Powering Ahead

The future of low-carbon cars and fuels

Duncan Kay, Nikolas Hill and Dan Newman
Ricardo-AEA
April 2013

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About the Authors

Duncan Kay is a senior technical consultant for Ricardo-AEA and has a background of 16 years' experience in the automotive sector, working as a research and development engineer developing new technologies to improve fuel economy and reduce emissions from passenger cars. Since leaving the industry he has spent the last 5 years advising and consulting on a wide range of transport issues, particularly analysis of the automotive industry and transport greenhouse gas emissions reduction. Duncan has led studies for the Low Carbon Vehicle Partnership, the European Environment Agency and the European Commission amongst others. In 2012, he completed a study for the Joint Research Council of the European Commission examining the role of research and development in maintaining the competitiveness of the European automotive industry.

Nik Hill is Ricardo-AEA's Knowledge Leader for Transport Technology and Fuels and has over 13 years of experience of consultancy project work on transportation issues for a range of public and private sector clients. He has particular expertise in transport emissions, low-carbon vehicle technologies and fuels, and in developing models to simulate future emissions trajectories. Nik's expertise includes assessing the energy and environmental impacts of transport, including model development, life cycle analysis and the economic evaluation of future vehicle technologies and fuels. Nik has led a number of influential projects for the UK government and European Commission in recent years, one of which was a high-profile European Commission project to identify and analyse potential options for a long-term policy framework to reduce transport greenhouse gas emissions out to 2050.

Dan Newman is a consultant for Ricardo-AEA with over two years of experience on sustainable transport projects for both governments and the private sector. Dan has particular expertise in battery/hybrid electric vehicles and natural gas fuelled vehicles. He has been involved in a range of work for the European Commission and has recently been instrumental in investigating the effect of environmental regulations and standards on vehicle prices over the past 15 years. Dan has led tasks assessing the impact of information communications technology (ICT) of the large-scale deployment of battery electric vehicles for the European Commission, and has modelled how natural gas can contribute to achieving cost-effective greenhouse gas emissions reductions across the European transportation sector.

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Disclaimer

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List of Abbreviations

ACEA	European Automobile Manufacturers' Association ('Association des Constructeurs Européens d'Automobiles')
AFV	alternative fuel vehicle
BEV	battery electric vehicle
BRIC	Brazil, Russia, India and China
B7	diesel with a FAME content of up to 7% by volume
B10	diesel with a FAME content of up to 10% by volume
B30	diesel with a FAME content of up to 30% by volume
Bio-CNG	bio-compressed natural gas, biomethane
BSG	belt-driven starter-generator
BSI	British Standards Institute
CARS21	Competitive Automotive Regulatory System for the 21st century
CCC	Committee on Climate Change
CCS	carbon capture and storage
CEN	European Committee for Standardisation ('Comité Européen de Normalisation')
CFRP	carbon-fibre-reinforced plastics
CNG	compressed natural gas
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CTL	coal to liquid
DECC	Department of Energy & Climate Change
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
E5	petrol with up to 5% ethanol by volume
E10	petrol with up to 10% ethanol by volume
E85	petrol with up to 85% ethanol by volume
E100	pure bioethanol
EARPA	European Automotive Research Partners Association
EGR	exhaust gas recirculation
ERTRAC	European Road Transport Research Advisory Council
ETP	European Technology Platform
EUCAR	European Council for Automotive R&D
EUROBAT	Association of European Storage Battery Manufacturers
EV	electric vehicle
FAME	fatty acid methyl ester (first-generation biodiesel)

FCC	Future Car Challenge
FCV	fuel cell vehicle
FT-BTL	‘Fischer–Tropsch biomass to liquid’ – refers to both the process and the resultant diesel fuel
GHG	greenhouse gas
GTL	gas to liquid
HCCI	homogenous charge compression ignition
HEV	hybrid electric vehicle
HFCV	hydrogen fuel cell vehicle
HGV	heavy goods vehicle
HMRC	HM Revenue & Customs
HVO	hydrotreated vegetable oil
ICE	internal-combustion engine
IEA	International Energy Agency
IFS	Institute for Fiscal Studies
ILUC	indirect land-use change
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Council (of the European Commission)
LCVIP	Low Carbon Vehicles Innovation Platform
LCVPPP	Low Carbon Vehicle Public Procurement Programme
LDV	light-duty vehicle
LBM	liquid biomethane
LiPF6	lithium hexafluorophosphate, used in battery chemistry
LFP	lithium–iron phosphate, used in battery chemistry
LMO	lithium–manganese oxide, used in battery chemistry
LMP	lithium–metal polymer, used in battery chemistry
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LTO	lithium–titanate oxide, used in battery chemistry
MJ	megajoules
MPV	multipurpose vehicle
NCA	lithium–nickel cobalt aluminium oxide, used in battery chemistry
NEDC	New European Drive Cycle
NiCd	nickel–cadmium, used in battery chemistry
NiMH	nickel–metal hydride, used in battery chemistry
NMC	lithium–nickel manganese cobalt oxide, used in battery chemistry

OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
OLEV	Office for Low Emission Vehicles
PEM	polymer electrolyte membrane
PEMS	portable emissions measurement system
PFCC	Polymer Fuel Cells Challenge
PHEV	plug-in hybrid electric vehicle
PICG	Plug-in Car Grant
PIP	Plugged-in Places
R&D	research and development
RED	Renewable Energy Directive
REEV	range-extended electric vehicle
RPI	Retail Prices Index
RTFC	Renewable Transport Fuel Certificates
RTFO	Renewable Transport Fuels Obligation
SMMT	Society of Motor Manufacturers and Traders
SULTAN	SUstainabLe TrANsport illustrative scenario tool
TMO	transition metal oxide, used in battery chemistry
TPMS	tyre pressure monitoring systems
TSB	Technology Strategy Board
TTW	tank-to-wheel
TWh	terawatt-hours
ULCVDP	Ultra Low Carbon Vehicle Demonstrator Programme
UNFCCC	United Nations Framework Convention on Climate Change
VCA	Vehicle Certification Agency
VED	Vehicle Excise Duty
WBCSD	World Business Council for Sustainable Development
WLTP	Worldwide harmonized Light vehicles Test Procedure
WTT	well-to-tank
WTW	well-to-wheel

Viewpoint

In 2007, HM Treasury published the seminal *King Review of low-carbon cars*.[1] Its aim was to "undertake an independent review to examine the vehicle and fuel technologies which over the next 25 years could help to decarbonise road transport, particularly cars".

Much has happened in the low-carbon vehicle sphere in the six years that have now passed: conventional new car carbon dioxide (CO_2) emissions have decreased by almost 20%, from 164.9 g/km in 2007 to 133.1 g/km in 2012; vehicle manufacturers are now offering an increasing range of electric vehicles, into which the government is pouring money; and, more recently, the government launched a 'UKH2 Mobility' platform setting out a plan for the roll-out of hydrogen vehicles from 2015 onwards.

To understand where expert thinking has got to, we commissioned environment and energy consultancy Ricardo-AEA to examine the relative merits of the major fuels and powertrains in delivering the UK's greenhouse gas reduction targets over the coming decades. We also wanted to know what each technology's market potential was. To achieve these research goals, the authors reviewed a wide range of market take-up scenarios from leading consultancies and other stakeholders around the world. While the average of expert opinion can be a pretty good estimate of what may happen, any market projection, of course, only paints a picture of what *could* happen. No one can predict with certainty what *will* happen: all forecasts have to make assumptions about what the world may look like in the future.

This report suggests that there will be a multitude of options for consumers to choose between, both in terms of fuels and powertrains: petrol, diesel, natural gas, plug-in hybrids, fuel cell vehicles – and others besides. Each has its own strengths and weaknesses, and will be used in a different application. The report also demonstrates that this range of fuels and powertrains can be used in various combinations, which is good news because it means that the transport system will be more resilient – for example, in terms of oil price shocks – and that there are many benefits to be realised across different technologies, such as making vehicles lighter and more aerodynamic.

