They can take the form of simple fixed angle-of-attack installations or the more sophisticated dynamic modification installations, which can be adapted depending on the trailer configuration.

More recently, research has been carried out on trailer aerodynamics including boat tales, side skirts and between cab and trailer. These interventions complement each other.

Table 3 summarises the CO_2 reduction benefits of the various aerodynamic interventions.

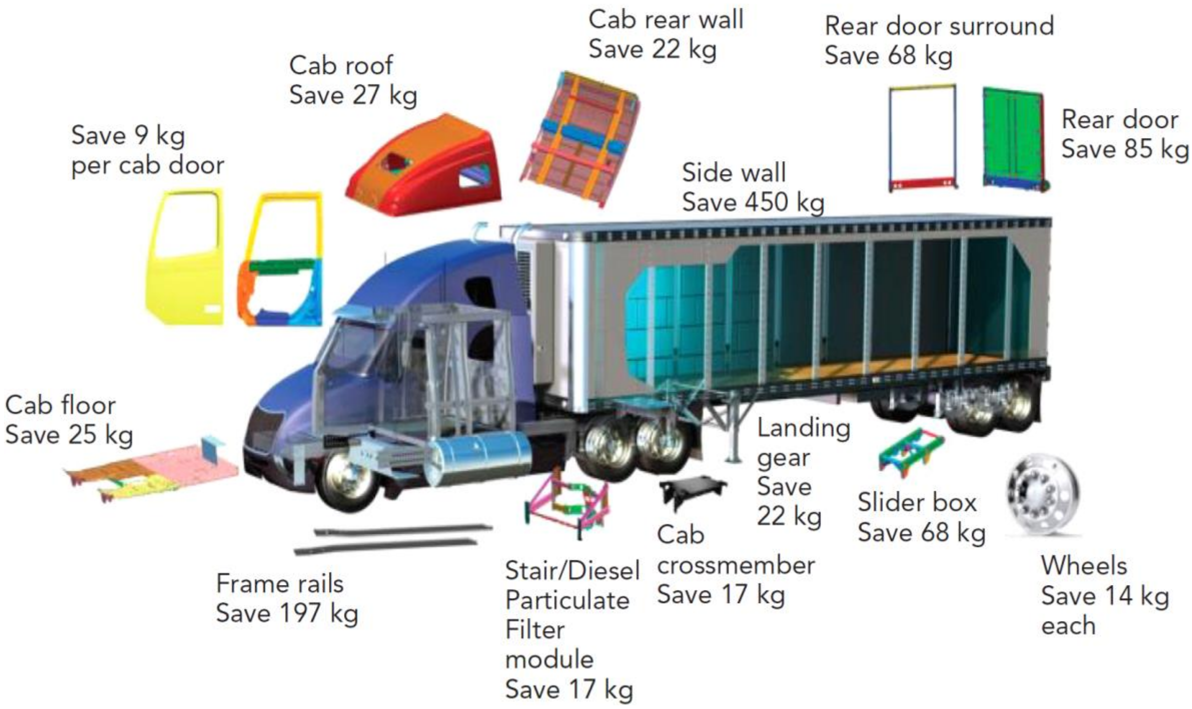
Table 3: Aerodynamic interventions	
Aerodynamic improvement	**CO_2 reduction**
Cab roof fairing	4–5%
Trailer side panels	3.4–6.4%
Side Skirts	3–7%
Boat tails	3–7%
Trailer sloping front roof	5–6%
Tear drop trailers	6%

Source: Centre For Sustainable Road Freight

Light-weighting

Light-weighting a vehicle reduces its fuel consumption (Hill et al., 2015). This can be done by removing unnecessary equipment from the vehicle and using lighter materials in the construction of the tractor and / or trailer. Greater priority can be given to tare weight[10] in the vehicle purchasing decision and full-life costing of new vehicles. 2–4%. Figure 16 shows the light-weighting opportunities on an American articulated vehicle. Although the opportunities may vary subtly when applied to a UK/European truck the diagram serves to illustrate the breadth of light-weighting application. The weight savings indicated in the diagram are due to switching to light-weight materials.

[10] Weight of an empty vehicle



Source: Adapted from Transportation Research Board and National Research Council (2010)

Figure 16: Light-weighting opportunities

It should be noted that the exact weight saved using the approaches described above would depend on the logistics function, task and sector being served. There is limited research on the potential fleet-wide benefits of light-weighting across the UK fleet.

Methane and biomethane

For the adoption of biomethane to become widespread in the UK, the availability of biomethane production and refuelling infrastructure is critically important (Ricardo-AEA, 2015). The transportation of gas from source to consumer will require pipelines or additional investment in road tankers for distribution. On the consumption side, additional investment is also required to purchase gas vehicles.

Electric vehicles

Batteries

A recent review of BEV technology by Andwari et al. (2017) found four main battery technologies currently in use, each with advantages and disadvantages in terms of energy density, cycle life, and safety. This results in a competitive battery technology market. These principal technologies are:

1. Lead acid, a mature low-cost technology with shorter lifespan and lower energy density;

2. Nickel metal hydride, a mature technology used in some hybrid vehicles but with an energy density considered too low for electric-only vehicles;
3. Lithium-ion, a technology with a number of sub-variants. Considered the most promising technology due to favourable energy density and longer lifespan than other battery technologies. However, there are cost and resource availability concerns;
4. Sodium nickel chloride, a low-cost and long-lasting technology which is not powerful enough (i.e. the speed at which it dissipates energy is too low) to power electric vehicles alone but could be used in combination with, for example, super capacitors.

Improvements in costs and lifespan can be achieved through battery management systems. Between 2007 and 2014, the estimated cost of vehicle batteries fell by 14% per year in an average of over 80 estimates (Nykvist and Nilsson, 2015) although variation and uncertainty around costs remain. As freight vehicles are larger and heavier than cars, battery weight and loss of loading space are critical issues, suggesting that the appropriate balance of battery technologies for cars and lorries may differ.

The precise benefits of electrification are dependent on the degree to which the electricity supply has been decarbonised. Whilst we appreciate the electricity supply will decarbonise going forward, as a conservative estimate, the figures presented in this report assume that the current carbon intensity of the electricity grid is maintained. The potential savings from the electrification of urban distribution under these conditions fall in the range of 60–65% reduction. If the grid is decarbonised at the forecasted rate, the savings are likely to reach 70–75%.

Overhead cables

Using overhead cables to deliver energy to the vehicle reduces the need for energy storage (Siemens, 2017). Siemens (see Figure 17) have developed a truck that uses catenary poles to connect the vehicle to overhead cables. The anticipation is that these highways will be implemented on key freight corridors and could deliver as much as 80% reduction in the carbon emissions from a long-haul articulated vehicle. The remaining 20% of carbon journeys would come from that part of the journey carried out on non-eHighway roads.

Source: Siemens, 2017

Figure 17: Siemens eHIghway

Several demonstrator projects have now been implemented across Europe. These include USA, Germany, Sweden, and the Netherlands. These projects have established feasibility, costs, and barriers to implementation.

Clearly, this solution requires new infrastructure, specifically overhead cables. The cost of this infrastructure is estimated to be £1 million per km. There are approximately 7,000 miles of suitable trunk roads in the UK setting the infrastructure costs of this approach at £7 billion.

Induction charging

Induction charging is one form of contactless charging. The vehicle batteries are charged using induction pads located in the road. This system operates at various efficiencies, which depends on the distance between the vehicle and the induction-charging pad. The most efficient solution will be one where the vehicle lowers a pad for efficient coupling with the pad embedded in the road surface.

This type of charging may be suitable for urban logistics as the vehicle has periods where it is stationary (notably while loading and unloading). The ability to fast charge at the beginning and end of a journey significantly reduces the need for energy storage and therefore maintains payload.

As with many electric vehicle solutions, induction charging will require significant infrastructure investment.

Hydrogen

There has been persistent concern about the economic viability of a shift towards a hydrogen-based energy economy, due to the scale of inefficiencies involved. Generation, storage, and movement of hydrogen all reduce its efficiency in comparison to electricity.

Looking at the transport sector specifically, Bossel (2006) states that, ‘Hardly 50% of the hydrogen energy contained in a vehicle tank is converted to motion in a car. The overall efficiency between electricity from renewable sources and wheel motion is only 20 to 25%. In comparison, over 60% of the original electricity can be used for transportation, if the energy is not converted to hydrogen, but directly used in electric vehicles.’ It therefore seems highly unlikely at present that technology and economics favour hydrogen over electricity as a vehicle fuel. That said, it is not impossible that conditions could change in hydrogen’s favour. If renewably generated electricity was extremely abundant but spatially concentrated, for example in equatorial countries, it could be exported as hydrogen. However, there are practical challenges involved, not least that the production of hydrogen by electrolysis requires large amounts of water. While copious electricity could be generated by photovoltaic panels in arid environments, large scale electrolysis in such areas would be very challenging. Nonetheless, the progress of hydrogen fuel cell technology should be monitored for progress as interest and investment in it continue.

Alternative fuels

Hybrid

Diesel-electric hybrid technology is best suited to the drive cycles of vans and rigid vehicles undertaking multiple-drop / collection deliveries in urban areas. It will have very limited application in heavier, articulated vehicles, other than for the powering of ancillary equipment. There is a trade-off between battery weight, vehicle range and payload. Moving heavy vehicles is particularly energy intensive, and so challenging. The potential savings in suitable applications range between 9–18%.

Biodiesel

Biodiesel can be blended with diesel to reduce carbon emissions. It can come in various blends. The most common ones are B5 to B20 blends. B5 contains 5% biodiesel and can yield carbon reductions of between 2 and 4%. If the biodiesel content is increased to 10% the carbon reduction ranges between 6 and 8%. Further increases in biodiesel content to 20% would yield a 14 to 16% reduction in CO_2.

Dedicated natural gas

A dedicated natural gas vehicle can run on either compressed natural gas (CNG) or liquefied natural gas (LNG). The gas is stored in a tank under the chassis like a diesel tank, but the tank is usually larger. In this way it gives the vehicle range without compromising cargo space. Dedicated natural gas vehicles can deliver carbon reductions of up to 9%.

Dual-fuel natural gas

Dual-fuel HGVs use both diesel and gas. Various reports show a substitution rate for 60% of diesel on an energy basis. A methane catalyst is installed in the vehicle to reduce tailpipe emissions of methane. Dual-fuel retrofits are available for converting existing diesel vehicles. Although dual-fuel retrofits can reduce carbon emissions by between 0 and 6% it should be noted that there are significant emissions of unburnt methane

(methane slippage) with current technologies and there is no net CO_2 equivalent benefit to this technology.

Dual-fuel bio gas

First generation biogas (i.e. biogas produced from food biomass) can be cleaned of impurities, dried and upgraded to use as biomethane in vehicles. Introducing biomethane in the same vehicle can lower the CO_2 emissions. The first generation dual-fuel biogas vehicles could yield to a 12% reduction in carbon emissions.

Second Generation dual-fuel biogas (i.e. dual-fuel biogas produced from non-food biomass) vehicles give benefits of up to 15% reduction in carbon emissions.

New vehicle improvements

Influence of energy vectors

Even a low uptake of electric articulated vehicles, or the use of electric vehicles in the large and small rigid fleets would have significant infrastructural and electricity demand impacts. These technologies would likely be battery-based, so recharging and battery exchange infrastructure would be required in depots and on freight corridors. Increased and re-timed electricity demands from road freight would also affect the grid and electricity generation. While electric vehicles produce zero tailpipe emissions, their total carbon footprint includes the production of electricity that they use.

The forecast emissions intensity of electricity in the UK is therefore critical. Between 1990 and 2010, emissions from grid electricity generation fell by 23% and are forecast in the fifth carbon budget to fall by 86% between 1990 and 2035 (CCC, 2015b). However, the future of electricity generation in the UK is uncertain and a number of scenarios are forecast (CCC, 2015a).

For comparison, in 2016, the emissions intensity of UK electricity generation was an average of 290 gCO2/kilowatt hour (EEE Consultancy, 2017). The range of emissions intensities shows the importance of timely investment in electricity generation capacity. In particular, if new nuclear power stations and carbon capture and storage were not available when required, the supply and decarbonisation of electricity would be more difficult. Such infrastructure requires both sustained investment and policy support, as it has lead-in times of decades. For the purposes of road freight scenarios, the potential impact on the electricity sector should not be overlooked. The Committee on Climate Change estimates that the electrification of the transport sector (including rail and passenger vehicles) would increase electricity demand by around 17 terawatt hours between 2020 and 2030 (CCC, 2015a). This represents an increase of approximately 6% on 2014 generation of 298 terawatt hours. The situation is, however, more complex, as the impact of freight electric vehicles will depend both on when they are adopted and when they are charged.

Prioritising technical interventions

The report uses four scenarios to prioritise the technical interventions:

1. Maximum CO_2 savings;
2. Positive NPV (measure uptake constrained by cost);
3. Maximum CO_2 savings, no electric vehicles (Scenario 1, without electric vehicles);
4. Maximum CO_2 savings, no long-haul electric vehicles (Scenario 1, without long-haul electric vehicles).

Table 4 below summarises the top CO_2 reduction measures for each of the four scenarios. In Scenarios 1 and 4 there are 87 measures adopted for the three types of vehicle (small rigid, large rigid, articulated) with the top 10 accounting for over 50% of the CO_2 savings. In Scenario 2 there are 72 measures adopted for the three types of vehicle with the top eight accounting for over 50% of the CO_2 savings. In Scenario 3 there are 85 measures adopted for the three types of vehicle with, again, the top eight accounting for over 50% of the CO_2 savings.

In the case of Scenarios 1 and 4, where only a lack of long-haul electric vehicles is the difference, the top measures are identical because, according to the relevant sources, the take-up percentage of articulated electric vehicles would only start in 2040, and therefore would not show as saving any significant CO_2. Where the total NPV cost is shown as negative this indicates that the total investment cost exceeds any fuel savings companies are likely to achieve using the measure. Therefore some form of government intervention would be necessary to encourage companies to adopt these measures.

In summary:

1. Scenario 1 shows an overall reduction of 62% by 2040 over the 2010 base.
2. Scenario 2 shows an overall reduction of 52% by 2040 over the 2010 base.
3. Scenario 3 shows an overall reduction of 56% by 2040 over the 2010 base.
4. Scenario 4 shows an overall reduction of 61% by 2040 over the 2010 base.

With government sources showing a net 9% reduction in road freight CO_2 between 1990 and 2010 this means that:

1. Scenario 1 shows an overall reduction of 71% by 2040 over a 1990 base.
2. Scenario 2 shows an overall reduction of 61% by 2040 over a 1990 base.
3. Scenario 3 shows an overall reduction of 65% by 2040 over a 1990 base.
4. Scenario 4 shows an overall rduction of 70% by 2040 over a 1990 base.

An optimistic adoption rate of electric vehicles post 2040 could result in CO_2 reductions of 76% by 2050. However, this would require significant infrastructure and energy generation investments.

Table 4: Summary of top CO_2 reduction measures for each of the scenarios

Scenario	Measure	Vehicle Type	CO2 saved up to 2040, (KgCO2)	Fuel saved (litres)	Total NPV Cost	Intervention by Government Required	% of CO2 saved in scenario	Cumulative percentage of CO2 saved
Option 2	Increase use of dual-fuel vehicles (Diesel + CNG)	Artic	679,686,551	0	£471,386,828	No	11.9%	12%
Option 2	Increase use of dual-fuel vehicles (Diesel + LNG)	Artic	660,911,826	0	£437,744,964	No	11.6%	23%
Option 2	Increase use of biodiesel vehicles	Artic	368,564,659	0	£38,766,865	No	6.5%	30%
Option 2	Increase use of hybrid vehicles	Artic	309,818,696	0	£2,563,672	No	5.4%	35%
Option 2	Use tear-drop vehicles	Artic	243,890,995	223,398,678	£28,814,294	No	4.3%	40%
Option 2	Increase use of dual-fuel vehicles (Diesel + CNG)	Large rigid	228,178,385	0	£104,901,696	No	4.0%	44%
Option 2	Increase use of CNG vehicles	Artic	201,381,458	0	£222,387,511	No	3.5%	47%
Option 2	Increase use of LNG vehicles	Artic	200,093,540	0	£216,437,698	No	3.5%	51%
Option 3	Increase use of hybrid vehicles	Artic	631,512,083	0	-£24,904,476	Yes	19.0%	19%
Option 3	Increase use of hybrid vehicles	Large rigid	257,808,219	0	-£193,375,593	Yes	7.8%	27%
Option 3	Use tear-drop trailers	Artic	217,907,245	224,922,801	£28,567,962	No	6.6%	33%
Option 3	Monitor and manage driver fuel performance (including use of telematics)	Artic	162,597,353	163,491,963	£259,907,300	No	4.9%	38%
Option 3	Give drivers training in fuel efficiency	Artic	133,622,105	134,386,684	£207,133,778	No	4.0%	42%
Option 3	Use trailer with sloping front roof (double deck/high cube vehicles)	Artic	108,092,947	111,522,140	£9,820,038	No	3.3%	46%
Option 3	Increase use of hybrid vehicles	Small rigid	105,722,248	0	-£320,871,797	Yes	3.2%	49%
Option 3	Use low 'rolling-resistance' tyres	Artic	90,213,952	92,596,242	£153,573,159	No	2.7%	51%
Option 1 and 4	Increase use of hybrid vehicles	Artic	631,512,083	0	-£24,904,476	Yes	8.1%	8%
Option 1 and 4	Increase use of dual-fuel vehicles (Diesel + CNG)	Artic	602,522,753	0	£470,147,552	No	7.7%	16%
Option 1 and 4	Increase use of dual-fuel vehicles (Diesel + LNG)	Artic	602,386,555	0	£418,484,246	No	7.7%	24%
Option 1 and 4	Increase use of hybrid vehicles	Large rigid	396,016,353	0	-£126,388,277	Yes	5.1%	29%
Option 1 and 4	Increase use of LNG vehicles	Artic	366,543,947	0	£385,214,141	No	4.7%	33%
Option 1 and 4	Increase use of electric vehicles	Large rigid	323,909,892	0	-£415,451,555	Yes	4.2%	37%
Option 1 and 4	Increase use of biodiesel vehicles	Artic	290,858,557	0	£50,972,551	No	3.7%	41%
Option 1 and 4	Increase use of dual-fuel vehicles (Diesel + CNG)	Large rigid	275,126,495	0	-£1,027,111	Yes	3.5%	45%
Option 1 and 4	Increase use of dual-fuel vehicles (Diesel + LNG)	Large rigid	275,066,098	0	-£63,956,740	Yes	3.5%	48%
Option 1 and 4	Increase use of electric vehicles	Small rigid	263,534,685	0	-£829,213,650	Yes	3.4%	52%

The concept of marginal abatement cost can be defined as cost per unit of pollution reduction by a particular method. So if electric vehicles had a marginal abatement cost of £20/tCO_2, reducing carbon dioxide emissions by a tonne through the adoption of electric vehicles would cost £20. Conversely, if reducing maximum vehicle speed had a marginal abatement cost of -£10/tCO_2, reducing carbon dioxide emissions by a tonne through lower maximum vehicle speeds would save £10. In both cases, the marginal abatement cost figures assume a baseline level of carbon emissions and a certain level of costs over time. Marginal abatement cost curves (MACCs) display the various marginal abatement costs of different measures for reducing pollution, with the intention of comparing which measures have the lowest and highest cost.