The most important finding is that conventionally powered petrol and diesel cars will remain with us for a long time yet, and that the lion's share of emissions reductions in the short to medium term will come from their improvement through, for example, engine downsizing with turbocharging. All the signs are that they will continue to be the dominant form of powertrain

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1 The King Review was published in two parts: the first was published in 2007 and examined the potential for CO_2 reduction in all the main fuels and powertrains; the second, published in 2008, made a series of (policy) recommendations for achieving the UK's carbon reduction targets for road transport over the long term.

until at least 2030: according to the average market projections, about 60% of vehicles in 2030 are likely to be powered, either in part or in full, by internal-combustion engines. Even in the 2050 scenarios the report anticipates that some cars will still feature an internal-combustion engine, although these are expected to be almost exclusively full hybrids, plug-in hybrids and range-extended electric vehicles driven mainly in electric mode.

Electric vehicles remain a controversial subject. Advocates will say that their market share has increased by hundreds of percentage points over the last years, and that this trend will continue. Critics will reply that this still only represents a small fraction of the market. But what do we actually mean by ‘electric vehicles’ anyway? The term is most often loosely applied to mean plug-in hybrid electric vehicles, range-extended electric vehicles and pure/battery electric vehicles. However, these technologies are quite different in their degree of electrification, and these differences lead to significant implications for their optimal application, costs of ownership and operation, as well as overall usefulness. Thus, while plug-in and range-extended hybrids could be described as ‘the best of both worlds’ and seem to make more sense as a mass-market proposition, pure electric vehicles appear to be less promising. Whatever people’s feelings about all these plug-in vehicles, the projections reviewed in this report show that by 2020 they are likely to account for anything between 5% and 15% of new car sales, and for between 20% and 50% by 2030.

Much of the limited utility of pure electric vehicles today comes down to simple physics: in terms of energy density, liquid fuels are still dozens of times better than electricity stored in batteries. Even though electric vehicles are now a practical proposition – evidenced by the fact that some people, albeit few, *are* buying and using them – big question marks still remain over how they will perform after several years in terms of day-to-day wear and battery rundown.

Central to all of this is battery technology. The future mass-market success of electric vehicles is highly dependent on breakthroughs in this field, both to increase energy density and to reduce cost, which are essentially two sides of the same coin. While there may be innovative ways of avoiding merely increasing battery size – battery swapping, more frequent trickle charging, rapid charging – all of these come with their own problems.

And then there is their future greenhouse gas reduction potential, which relies largely on decarbonisation of the grid. Although this is strongly implied by the Climate Change Act 2008, it cannot be accepted as a given because of the vast investment required and the potential competition for low-carbon electricity from other sectors like heating homes. There are ongoing discussions in the context of the UK Energy Bill – a proposed legislative framework for delivering secure, affordable and low-carbon energy, which at the time of writing is at report stage prior to its third reading – as to whether it should include a decarbonisation target for power generation by 2030. Whether such a target will be set, and if so at what level, is yet to be determined.

Similar arguments apply to hydrogen fuel cell vehicles, which are not only costly but require both expensive infrastructure for market adoption and 'clean' hydrogen to realise greenhouse gas savings. While the recently launched UKH2 Mobility platform does not guarantee any take-up by the market, it does show that the government is interested in these vehicles.

There appears to be a false perception that investment in electric vehicles comes at the expense of encouraging improvements to the internal-combustion engine. However, the two technologies are at quite different stages of market development: while conventional vehicles are very well established, electric vehicles are only at their infancy. They therefore require different types of government policy. Conventional vehicles need strict but achievable environmental standards while, in theory at least, electric vehicles need supply-push (subsidies for the industry) and demand-pull (consumer incentives such as purchase grants) policies. However, whether the degree of public investment in electric vehicles is appropriate, given their current prospects as a viable form of transport for ordinary people, is another matter, and the subject of considerable debate. If there is any kind of trade-off, it could be said to lie between electric vehicles, particularly pure electrics, and hydrogen fuel cell vehicles. But even here the two technologies are at different market stages – compared to electric vehicles, hydrogen vehicles are far from being a mass-market proposition.

Ultimately, it is not clear which technology will 'win' in the long term. The common consensus in the industry, supported by the market projections reviewed in this report, is that there will not be a single, dominant technology or fuel in the way that there has been over the last century with the monopoly of the internal-combustion engine, but that there will be a range of solutions for different transport applications.

For policymakers this presents a challenge, as it will be difficult for them to decide what policies they should adopt, let alone when and in what form. The case of biofuels shows that decision-makers sometimes get it wrong. In October 2012, the European Commission published proposals to amend the Renewable Energy Directive[2] by capping the share of 'first-generation' biofuels – that is, those derived from food crops – to half of the possible 10% by energy to meet the EU's 2020 targets for renewable road transport fuels. This change of policy caused outrage among the biofuels industry, since these biofuels already account for 4.7% of total fuels, and the industry has huge sunk investments which, effectively, would be wasted if the amending Directive were passed. This example clearly illustrates the need for decision-makers to keep policies under review in the light of new technology and other developments.

It is very clear to us that government policies should be technology-neutral; the emphasis should be on using fiscal and regulatory levers, and other policies,

2 Directive 2009/28/EC: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF

to incentivise both the demand and the supply of low-carbon vehicles in the market place. The record so far has demonstrated how effective this can be. The automotive industry, with the associated huge research and development effort going on, should lead the evolution and the bringing to market of the different technologies, to which consumers will respond. However, we do recognise that government has a role in supporting fledgling research (through, for example, the successful programmes of the Technology Strategy Board). And from time to time there are consequential policy issues (as in the case of biofuels) which cannot be avoided.

Overall, we believe that this report has made a valuable contribution to the discussion on the road ahead for all types of low-carbon vehicles. Only time will tell what exactly we will be driving in the next couple of decades. Whatever it is, it will be low-carbon and very efficient. And, it is to be hoped, also exciting.

On the basis of the evidence in this report, we make the following recommendations:

- Regulation based on tailpipe emissions is increasingly no longer fit for purpose and must be changed to be based on well-to-wheel, and ultimately even life cycle, emissions.
- Government should push strongly for a move away from the current ‘New European Drive Cycle’ (NEDC) test cycle, towards the ‘Worldwide harmonized Light vehicles Test Procedure’ (WLTP) cycle to capture tailpipe emissions and fuel consumption more accurately, as the discrepancy between stated and real-world performance is wide, and confusing for consumers. This must be introduced in tandem with tightening the entire vehicle type approval test.
- The 2025 new car CO_2 target should be set at a maximum of 70 g/km from the tailpipe, with a preferred target of 60 g/km. Regulation must be carefully designed to capture well-to-wheel (or even life cycle) emissions, whilst spreading the burden on vehicle manufacturers in an equitable manner.
- Government should take a technology-neutral approach to the encouragement of low-carbon vehicles. It should focus on the use of fiscal, regulatory and other policy levers to drive both the demand and supply of such vehicles, leaving the automotive industry to lead the evolution, and the bringing to market, of the various technologies.
- Government must deal with the ‘ILUC issue’ – indirect land-use change, in other words secondary and often unanticipated negative environmental impacts – if it wants to seriously consider biofuels and avoid any potential negative indirect consequences.

RAC Foundation

UK Petroleum Industry Association

Executive summary

Introduction

This report examines how the challenge of achieving the UK's legally binding commitment to a substantial reduction in greenhouse gas (GHG) emissions by 2050 is likely to affect the cars and fuels we will use over the next 20 years.

In 2008, Professor Dame Julia King set out her recommendations for action to reduce carbon dioxide (CO_2) emissions from the passenger car sector in the *King Review of low-carbon cars*. Since then policies and initiatives to promote the uptake of lower-carbon cars have been introduced at both European and national levels, and manufacturers and fuel suppliers have worked to develop lower-carbon options for consumers.

Policy context

In 2008, the UK became the first country in the world to introduce a law committing the government to cut GHG emissions: the Climate Change Act 2008. This requires an 80% reduction in GHG emissions by 2050 relative to a baseline of 1990.

Transport is responsible for 21% of UK GHG emissions by source, with cars accounting for 55% of that share or 12% of the total.

Later this year the European Commission is expected to confirm that new cars sold in Europe should emit an average of 95 gCO_2/km or less by 2020. Consultation will also be held until 2014 regarding a new target for 2025.