Marginal abatement costs are calculated for each emissions reduction measure as follows:

$$Marginal\ abatement\ cost = \frac{-Total\ net\ present\ value}{Total\ carbon\ emissions\ abatement}$$

The total NPV of the measure collects monetary costs over time, adjusted through discounting for the diminishing value of money as time passes. If the total NPV is positive, the measure saves money overall. If the total NPV is negative, it costs money overall. NPV is used to project returns on investment and is influenced by the choice of discount rate, in this case 10%. The total carbon emissions abatement figure consists of the projected total carbon emissions prevented as a result of the measure. A worked example is shown below for the measure driver fuel efficiency training in small rigid vehicles from 2010 to 2040, using figures from the first model scenario:

$$MAC = \frac{-NPV}{Total\ CO_2\ abatement}$$

$$MAC = \frac{-(\text{£}18{,}376{,}190)}{1{,}136{,}961\ \text{tonnes C0}_2}$$

$$MAC = -\text{£}16.16$$

In this example, the use of driver fuel efficiency training in small rigid vehicles over 30 years would save £16.16 per tonne of CO_2 also saved. This is because more fuel-efficient driving reduces fuel demand and driver-training incurs low capital costs.

MACCs show the distribution of total costs and total emissions reduction potential across a range of measures. This is helpful as no single measure can reduce carbon emissions to the extent required. MACCs are a helpful tool for prioritising and sequencing measures although, to be useful, the context of the data they present must be clearly shown.

The MACCs presented here were generated using data from the Centre for Sustainable Road Freight road map model. This model estimates the total carbon dioxide emissions from GB road freight in the future, based on the uptake of carbon emissions reduction measures. They summarise the costs of carbon dioxide emissions abatement in the UK road freight sector from 2010 to 2040, based on four different scenarios. These figures are thus average projections of both cost and emissions reduction potential over 30 years. This is calculated separately for each emissions reduction measure within the model, so that they can be compared.

The MACC displays these marginal abatement cost (y axis) against the average tonnes of carbon dioxide saved per year by each measure (x axis), in the form of a block. The taller the block, the higher the marginal abatement cost of that measure. The wider the block, the greater the potential annual carbon emissions reduction of that measure.

As the model projects significant increases in uptake of carbon mitigation measures between 2010 and 2040, this 30-year average conceals considerable variation. The aim of the MACCs is to summarise the model results in a succinct format that shows the overall variation in carbon savings from different measures by: a) type of freight vehicle: small rigid, large rigid, artic, and b) each of the four scenarios.

The variation in a) is due to robust assumptions within the roadmap model, reflecting the constraints on the use of certain measures for certain freight activities. For example, electric vehicle uptake is expected to be faster for urban freight movements. The emissions savings from each measure also vary on this basis.

The latter variation, between the four scenarios, reflects the fact that the roadmap model can constrain uptake of emissions reduction technologies based on NPV, in other words, cost. The MACCs in Scenarios 1, 3, and 4 assume measure uptake based on feasible potential and prioritisation of maximum carbon abatement. Conversely, the 'Positive NPV' MACCs in Scenario 2 only show uptake that is cost saving after three years at a 10% discount rate. Unsurprisingly, the additional of a positive NPV constraint on uptake results in lower projected measure adoption and thus lower carbon savings. Further adjustments to the model allow for the exclusion of all electric vehicles, or just long-haul electric vehicles. The four scenarios are listed below:

1. Maximum CO_2 savings;
2. Positive NPV (measure uptake constrained by cost);
3. Maximum CO_2 savings, no electric vehicles (Scenario 1, without electric vehicles);
4. Maximum CO_2 savings no long-haul electric vehicles (Scenario 1, without long-haul electric vehicles).

The bar graphs that accompany each MACC show total capital costs over 30 years associated with each scenario. It must be noted that, while total costs are lower under the positive NPV scenarios, so are total carbon emissions savings over 30 years. The gap between scenarios suggests a need for policy intervention in order to meet carbon emissions targets.

The colours in each MACC denote type of emissions reduction measure:

- Alternative fuels, including autonomous vehicles, are green.
- Aerodynamic measures are blue.

- Other measures, including driver-training, tyres, and optimised routing, are yellow.

It should be noted that MACC curves do not consider the reorganisation of logistics interventions. These interventions are assumed not to incur any incremental costs.

Figures 18–29 summarise the MACCs for the four scenarios.

Scenario 1: Maximum CO_2 savings (all measures adopted)

Examination of the MACCs for Scenario 1 identifies some contributions for developing a roadmap for the reduction of carbon emissions. Scenario 1 describes a context where it is assumed businesses do everything possible to reduce emissions. It is differentiated from Scenarios 3 and 4 in that all electric vehicle interventions are assumed to be feasible, although it should be noted that the uptake rate of electric long-haul articulated trucks is still constrained by infrastructure and technology.

Scenario 1 reveals that electric rigids will make the biggest contribution to CO_2 reduction although they are also among the most expensive. The biggest CO_2 reduction for articulated vehicles is achieved by using alternative fuels in both dual-fuelled and single-fuelled vehicles. In this context it should be remembered that dual-fuelled vehicles still suffer from methane slip.

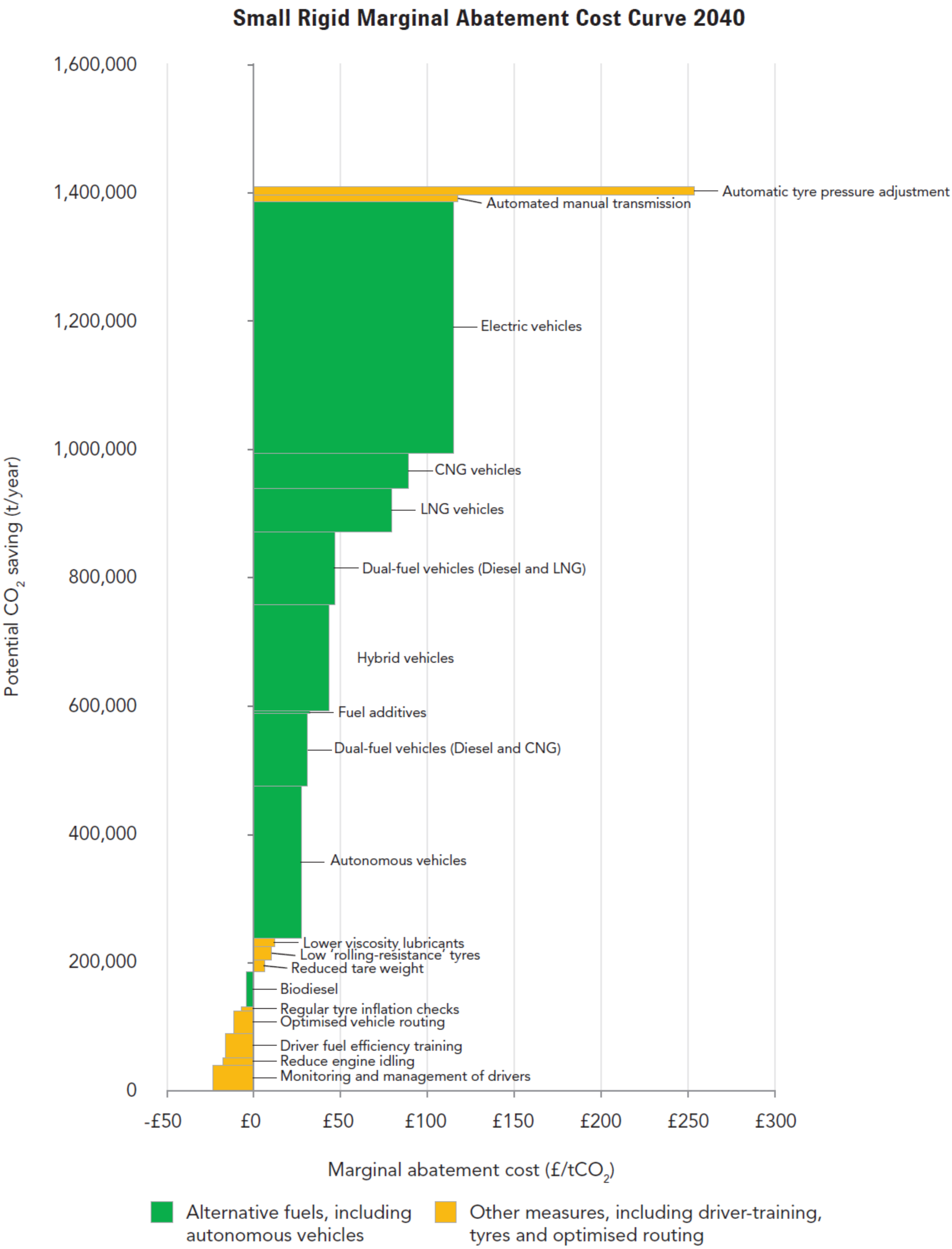


Figure 18: Scenario 1 small rigids MACC

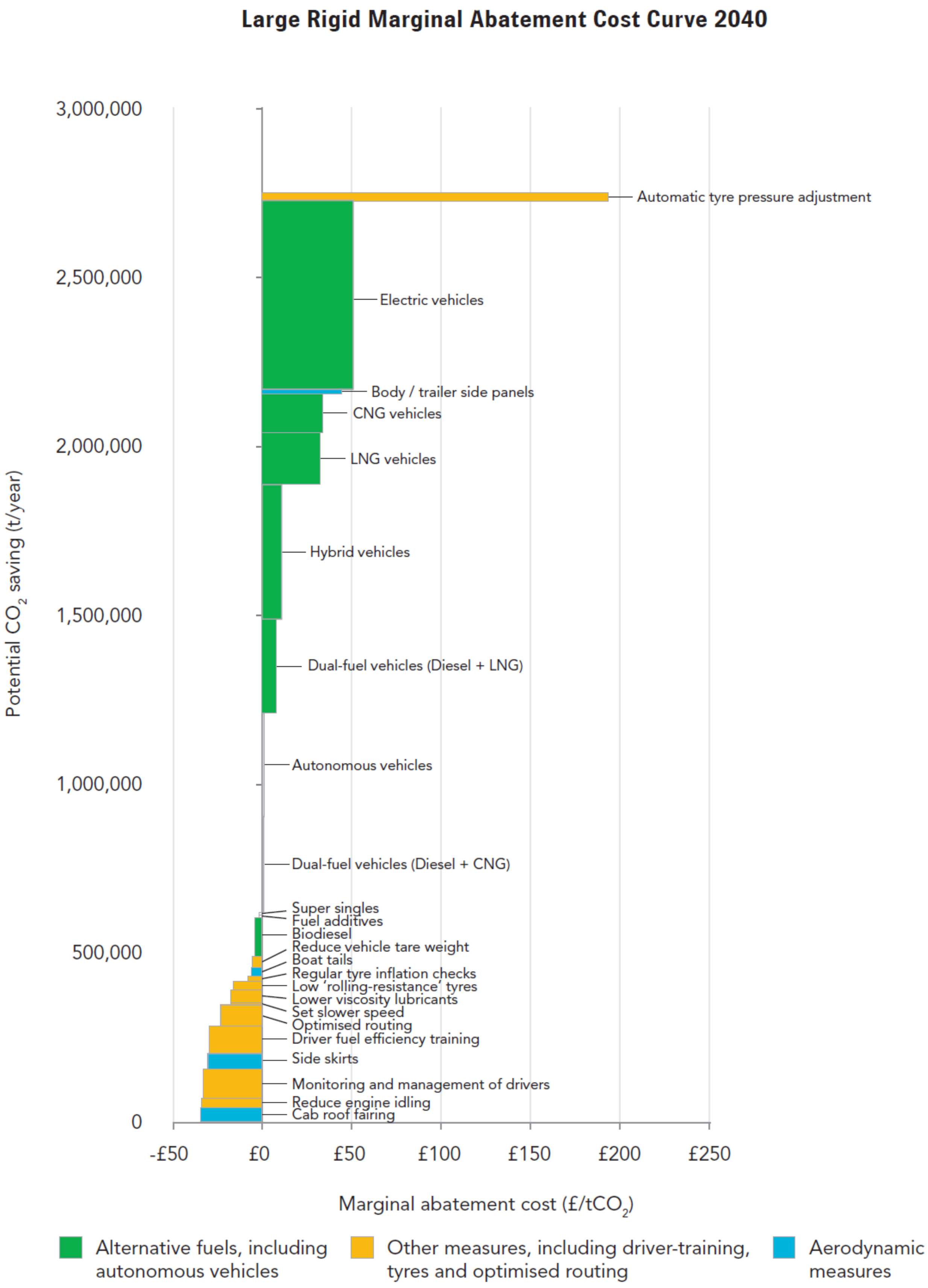


Figure 19: Scenario 1 large rigid MACC

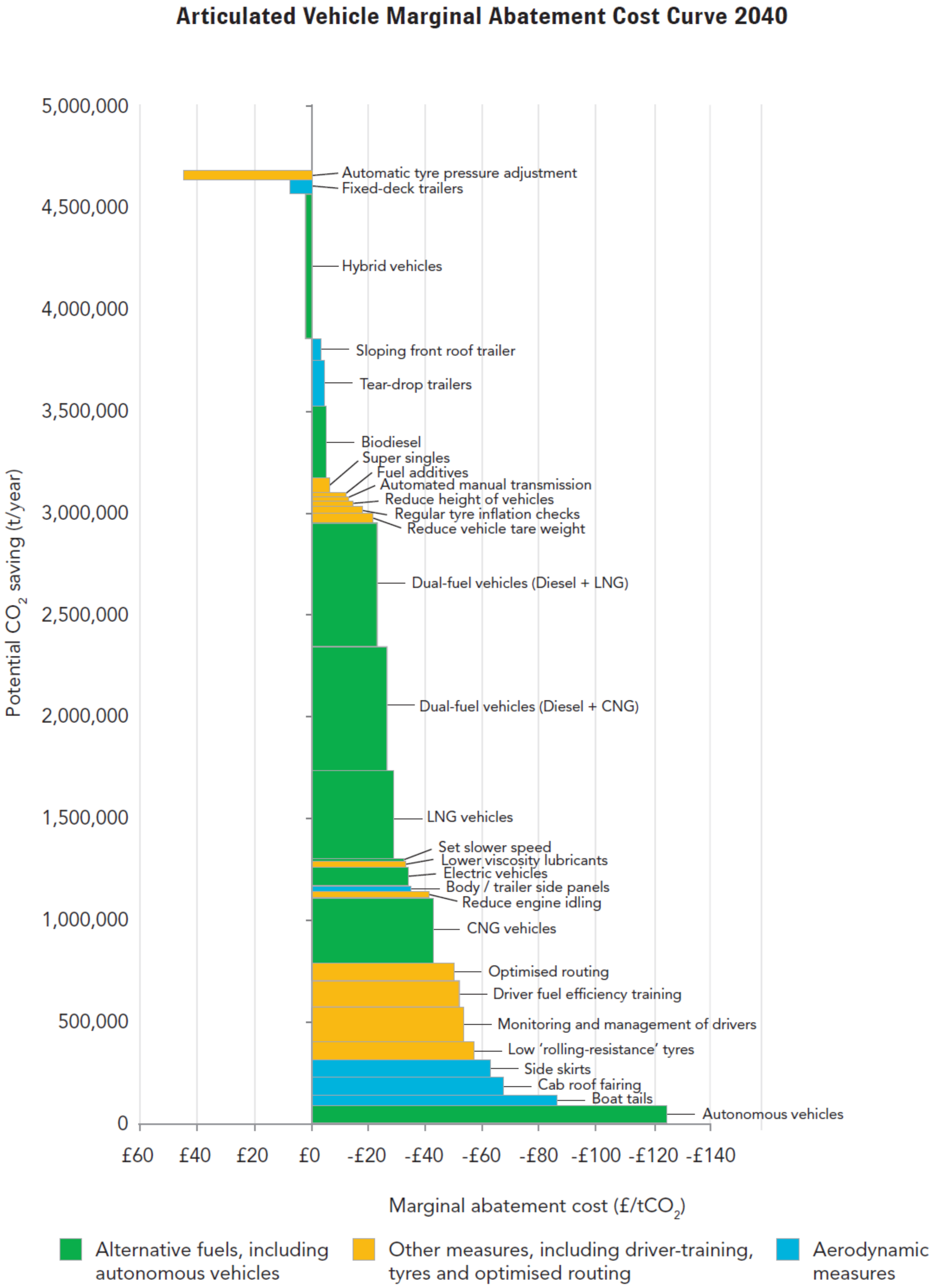


Figure 20: Scenario 1 artic MACC

Scenario 2: Positive NPV

Scenario 2 assumes that feasible interventions are constrained by cost (negative NPV and less than three- year payback). Furthermore, this analysis assumes that there will only be autonomous large rigid and articulated trucks.

It is worth noting that autonomous vehicles yield the lowest marginal abatement costs because driver costs represent approximately 25% of the total cost of running a driven truck. The CO_2 reduction per vehicle will be the equivalent of the best drivers being used in non-autonomous vehicles.

It is also noticeable that electric vehicles are too expensive to be feasible in this scenario.