Alongside this, the Commission has introduced directives governing renewable energy and vehicle fuels, which require that at least 10% of transport fuels by volume (excluding aviation fuels) must originate from renewable sources by 2020. It had been expected that the vast majority of this would be met through the use of biofuels. However, there are continuing concerns about the true level of biofuel GHG savings, particularly for first-generation biofuels, once 'indirect land-use changes' (ILUCs) have been taken into account. As a result, in October 2012, the Commission announced proposals to amend the Renewable Energy Directive so that no more than half of the 10%-by-energy target can be met through the use of first-generation crop-based biofuels. Given that current production volumes of alternative next-generation biofuels are relatively small, and that uptake levels of plug-in electric vehicles using renewable electricity may well provide only a limited contribution, it is not clear how this target will be reached by 2020.

The UK has introduced a range of policies to encourage uptake of lower-emission vehicles. Vehicle Excise Duty (VED) and company car tax have been progressively revised to strengthen incentives to choose low-CO_2 options. The UK's colour-coded vehicle fuel economy labelling system is designed to make it easier for consumers to choose more fuel-efficient models. In 2010, a new 'first-year rate' of VED was introduced to provide a stronger signal at the point of purchase, with rates for the highest-CO_2 vehicles now set at over £1,000.

The Plug-in Car Grant scheme provides 25% (capped at £5,000) towards the cost of eligible plug-in cars (and 20% – capped at £8,000 – for plug-in vans). The Plugged-in Places scheme has seen over 2,800 charging points installed, in eight areas of the country.

Together these policies appear to be having the desired effect. According to the SMMT (Society of Motor Manufacturers and Traders), the average tailpipe CO_2 emission figure for cars sold in the UK in 2012 was 133.1 g/km, representing a fall of almost 23% over the last decade.

Maintaining this good rate of progress in the reduction of carbon emissions from cars will require that future policies continue to drive technological progress. Perhaps the most important decision facing policymakers is what level to set as the target for CO_2 emissions in 2025. The European Commission has announced that it will explore a level of 70 g/km, and is expected to seek stakeholders' views on both this and a target for vans sometime in 2013. Some environmental groups feel that the 2020 target of 95 g/km lacks ambition, and are already pushing for 60 g/km by 2025.

Alongside this is the problem of a growing gap between the type-approval fuel economy figures obtained using the official test cycle (the NEDC – New European Drive Cycle) and those that drivers achieve in the real world. It has been noted that some of the largest differences are for the vehicles with the lowest official CO_2 figures, meaning that consumers who choose the most 'environmentally friendly' option may be the most disappointed by their vehicle's actual fuel economy.

The Commission aims to address this by introducing the new 'Worldwide harmonized Light duty vehicles Test Procedure' (WLTP), which is considered to be more representative of real-world driving conditions. The WLTP is being developed under the UNECE (UN Economic Commission for Europe) for global application. Alongside this, changes are also planned to the way that emissions tests are conducted.

In the longer term there is an increasing need to consider not merely the CO_2 emissions from vehicle exhausts, but the whole life cycle environmental impacts of vehicles. For pure electric vehicles, referred to here as battery electric vehicles (BEVs), it does not make sense for legislation to relate solely to tailpipe emissions, since there are none. However, there are certainly emissions associated with the production of the electricity needed to power the vehicle. Equally, BEVs' manufacturing emissions are currently significantly higher than those of a comparable conventional vehicle (owing primarily to the batteries).

Future fuels and vehicle technologies

In the past, conventional petrol- and diesel-fuelled internal-combustion engines (ICEs) were the dominant technology. But a much wider range of technologies and fuels is already becoming available, and these will become ever more common in the coming years.

Chapters 3 and 4 of this report investigate, respectively, the future potential of a range of fuels and of powertrain technologies and other aspects of vehicle technology that improve efficiency. For each option the chapters set out, and where possible quantify, their characteristics in terms of GHG reductions, advantages and disadvantages, infrastructure requirements, availability, and cost. A high-level summary of the findings is presented here:

Petrol and diesel: Conventional petrol- and diesel-powered cars accounted for virtually all (99%) of new cars sold in the UK in 2012. The diesel engine's higher efficiency offers a reduction in life cycle GHG emissions per km of about 14% compared to an equivalent petrol vehicle, although technologies such as petrol direct-injection in combination with downsizing and turbocharging might reduce this advantage. Petrol engines produce lower NO_x and particulate emissions, although the Euro standards on air pollutants will narrow the gap between petrol and diesel vehicles. However, the additional exhaust aftertreatment needed for diesel vehicles to meet these standards may further erode their fuel economy advantage.

LPG (liquefied petroleum gas) / CNG (compressed natural gas): Gas-powered vehicles account for only a tiny fraction of new car sales in the UK. Many manufacturers offer natural gas vehicles in other countries, and aftermarket conversions are available here. Life cycle CO_2 emissions for CNG are up to 24% lower than for a comparable petrol car. For LPG the figure is about 14%. LPG- and CNG-powered vehicles also produce lower NO_x emissions and very low particulate emissions. However, the lack of refuelling infrastructure, and the reduced range compared to petrol or diesel, continue to constitute barriers to their uptake.

First-generation biofuels: There is a range of first-generation crop-based biofuels currently available. Bioethanol and biodiesel are already used by motorists, in that forecourt petrol and diesel contains a *c.*5% blend of biofuel. High-blend strength biofuels (e.g. E85 – petrol with an ethanol content of 85%) are not available to the mass market in the UK. The GHG savings for first-generation biofuels vary considerably according to the feedstock used, the manufacturing process, and in particular issues of ILUC. Some are calculated to result in GHG emissions that are actually higher than those of fossil fuels. However, the use of biomethane (a purified form of biogas) can result in life cycle GHG emissions savings of over 70–80% compared to petrol. Biogas is typically produced from waste biomass or manure, meaning that there are little or no emissions caused by ILUC. The disadvantages of biomethane are much the same as those of CNG.

Next-generation biofuels: Next-generation biofuels are made using more advanced processes, and usually from non-crop biomass such as stems, leaves and husks, or grasses or woody energy crops, or possibly waste wood. They are therefore less likely to result in competition with food. There are several alternative processes used to create next-generation biofuels. The GHG savings vary significantly depending on the feedstock and the production process; however, they are typically much greater than for first-generation biofuels, partly because they largely avoid the issue of ILUC. However, current production volumes are low, and next-generation biofuels may not make a significant contribution to meeting carbon reduction targets until after 2020. A further issue is that in the future they might need to be prioritised for use in aviation and shipping, sectors in which there are fewer technical alternatives to liquid fuels for GHG reduction.

Hybrid and electric vehicles: The increasing electrification of powertrains is widely regarded as the most likely route to achieving GHG reduction targets for passenger cars. The progression in technology is expected to be from widespread use of stop–start (so-called ‘micro hybrid’) technology, to a growing market share for hybrid electric vehicles (HEVs or ‘full hybrids’), through to plug-in hybrid electric vehicles (PHEVs) and range-extended electric vehicles (REEVs), and ultimately BEVs. Hybrid technology (non-plug-in) is currently gaining market share and can reduce GHG emissions by 15–25%. Currently the average fuel life cycle GHG saving for a BEV over its full life is calculated to be over 50% under UK conditions – that is, with the current mix of grid electricity generation. This could increase to 75% in 2020 and to 83% by 2030 with the anticipated decarbonisation of grid electricity. However, BEVs face major challenges in gaining market share because of their high prices and limited range. Breakthroughs in technology, particularly in the cost and performance of batteries, are required before PHEVs and BEVs can achieve significant market share.

Hydrogen fuel cell vehicles: Renewably produced hydrogen used in fuel cell vehicles (FCVs) offers amongst the largest potential GHG reduction possible (next to BEVs). FCVs also offer the benefit of a range comparable to conventional vehicles. However, they face a number of barriers. They are currently substantially more expensive than conventional vehicles, or even BEVs, as a result of fuel cell costs. There are also very few locations where they can be refuelled. Their actual GHG savings are dependent on the source of the hydrogen. Typically they are expected to achieve around 70% savings in 2030, assuming hydrogen sourced from a mix of natural gas reformation and electrolysis.