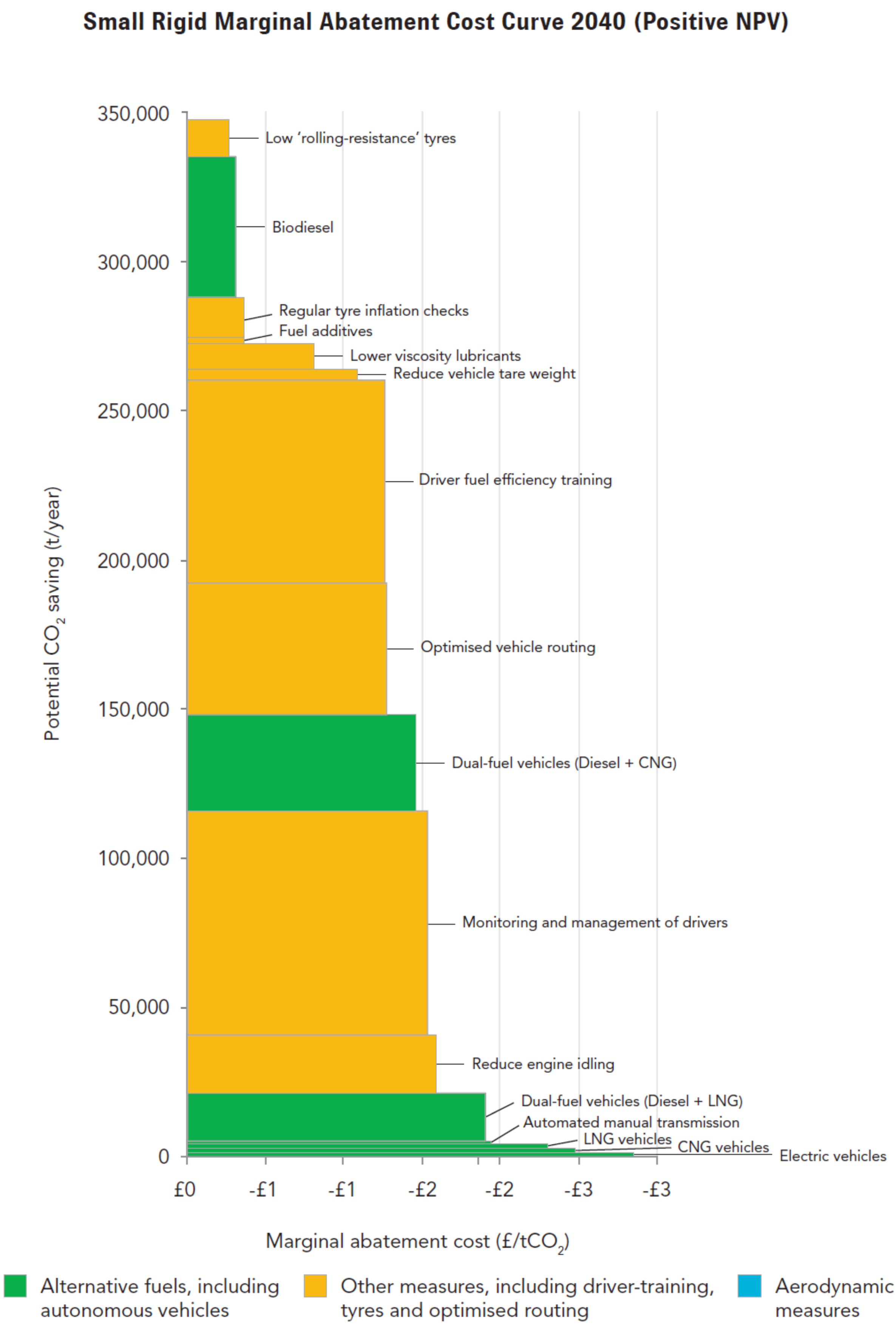


Figure 21: Scenario 2 small rigid MACC

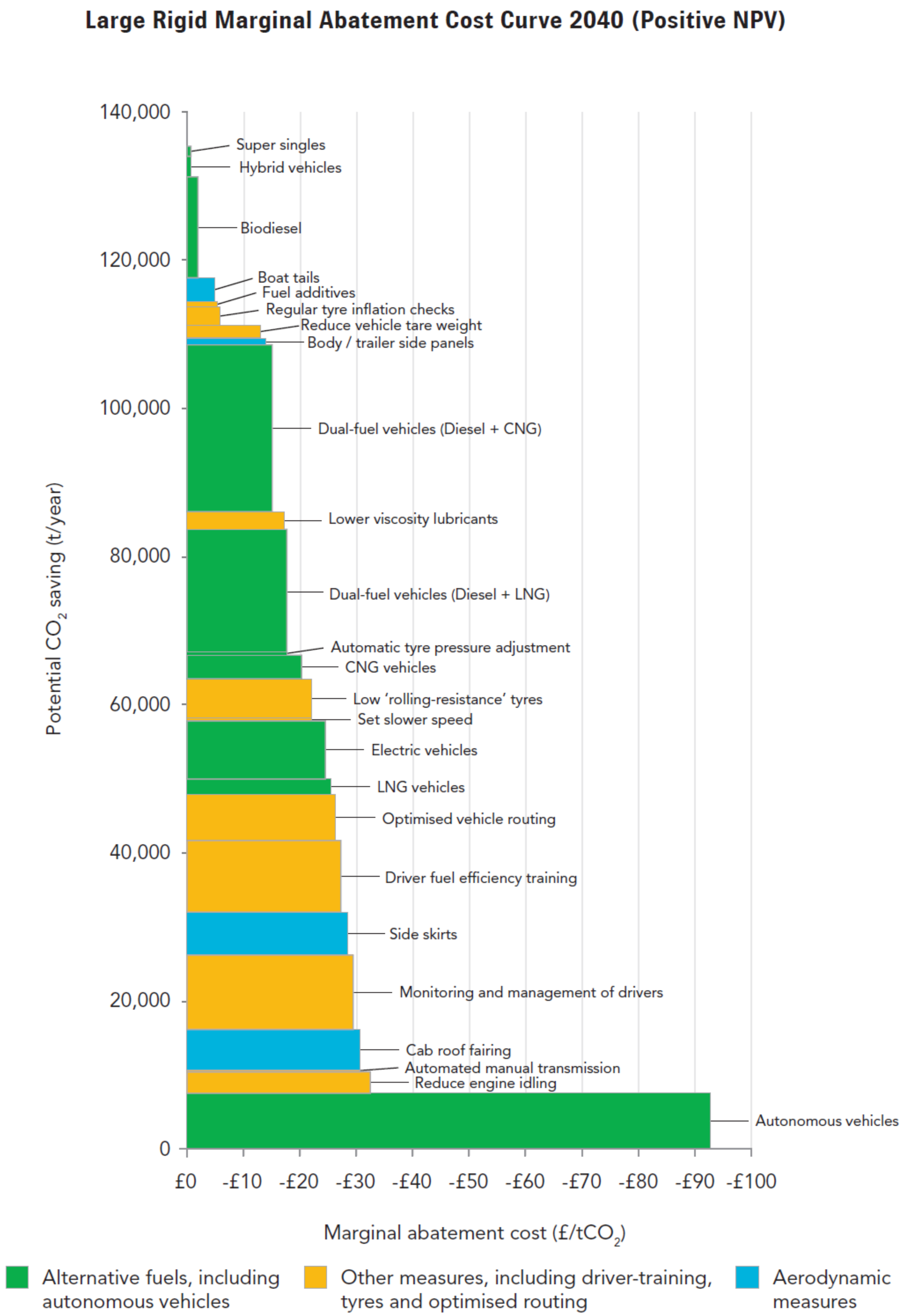


Figure 22: Scenario 2 large rigid MACC

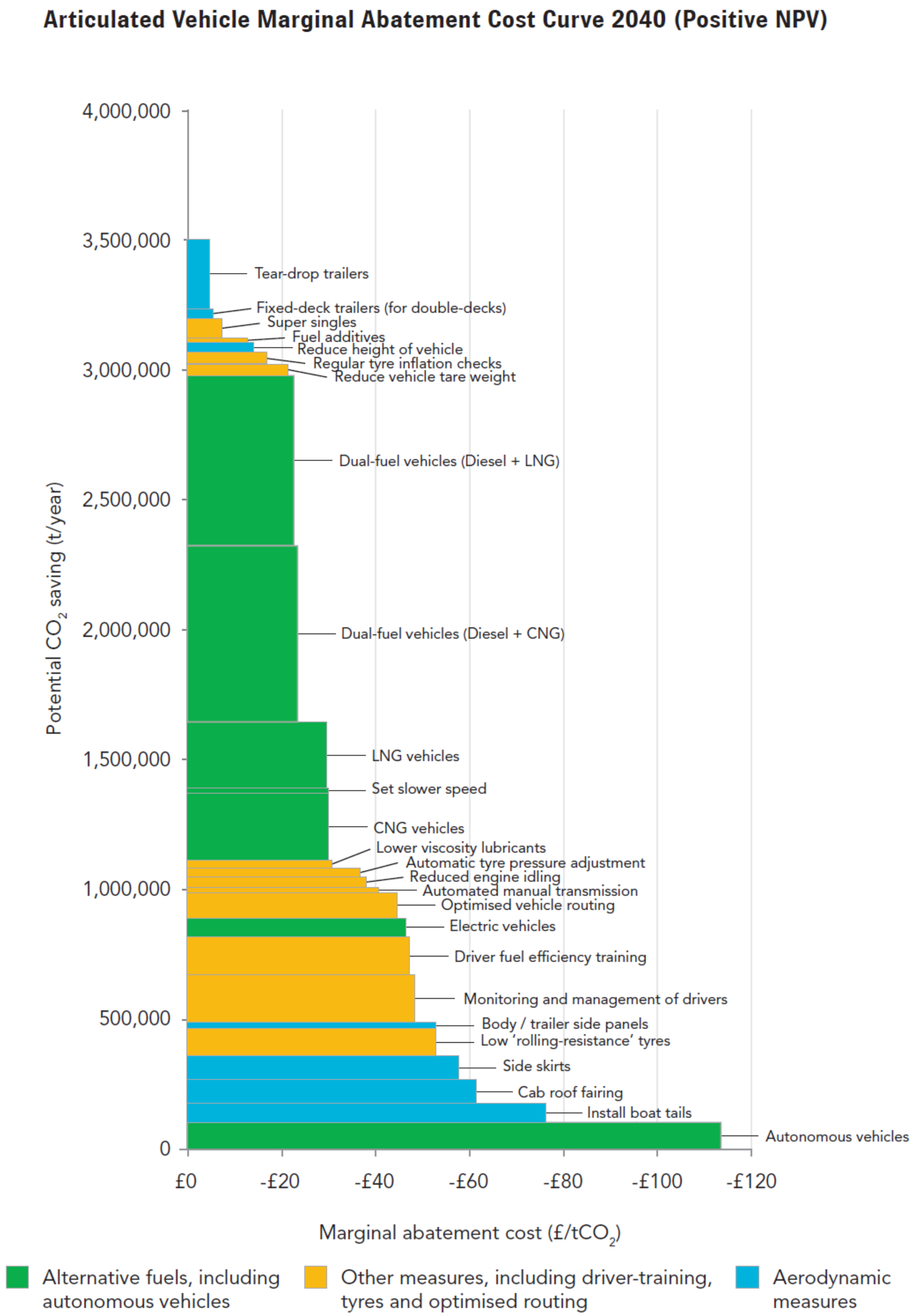


Figure 23: Scenario 2 artic MACC

Scenario 3: Maximum CO_2 savings, no electric vehicles

This scenario assumes that electric vehicles are not feasible; under such circumstances driver-training delivers the most effective group of interventions, although bigger reductions are achieved by using alternative fuels.

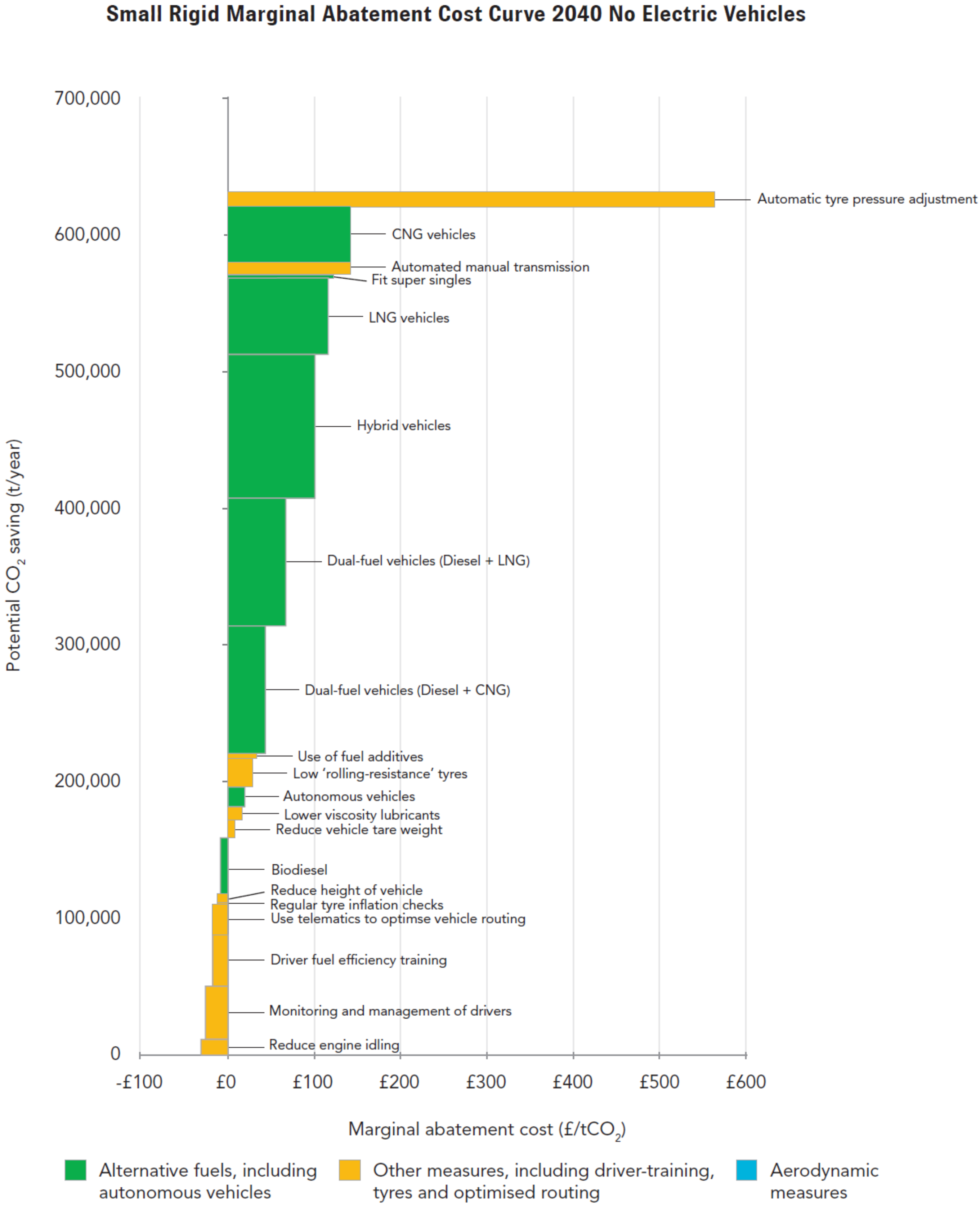


Figure 24: Scenario 3 small rigid MACC

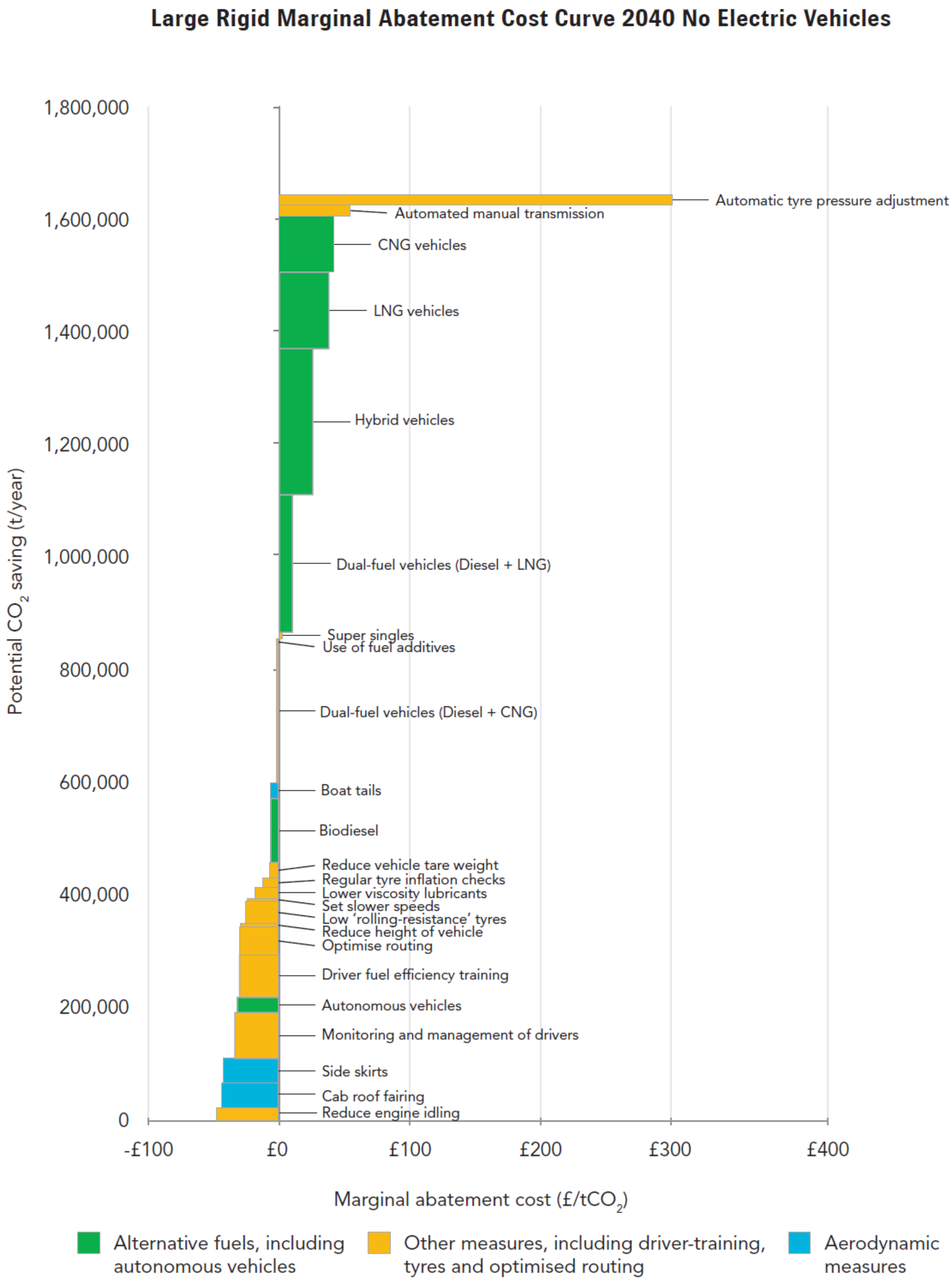


Figure 25: Scenario 3 large rigid MACC

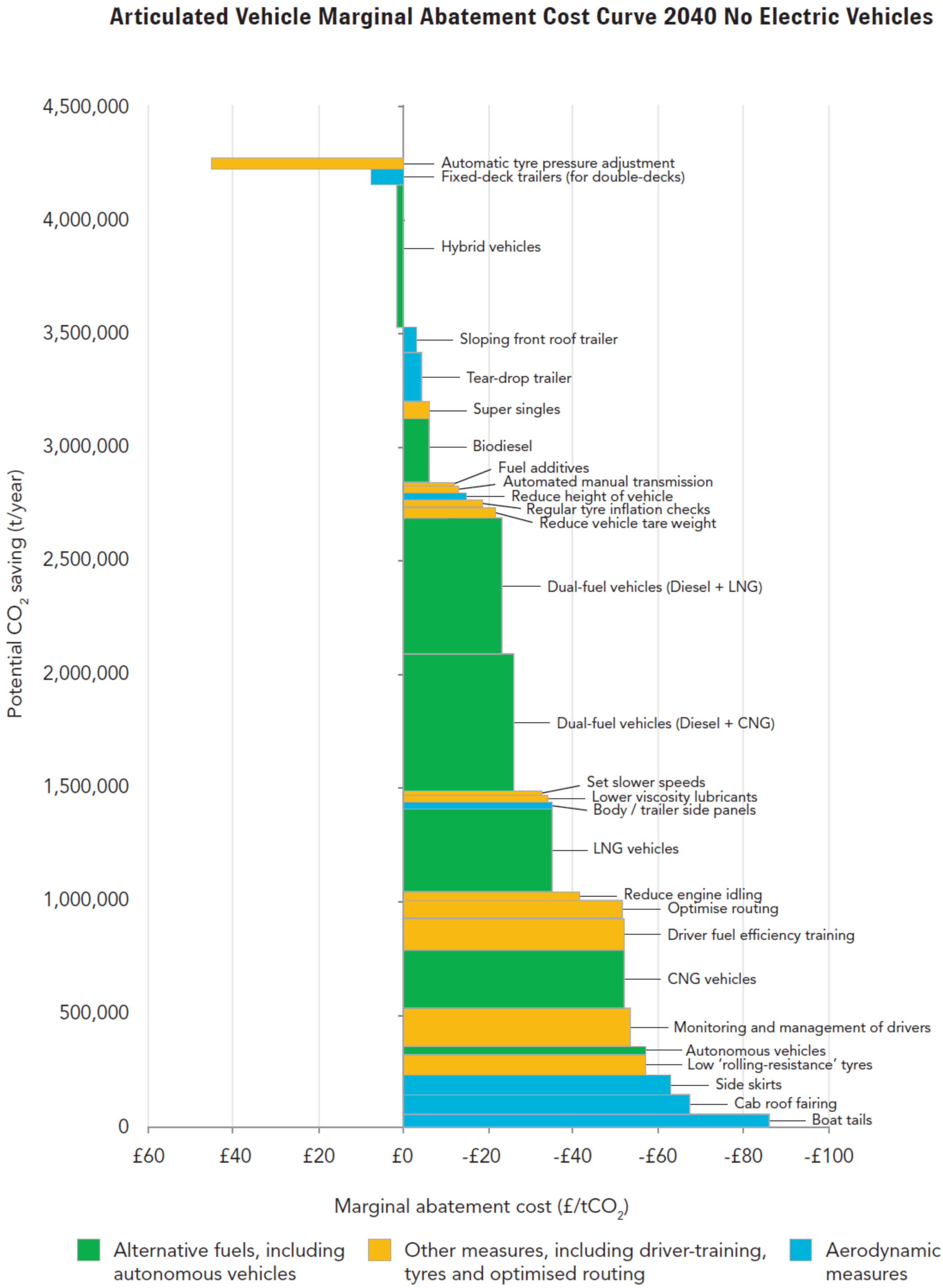


Figure 26: Scenario 3 artic MACC

Scenario 4: Maximum CO_2 savings, no long-haul electric vehicles

This scenario makes the point that electric vehicles, where feasible, will always yield the biggest reductions in CO_2, while driver-training and aerodynamics yield the most cost-effective interventions.