In summary, each of these options involves trade-offs between GHG savings, cost, range and required refuelling infrastructure. However, one area which will benefit all these options is that of **improving vehicle energy efficiency through reduced weight and reduced drag**. A greater focus on the use of ultra-lightweight body structures and achieving the lowest possible drag coefficient and frontal area, together with reducing rolling resistance, can substantially reduce the overall energy requirement. This is particularly beneficial for BEVs, where drag and rolling resistance represent the majority of the energy losses. Reducing these losses can allow a smaller battery or fuel cell to be used, reducing costs.

Predicted future market shares of vehicle technologies

In order to understand the likely growth in market shares for the different car technologies available, 14 separate studies were analysed, and their predictions – and the underlying assumptions – were compared. It is important to note that some studies attempt to forecast on the basis of existing trends, whereas others 'backcast' from a future scenario. These two methods can result in significantly differing results.

The technologies covered by the studies reviewed included HEVs, PHEVs, REEVs and BEVs. These studies provided a range of estimated market shares for each of the technologies; from these a series of 'mainstream' predictions (rounded to the nearest 5%) were then identified, as shown in the table.

To put these figures into context, in 2012 the UK market share for hybrid cars was 1.2%. For Plug-in Car Grant eligible vehicles it was just 0.1%, with pure BEVs accounting for 0.06%.

Predicted market share of low-carbon vehicles

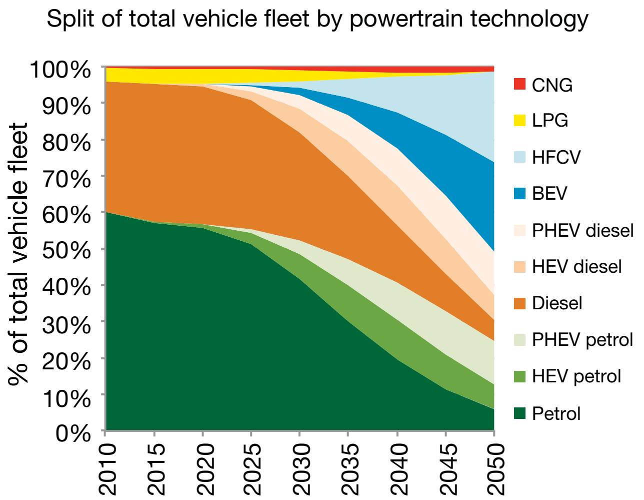
Technology	2020	2030
Full hybrids	5–20%	20–50%
Plug-in hybrids	1–5%	15–30%
Range-extended electric vehicles	1–2%	5–20%
Battery electric vehicles	1–5%	5–20%

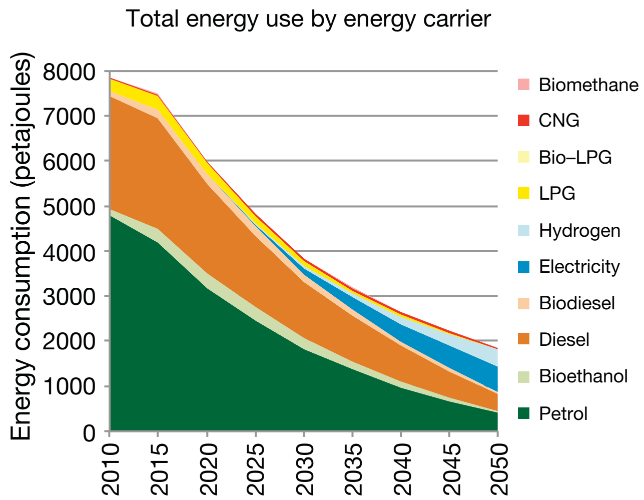
Notes: The ranges presented in the table above are for individual powertrain options, and often from different sources. There will necessarily be interaction between the deployment of different options, and also with conventional ICE powertrains. The respective upper/lower limits for the different technologies cannot therefore be simply added together. There was insufficient data to provide estimates for FCVs. The remainder of the market will remain conventional ICE powertrains.

Each of the studies from which these average figures are taken makes a set of assumptions regarding certain key sensitivities. The factors which appear to have the strongest influence over the predictions are, firstly, future government policy, and, secondly, the likely speed with which breakthroughs in technology, particularly with respect to batteries and fuel cells, will be achieved.

Predicted future market shares of fuels

The expected changes in terms of the fuels which are likely to be used in future vehicles are shown below. These figures show Ricardo-AEA's assessment of the most likely scenario for meeting EU 2050 carbon reduction targets, based on known measures identified in the European Commission's 2011 Transport White Paper and recent concerns about the availability and sustainability of biofuels. On the left-hand side it can be seen that petrol and diesel vehicles are expected to remain the dominant technology in the overall vehicle fleet until at least 2030. However, the plot on the right illustrates how the actual quantities of petrol and diesel used (and as a result the energy provided) will fall dramatically as a result of the continuing improvements in ICE vehicle efficiency.





Source: Ricardo-AEA analysis

Many other factors might affect the speed of uptake of low-carbon cars. These include rising oil prices, potential resource constraints (e.g. for the rare earth metals needed for electric drivetrains), and the possibility of increasing urbanisation leading to a shift away from car ownership to alternatives such as car sharing, improved public transport, and other forms of personal mobility such as electric bikes and scooters – all developments, of course, which would in themselves lower GHG emissions, without reference to low-carbon cars.

Conclusions

In the near future, the expectation is that conventional petrol and diesel vehicles will continue to dominate personal transport, with advances in fuel economy being achieved by means of innovations in engine technology combined with a greater focus on improving vehicle efficiency through reduced weight and drag. At the same time, technologies such as stop–start systems are expected to become commonplace, and full hybrid technology will continue to increase its market share.

In the medium term, if breakthroughs in battery technology deliver the necessary performance improvements and cost reductions, there will be increasing electrification of powertrains. Increasing numbers of vehicles will offer an ‘electric-only’ drive mode, and the numbers of plug-in hybrid models available will increase. BEVs will start to gain market share too, as consumer confidence in electric powertrain technologies increases.

In the longer term, the likely mix of technologies is extremely difficult to predict. The speed with which PHEVs and BEVs (including fuel cell vehicles) will achieve significant market shares is highly dependent on their total cost of ownership in comparison to that of more conventional alternatives. This is, in turn, dependent on factors such as oil prices, further battery and fuel cell cost reductions, and government policies.

In the meantime the key question facing policymakers at present is at what level to set the target for tailpipe CO_2 emissions in 2025. Our analysis suggests that to achieve a 70 g/km target may require the new vehicle market share for PHEVs and BEVs to reach around 5% by 2025, in combination with further improvements to conventional and hybrid powertrain vehicles. This matches the most pessimistic market uptake projections of such vehicle types. A 60 g/km target would likely require PHEVs and BEVs to gain market shares which are towards the midpoint of the range of current projections.

There is no doubt that meeting a target of 60 g/km would be a challenge. However, some experts believe that this could be achieved, were government and the automotive industry to work to create the right policy framework and to try and ensure that the necessary advances in technology are realised.

1. The Challenge

1.1 Introduction

This report examines how addressing the challenge of achieving an 80% reduction in greenhouse gas (GHG) emissions by 2050 is likely to affect the cars and fuels that we use over the next twenty years. It reviews the range of different vehicle and fuel technologies, examining their comparative advantages and disadvantages. It also reviews predictions for their likely market shares through to 2030.

It is now six years since Professor Dame Julia King set out her recommendations for action to reduce carbon dioxide emissions from the passenger car sector in the *King Review of low-carbon cars* (King, 2007). In that time there have been many changes: policies have been introduced designed to promote the uptake of lower-carbon cars; regulations have come into force to drive down the ‘tailpipe emissions’ (i.e. those generated directly from the use of the fuel in the vehicle) of new cars; and new vehicle technologies have come to market. As a result, the average level of CO_2 emissions for new cars sold in the UK in 2012 was almost 23% lower than in 2002 (SMMT, 2013a).

Much of the progress so far has been achieved through comparatively low-cost improvements to conventional technologies – indeed, some has been due simply to the continuing growth in the proportion of diesel vehicles and a shift to smaller vehicles. Looking to the future there remain many questions. Can this rate of progress be maintained? Which new technologies and fuels will become commonplace over the next twenty-five years?

This report synthesises the vast array of literature that has been written on the subject of low-carbon cars and aims to present a clear explanation of the range of fuels and technologies that might be seen on the road in the future. It also examines whether they are likely to be niche, low-volume products or can be expected to grow to dominate the market.