Small Rigid Marginal Abatement Cost Curve 2040 No Long Haul Articulated Vehicles

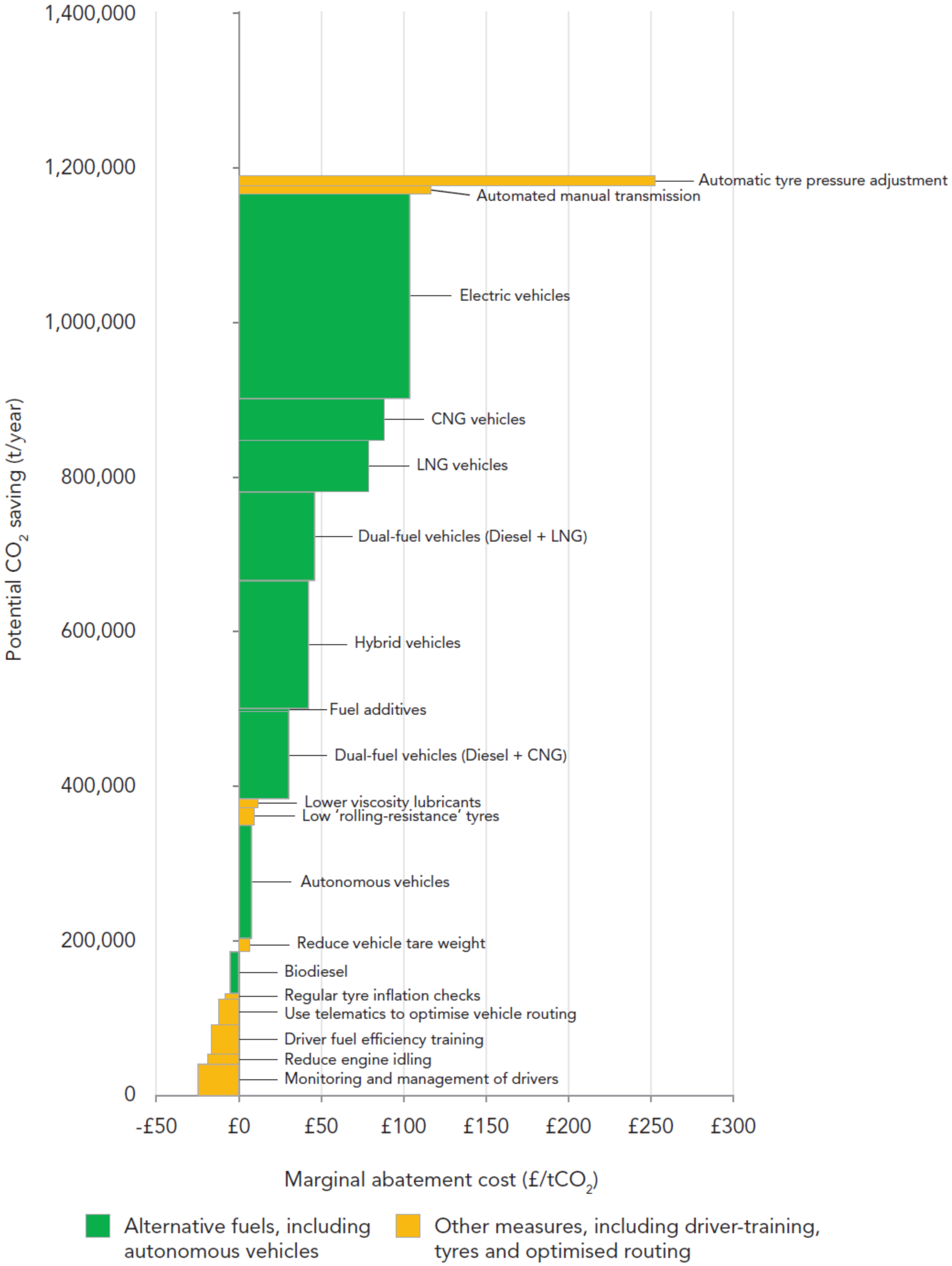


Figure 27: Scenario 4 small rigid MACC

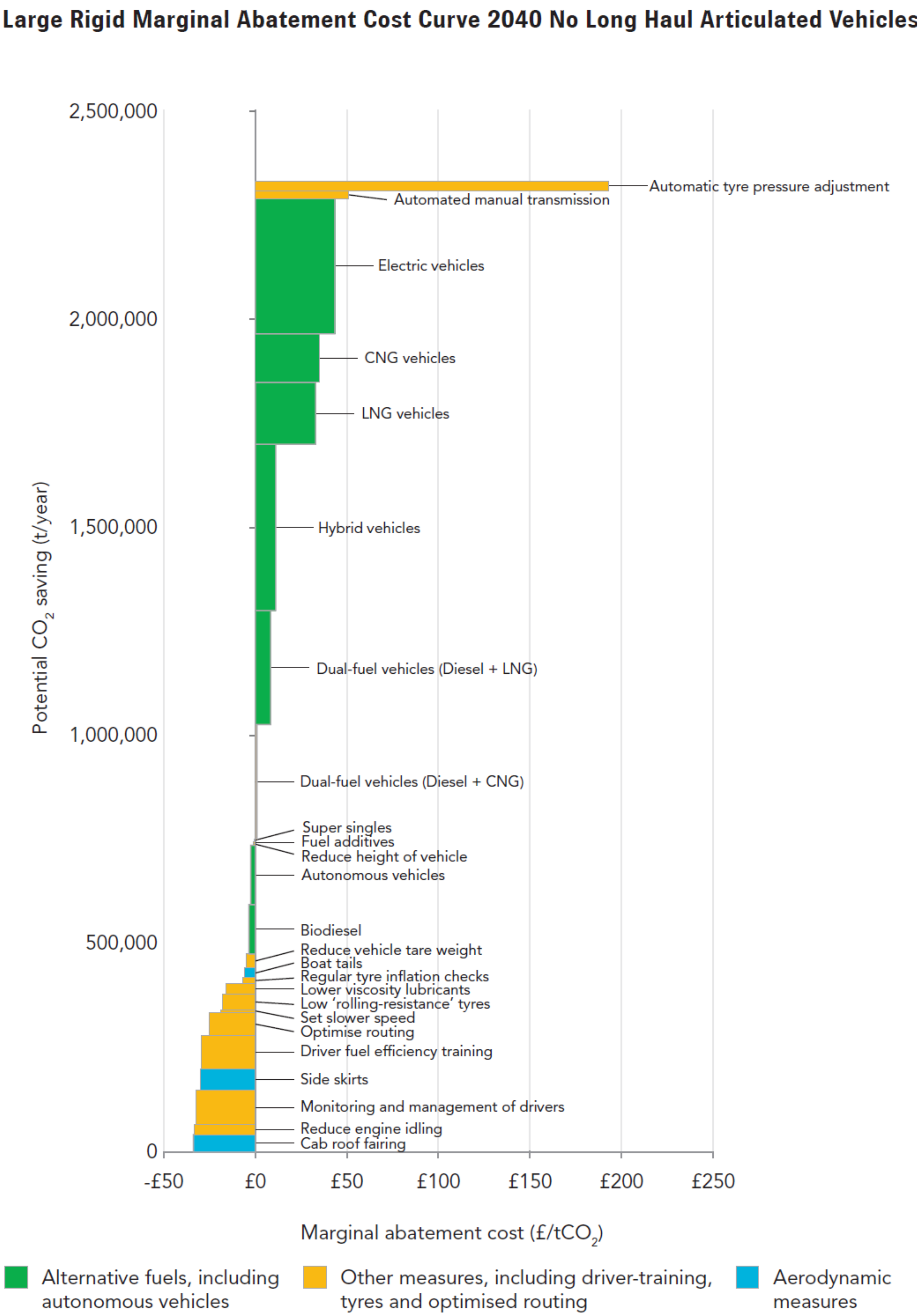


Figure 28: Scenario 4 large rigid MACC

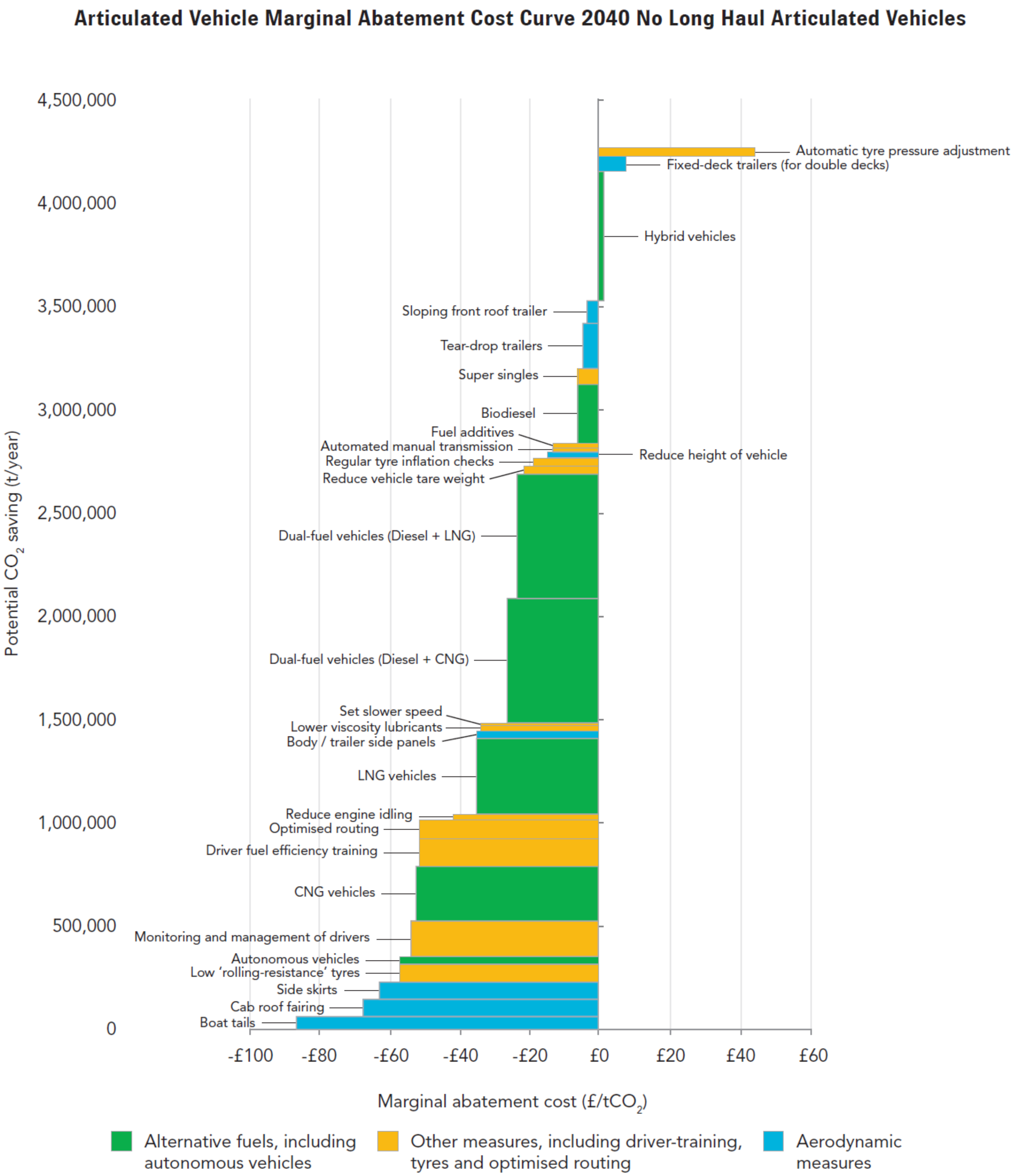


Figure 29: Scenario 4 artic MACC

Note: The MACCs for artics are the same in the final two scenarios, as it is assumed that artics only carry long-haul freight and therefore no electric artic vehicles are included in either scenario.

Logistics interventions cannot be prioritised using the same approach as, typically, the implementation costs are not transparent or obvious. However, logistics interventions can be prioritised by qualitatively assessing the difficulty of implementation of benefits and difficulty to implement.

The above analysis clearly shows that to meet the 2050 Climate Change Act target (an 80% reduction in CO_2 emissions compared to 1990 levels) will require the electrification of artic HGVs. The possible options for the electrification of HGVs are discussed in the roadmaps that follow.

The roadmaps

Technology roadmap

Synthesis of the MACCs permits the development of a roadmap, which describes the activities required to deliver the technical interventions (Phaal et al., 2001; Phaal et al., 2004) that, when combined with logistics interventions, will result in an 80% reduction in CO_2 emissions. Figure 30 summarises the roadmap that reflects the assumptions used in developing the MACCs and associated analysis.

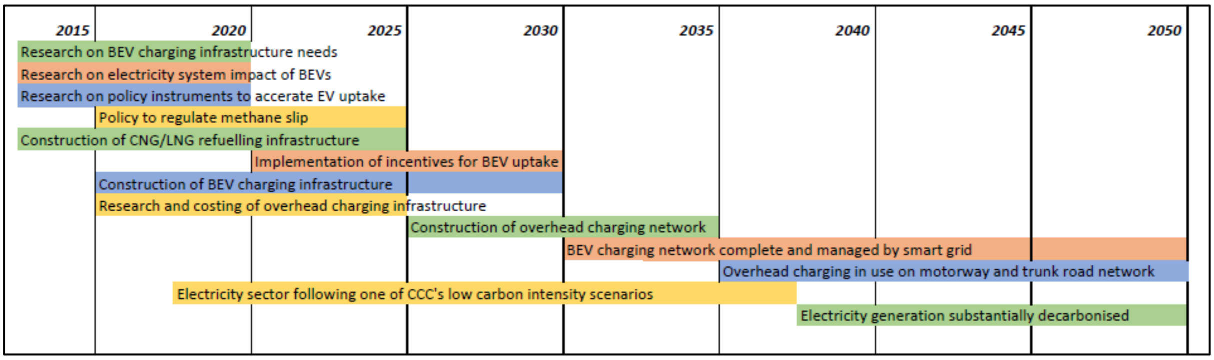


Figure 30: Technology roadmap

This roadmap was developed following a series of workshops that used the CfSRF computer model for assessing the system-wide benefits of various measures applied to various vehicle categories and disaggregated commodity-based activity profiles.

Logistics roadmap

Assessment of the barriers and enablers to the implementation of the logistics interventions results in the roadmap summarised in Figure 31. The logistics roadmap prioritises research to enable the adoption of higher capacity vehicles and the pooling of standardised data sets.

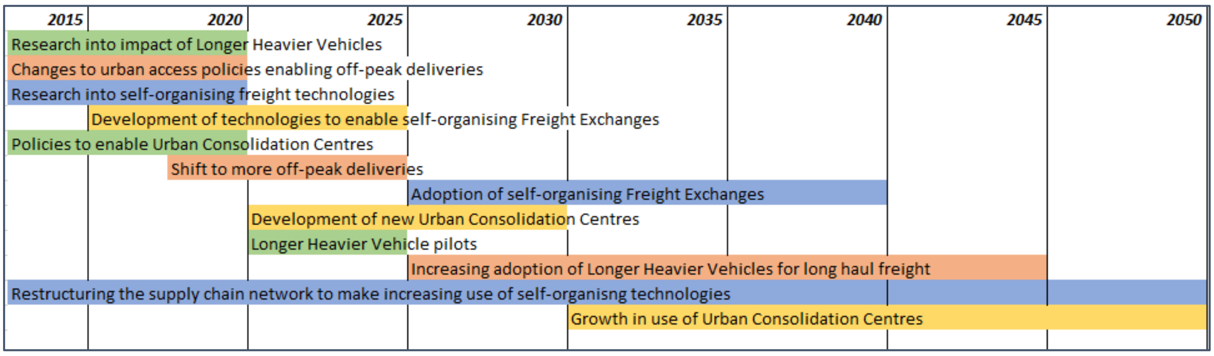


Figure 31: Operations roadmap

Data to support the analysis described in previous sections was collected in a series of workshops comprising practitioners and academics. Expert panels then validated the workshop outputs to formalise the roadmap.

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