However, it is first important to re-examine the reasons why we need low-carbon vehicles (LCVs) and fuels.

1.2 Meeting UK greenhouse gas reduction targets

1.2.1 Global scientific position on climate change

The primary organisation charged with compiling and summarising scientific analysis of climate change is the Intergovernmental Panel on Climate Change

(IPCC). Its Fourth Assessment Report, published in 2007, concluded that "warming of the climate system is unequivocal" and stated that:

> "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic [caused by human activity] GHG concentrations" (IPCC, 2007).

It should be noted that despite the widely reported criticism of the report and the discovery of some minor errors, these conclusions still stand.

Scientific studies since 2007 indicate that the situation appears to be worsening. In May 2009, ahead of the UNFCCC (United Nations Framework Convention on Climate Change) negotiations at Copenhagen, a joint statement from science academics stated that:

> "climate change is happening even faster than previously estimated; global CO_2 emissions since 2000 have been higher than even the highest predictions, Arctic sea ice has been melting at rates much faster than predicted, and the rise in the sea level has become more rapid" (G8+5 Academies, 2009).

The IPCC's Fifth Assessment Report will review the more recent scientific evidence for climate change and draw conclusions based on this. It is due for finalisation in 2014.

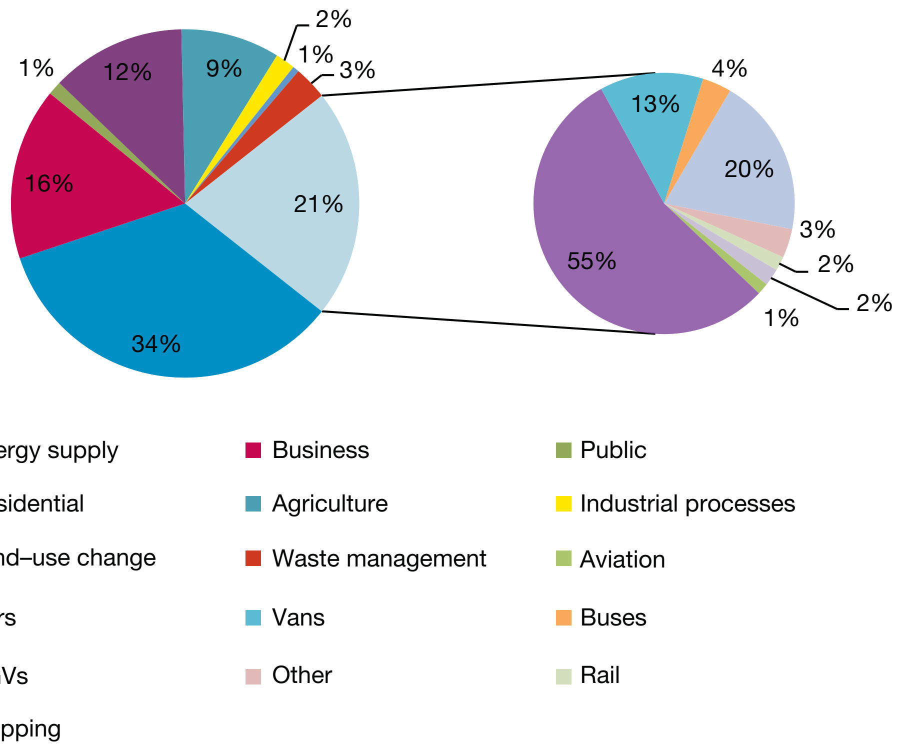
1.2.2 UK policy on climate change

The *King Review of low-carbon cars* was published the year after Sir Nicholas Stern's influential report on the economics of climate change (HM Treasury, 2006). The Stern Review recommended that strong, early action should be taken to address climate change.

In 2008, the UK became the first country in the world to introduce a law committing the government to cut GHG emissions. The Climate Change Act 2008 requires an 80% reduction by 2050 relative to a baseline of 1990.

The Department of Energy & Climate Change (DECC) reports on UK GHG emissions. Data for 2011 shows transport to be responsible for 21% of these emissions, with cars accounting for 55% of that share (Figure 1.1). The dominant GHG is carbon dioxide (CO_2), and road transport accounts for 24% of the UK's total CO_2 emissions (NAEI, 2013).

Figure 1.1: UK greenhouse gas emissions by source (2011 figures)



Source: NAEI (2013)

The UK needs to do more if it is to meet carbon reduction targets

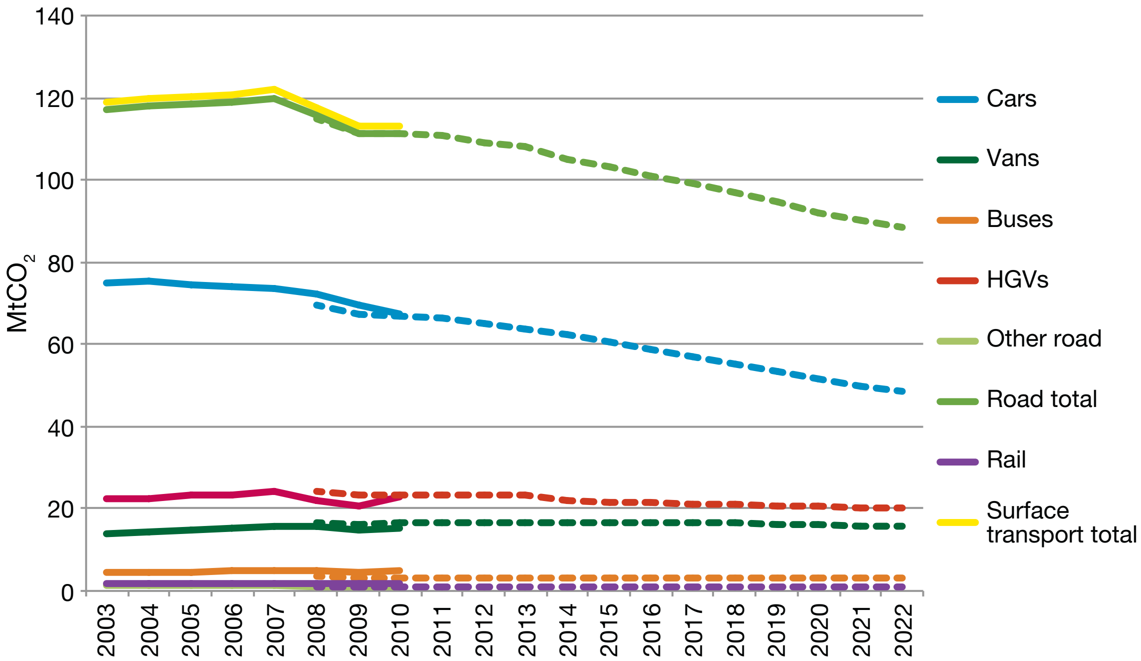
The Climate Change Act 2008 also established the Committee on Climate Change (CCC), an independent body which advises the UK government on setting and meeting carbon budgets and on adapting to climate change.

The Committee's identified carbon budgets are designed to ensure that the target of an 80% reduction by 2050 on 1990 levels is met. The Committee has developed three abatement scenarios for savings which could be achieved by 2020: 'Current Ambition', 'Extended Ambition' and 'Stretch Ambition'. In the Current Ambition scenario, transport is expected to contribute only 5 $MtCO_2$ (million tonnes of carbon dioxide) reductions, which is 6% of the total identified reductions. In the Stretch Ambition scenario, this increases to 32 $MtCO_2$ reductions equating to 23% of the total identified UK abatement potential across all sectors in 2020.

The Committee's progress report to Parliament in June 2012 highlighted the fact that although surface transport emissions had fallen between 2007 and 2009, in 2010 there was no further reduction (Figure 1.2).

Data on emissions levels and distances travelled suggests that overall emissions from cars fell in 2010. This is partly a consequence of a reduction of 2% in the distance travelled by cars, but an increase in biofuel use from 2.1% to 3.2% and new car CO_2 emissions falling by 3.5% will also both have contributed. Emissions from vans and heavy goods vehicles (HGVs) are reported to have increased, with distances travelled rising in both cases. For vans this outweighed the slight improvement in new van CO_2 emissions, while for HGVs the fleet efficiency is also estimated to have worsened (CCC, 2012). The Committee estimated that emissions from cars are likely to have decreased by a further 1.8% in 2011, despite a slight (0.5%) increase in car use, but warned that significant cuts in surface transport emissions are needed if future carbon budgets are to be met; it also highlighted that planned changes to company car tax, and discussion about raising the motorway speed limit, risk increasing emissions rather than reducing them (CCC, 2012).

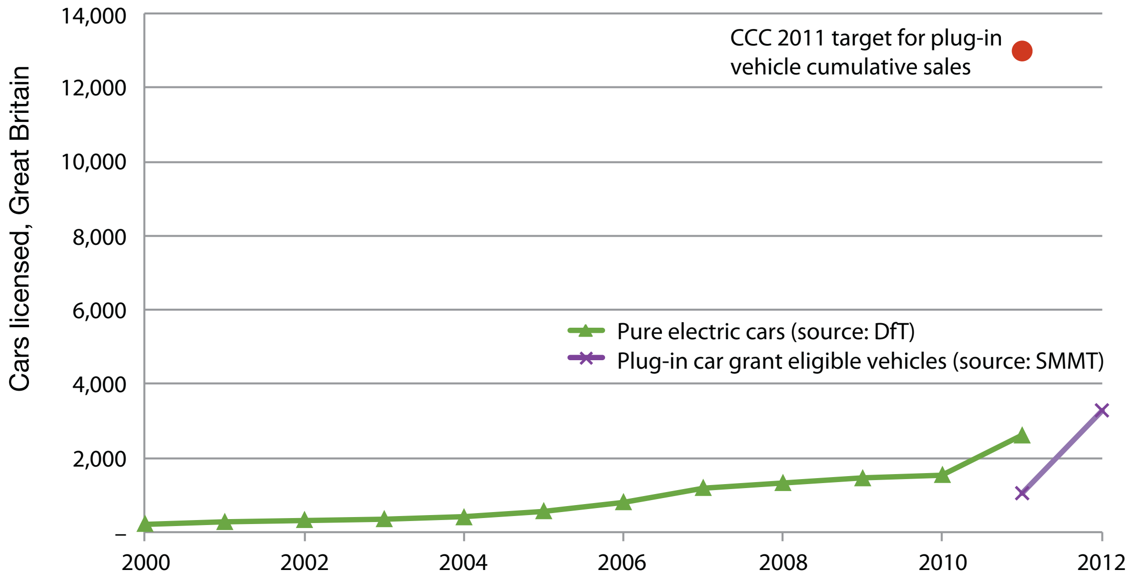
Figure 1.2: UK surface transport CO_2 emissions historic and indicator trajectories, 2003–22



Source: CCC (2012)

Meanwhile, sales of plug-in hybrid electric vehicles (PHEVs), range-extended electric vehicles (REEVs) and battery electric vehicles (BEVs) are well behind the Committee's estimates of required uptake, with total registrations of vehicles eligible for the Plug-in Car Grant reported as 3,293 at the end of December 2012 (SMMT, 2013b), against a target of 13,000 by the end of 2011 (CCC, 2012) – see Figure 1.3. The Committee's scenarios for meeting carbon budgets envisage that by 2020, up to 1.7 million BEVs, PHEVs and hydrogen fuel cell vehicles (HFCVs) will need to be on the road. By 2030 this is targeted to rise to 11 million, with almost all new vehicle sales in the mid-2030s being electric.

Figure 1.3: Pure electric and Plug-in Car Grant eligible vehicles licensed in Great Britain



Source: DfT (2012a) and SMMT (2013)

The Committee is also critical of the poor progress made in encouraging 'eco-driving' techniques (adopting more efficient driving styles), enforcing speed limits, and encouraging increased use of alternatives to cars.

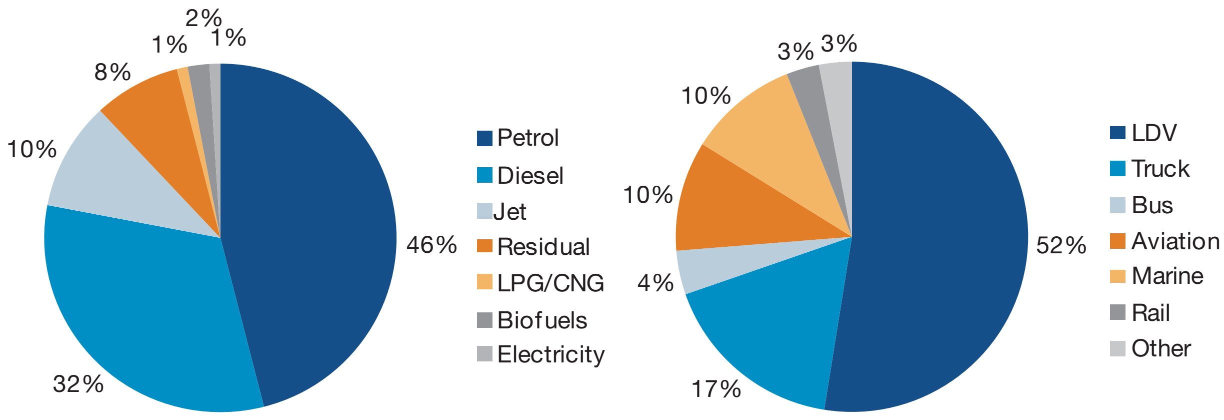
Thus, while progress is being made to reduce GHG emissions from the UK passenger car fleet, the rate of reduction needs to increase if the legally binding carbon budgets are to be met.

1.3 Road transport's contribution globally

The automotive industry consists predominantly of global multinational companies designing products which will be sold in many different markets across the world. Research and development (R&D) priorities for future models will be dictated by the legislative requirements and customer demands across many countries.

Globally, transport accounts for about 25% of CO_2 emissions (IEA, 2009a) – similar to the UK's figure of 26% (NAEI, 2013). Of this, road transport is responsible for around 73% of total transport energy use, with light-duty vehicles (LDVs: primarily passenger cars) accounting for 52% (Figure 1.4), or around two thirds of the road transport total (World Economic Forum, 2011).

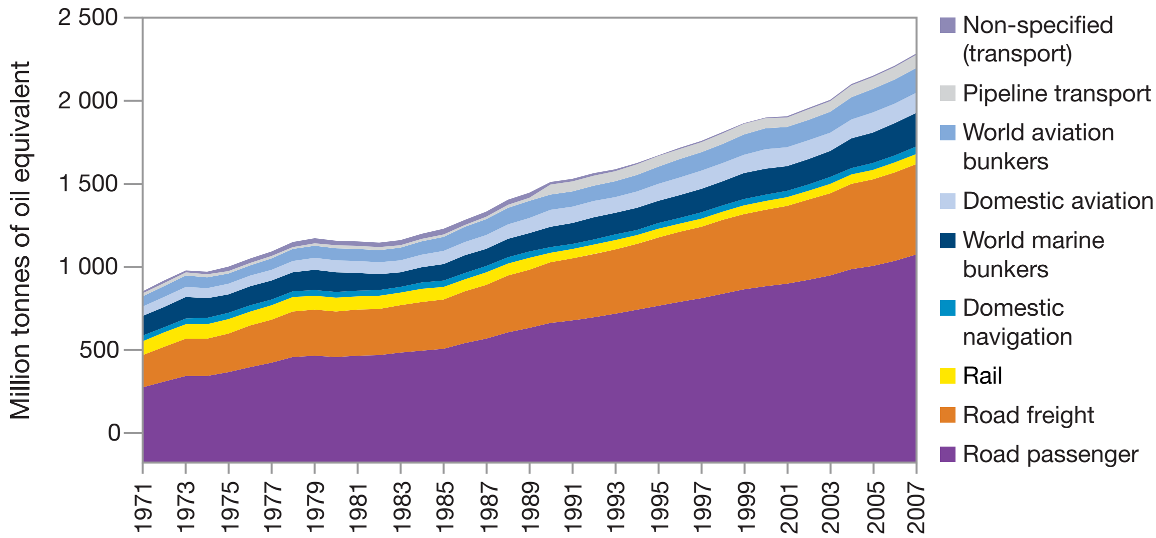
Figure 1.4: Global transport energy use (diagram from World Energy Council's Global Transport Scenarios, 2011)



Source: World Economic Forum (2011)

Road passenger transport has also been responsible for the vast majority of growth in absolute energy consumption by the transport sector over the last four decades (Figure 1.5).

Figure 1.5: World transport final energy use by mode



Source: IEA (2010)

One billion cars now, rising to three billion in 2050?

The growth in road passenger transport energy consumption results from increasing numbers of vehicles, but also from increasing intensity of their usage. The global stock of light-duty passenger vehicles stood at around 780 million in 2007, representing an increase of around 60% over 1990 numbers; in 2012 it has been estimated that this figure could top one billion (Elmer, 2012).

The International Energy Agency's (IEA) World Energy Outlook 2012 estimates that the passenger vehicle fleet will be almost 1.7 billion vehicles by 2035 (Lucas, 2011). The IMF (International Monetary Fund) has estimated that three billion cars will be on the world's roads by 2050 (IMF, 2008). Most of this growth will be in countries outside the OECD (Organisation for Economic Co-operation and Development) in which both population and GDP growth will be strongest, particularly the BRIC countries (Brazil, Russia, India and China) – these are expected to account for 83% of future market growth (Roland Berger, 2011). If car ownership and use in non-OECD countries continues to develop in the same way as it did in the OECD, then car use outside the OECD would be around 3.6 times as high in 2050 as it was in 2010 (International Transport Forum, 2012).

While the IMF estimates the personal income levels to purchase three billion cars will be reached, such levels of growth call into question the sustainability of the sector. Problems of congestion may mean that the attraction of personal car ownership declines, particularly when combined with rising fuel costs. From an environmental perspective, without a substantial shift away from conventional internal-combustion engine (ICE) vehicles, not only would global transport GHG emissions grow substantially, but issues such as oil reserves, energy security, and air pollution would have to be faced far sooner than otherwise. Even with the introduction of ultra-low-carbon vehicle technologies, there still remain questions over resource constraints.

There is thus an urgent need to develop highly efficient, low-emission passenger cars, and to find ways to manufacture them within environmental limits.

1.4 Europe and the UK's role

While the strongest growth in future car sales is likely to be outside Europe, many consider it unlikely that markets such as China and India will see the strongest take-up of future low-carbon car technologies and fuels. Instead, the growth in these markets is expected to be primarily in low-cost conventional technologies. For example despite China's aggressive promotion of electric vehicle technologies, only 0.06% of car sales in China were hybrids in 2010, compared to 0.7% in Europe, 2.5% in the USA and 11% in Japan.

Europe is expected by many to lead the world in the take-up of hybrid and electric vehicle technologies. This is a key role – vehicle manufacturers need market demand in developed markets such as Europe, Japan and the USA in order to be able to invest in the substantial R&D required for these technologies.

However, take-up of advanced technologies such as BEVs has been low so far. In addition, passenger car ownership and use in many OECD countries appears to be reaching saturation levels, and in some major markets – such as Japan, France, Italy, the UK, and the USA – levels of personal car use have started to decline, leading some commentators to refer to 'peak car' (Schipper & Millard-Ball, 2011). More detailed analysis of the situation in the UK suggests that this phenomenon needs careful interpretation, with strong variations between different geographic regions and sections of society. For example, in London, which benefits from perhaps the best public transport systems in the UK, car use has declined markedly, but for other regions it is increasing, particularly when company car mileage is excluded (Le Vine & Jones, 2012). Nevertheless, while a decline in use may help reduce greenhouse gas emissions in OECD countries, it could make it difficult for automotive OEMs (original equipment manufacturers) to justify investment in what may be stagnant or declining markets.

If policymakers wish to achieve the carbon reduction targets set out, it will be essential to ensure that there is sufficient support available to allow the market for these new technologies to grow. This policy context is explored in the next section.

2. The Policy Context

2.1 Introduction

The growth in UK sales of new low-carbon cars, and the fuels needed to run them, will be strongly influenced by government policies both at a national and a European level.

At a national level, the UK's Climate Change Act 2008 has already been discussed and remains a strong high-level driver of change, but many other more detailed actions have been put in place to promote take-up of low-carbon cars since the King Review was published in 2007.

However, it is important first to understand the key role played by European transport policy, and its impact on the UK.

2.2 European transport and fuel policy

The key policy document for transport in Europe is the 2011 Transport White Paper, which has the aim of “growing transport and supporting mobility while reaching the 60% emission reduction target [by 2050]” (European Commission, 2011f). This includes objectives of:

- halving the use of ‘conventionally fuelled’ cars in urban transport by 2030 and phasing them out in cities by 2050;
- halving road casualties by 2020 and moving close to zero casualties by 2050;
- reducing oil dependency;
- improving air quality in cities.

The White Paper states:

> “The race for sustainable mobility is a global one. Delayed action and timid introduction of new technologies could condemn the EU transport industry to irreversible decline. The EU’s transport sector faces growing competition in fast developing world transport markets” (European Commission, 2011f: 5).

It goes on to say:

> “The synergies with other sustainability objectives such as the reduction of oil dependence, the competitiveness of Europe’s automotive industry as well as health benefits, especially improved air quality in cities, make a compelling case for the EU to step up its efforts to accelerate the development and early deployment of clean vehicles” (ibid.).

The European Commission’s strategy for the automotive sector is informed and guided by a number of bodies, including:

CARS21 (the Competitive Automotive Regulatory System for the 21st century) has as its aim "to make recommendations for the short-, medium-, and long-term public policy and regulatory framework of the European automotive industry."

European Green Cars Initiative – a Public-Private Partnership formed to "support R&D on technologies and infrastructures that are essential for achieving breakthroughs in the use of renewable and non-polluting energy sources, safety and traffic fluidity."

ERTRAC (the European Road Transport Research Advisory Council) – this body is supported and recognised by the European Commission as the European Technology Platform for Road Transport, and on its website it states that its aim is "to develop a shared vision and to ensure a timely, coordinated and efficient implementation of Research in Europe, with the objective to tackle the societal challenges of road transport and to enhance the European Competitiveness".

In November 2012, the European Commission published *CARS 2020*, its action plan for the automotive sector (European Commission, 2012b). This emphasises a broad approach to reducing CO_2 emissions from the automotive sector, focusing not merely on powertrain technology, but also on complementary measures such as alternative fuels, driver behaviour, and other technological improvements such as improved aerodynamics. It reaffirms the Commission's commitment to 2020 CO_2 targets for cars and vans, including the use of eco-innovation provisions and 'super credits' for low-CO_2 vehicles (whereby cars that emit less than 35 gCO_2/km count as 1.3 vehicles), and announces a broad consultation on post-2020 targets. This is expected to lead to goals for 2025 and 2030 being announced by the end of 2014.

2.2.1 European passenger car CO_2 policy

In February 2007, the Commission set a legislative framework (Table 2.1) to achieve the EU objective of average passenger car tailpipe CO_2 emissions of 120 g/km, which is being implemented through Regulation (EC) No 443/2009. This regulation mandates reductions in CO_2 emissions to reach an average of 130 g/km for the new car fleet though improved vehicle motor technology by 2015, which equates to around a 7% reduction from the average levels of 2010. A further reduction of 10 g/km or equivalent is to be achieved by other technological improvements and by increased use of biofuels. The overall target applies to all new car sales; however, individual manufacturers (or groups of manufacturers) are assigned targets based on the average mass of the new cars that they sell.

Table 2.1: European car tailpipe CO_2 emissions targets summary

Year	CO_2 target	Additional reduction	Eco-innovations	Super credits	Penalties
2015	130 g/km (phased in from 2012).	10 g/km through technological improvements and increased use of biofuels	Up to 7 g/km credits p.a. for technologies which reduce off-cycle, unmeasured CO_2	Each car sold below 50 g/km can be counted as 3.5 cars in 2012–13, as 2.5 in 2014, and as 1.5 in 2015	€95 per g/km over the target (but only €5, €15 or €25 for being 1 g, 2 g, or 3 g over respectively till 2018)
2020	95 g/km (adjusted to ensure comparable stringency when new test cycle is introduced)	Not applicable	Eco-innovations are retained when the revised test procedure is implemented; details to be established	Each car sold below 35 g/km can be counted as 1.3 cars from 2020–3, limited to a cumulative figure of 20,000 vehicles per manufacturer over the duration of the scheme	€95 per g/km over the target

Source: Ricardo-AEA

Eco-innovations

Because of the nature of the test used to assess new car CO_2 emissions, some technologies which may help to reduce CO_2 emissions in the real world will not give CO_2 reductions on the test cycle. For example, a more efficient air conditioning system might reduce fuel consumption and emissions for drivers, but during the test cycle it is mandated that the air conditioning system is switched off. Manufacturers can be granted emissions credits equivalent to a maximum emissions saving of 7 gCO_2/km per year for their fleet if they equip vehicles with innovative technologies, based on independently verified data (European Commission, 2012g).

Super credits

Super credits give manufacturers additional credit for selling very low-CO_2 vehicles. Currently each vehicle sold below 50 g/km can be counted as 3.5 vehicles when calculating a manufacturer's average fleet emissions. It is argued that this incentivises manufacturers to introduce innovative very low-CO_2 technologies. Others have pointed out that the system can provide a way for manufacturers who do this to continue to sell more high-CO_2 vehicles (Transport & Environment, 2012).

Limit value curve and the importance of the slope

The 'limit value curve' is actually a straight line which defines the relationship between the CO_2 emissions target and the mass of a vehicle. Manufacturers of heavier cars are allowed higher emissions limits than those of lighter ones. This is in recognition of the fact that it is important that a wide range of vehicle types is available to meet people's needs. Weight is used as a 'proxy' for utility, as a larger vehicle with more carrying capacity will generally be heavier, and is therefore likely to use more energy and produce higher CO_2 emissions.

For the 2015 target, the slope of this line is set such that the CO_2 emissions target for a manufacturer is increased by 4.57 g/km for each 100 kg additional vehicle weight. It is important that this allowance does not incentivise manufacturers to increase vehicle weight, so the slope of this relationship must be shallow enough to avoid this.

Additional legislation to reduce greenhouse gas emissions from cars

The Commission has also introduced other legislation aimed at reducing GHG emissions from passenger cars. Regulation (EC) No 661/2009 mandates that all new passenger cars offered for sale must have tyre pressure monitoring systems (TPMS) and gear shift indicator lights from 1 November 2014. Low rolling resistance tyres must also be fitted, although these are to be phased in from November 2014 to November 2018. Together the Department for Transport (DfT) expects these to have the potential to reduce fuel consumption by 20% by 2020 (DfT, 2010b). Regulation (EC) No 1222/2009 requires tyre labels to be fitted indicating their performance level for rolling resistance, grip and noise on a scale of A to G. This will help inform consumer choice, and is hoped to encourage use of low rolling resistance tyres on all cars.

Regulations to reduce tailpipe CO_2 emissions from vans were introduced in May 2011. These set targets of 175 g/km in 2014, falling to 147 g/km by 2020.

The new 95 gCO$_2$/km target for 2020

In July 2012, the European Commission issued a proposal for a regulation which set out how it plans to define calculations to reach the 2020 target of 95 gCO$_2$/km (European Commission, 2012e). This proposal is now being reviewed by the European Parliament and Council of Ministers. The proposal continues to use a mass-based target, whereby heavier vehicles are given more lenient targets than lighter ones. This is despite criticism of this approach by those who argue that it tends to discourage manufacturers from reducing vehicle weight, whereas adopting a 'footprint'-based approach would lessen this effect (Transport & Environment, 2008; 2011). However, the 'slope' of the limit value curve has been flattened to 3.33 gCO$_2$/km for each 100 kg of additional vehicle weight, which should help to discourage any tendency to increase weight.

The system of eco-innovations is being continued, and super credits are to be reintroduced from 2020 to 2023, but for cars below 35 gCO$_2$/km – where previously the threshold was 50 gCO$_2$/km.

2.2.2 European fuel directives

European Directives also affect the quality and nature of the fuels available in the UK. For example, since 2009 all fuels have had a sulphur content of less than 10 ppm (parts per million). The development of tightly specified, high-quality fuels has allowed manufacturers in turn to develop engine technologies – particularly those related to the combustion system and fuel injection – which are optimised to suit these fuels. This has enabled the introduction of direct-injection engines and also reduced emissions of conventional pollutants from the existing fleet of vehicles.

An overview of the two main European fuels directives affecting the industry is provided in Table 2.2.

Table 2.2: European fuel directives

Renewable Energy Directive Directive 2009/28/EC (which replaced 2003/30/EC)	The EU committed to a binding target to ensure that 10% of the energy content (effectively meaning more than 10% by volume) of transport fuels (excluding aviation fuels) would originate from renewable sources by 2020 as part of a broader Directive on Renewable Energy (2009/28/EC). Bi-annual reporting on progress has been required since 31 December 2011. This Directive replaced the earlier Biofuels Directive (2003/30/EC), which had required a minimum share of biofuels sold to be 5.75% by the end of 2010. On average, member states achieved an overall level of 4.9% by 2010, although some exceeded 5.75%.
Fuel Quality Directive Directive 2009/30/EC (which amended 98/70/EC)	This Directive sets environmental requirements for petrol and diesel fuel to reduce their air pollutant emissions. Under this Directive, member states have been required to implement mandatory full conversion to sulphur-free fuels (i.e. with less than 10 mg/kg sulphur) from 1 January 2009. The Directive requires suppliers to deliver a 6% reduction in life cycle GHG emissions from transport fuels by 2020. It also introduces a new petrol grade (E10) with up to 10% ethanol by volume, and includes a requirement for suppliers to ensure that diesel has a fatty acid methyl ester (FAME) content of up to 7% by volume (such diesel being labelled B7), and encourages the European Committee for Standardisation (CEN) to develop a new standard for B10 (diesel with a 10% FAME content by volume).

2.2.3 Biofuel policy

While the use of renewable electricity in transport counts towards the Renewable Energy Directive (RED) requirements, the vast majority of the mandated reductions in GHG emissions from fuels had been expected to be met through the use of ‘first-generation’ crop-based biofuels. However, there has been increasing criticism of the use of these fuels, focused primarily around how ‘indirect land-use change’ is calculated (see Box 2.1).

Box 2.1: Potential issues with biofuels

Direct and indirect land-use change in biofuel calculations

In simple terms, the use of biofuels can be thought of as carbon-neutral since the amount of carbon dioxide absorbed from the atmosphere while the biofuel is growing is the same as that released when it is burned. However, it is easily seen that to calculate the GHG effects of biofuel use, other emissions associated with cultivation, harvesting, storage, transportation and processing must also be taken into account.

To calculate the total GHG emissions associated with biofuel use, however, two further impacts must be included: direct land-use change and indirect land-use change (ILUC).

- **Direct land-use change** looks solely at the land being used for biofuel cultivation. It accounts for the change in GHG emissions due to the discontinuation of its previous use. Accounting for this is now reasonably well understood and agreed upon.
- **Indirect land-use change** looks at the wider impacts of the biofuel cultivation on land-use changes across a whole geographic region, recognising that land is a finite resource and that change in land use in one location may result in land-use changes elsewhere. It attempts to estimate the change in GHG emissions due to these wider land-use changes. There are various approaches to this, resulting in large differences in estimated ILUC values.

Because of the problems associated with the calculation of ILUCs, quantifying the actual impact on GHG emissions of some biofuels becomes much more difficult.

Food versus fuel

With a growing global population and a tendency for diets to demand more land per head as GDP increases, the question of whether finite land resources should be used for growing food or fuel has been raised. Debate becomes heated when there are reduced crop yields – as happened again in the summer of 2012 with the drought in the USA – which then lead to sharp rises in food prices. The long-term impacts of climate change and more unstable and extreme weather patterns are likely to exacerbate such problems.

The issue is compounded by the fact that rises in grain prices disproportionately impact the poorest in the world. For the 2.8 billion that live on less than US$2/day, food accounts for more than half their expenditure. Their diet has a greater proportion of grain bought directly, so any price rise will have a greater impact on them than on someone living on a diet consisting largely of processed food.

There is disagreement about the extent to which biofuel production contributes to food price rises, but with finite resources and increasing demand there is no doubt that there is an effect. It is also important to note that policies to protect against deforestation (or even promote reforestation – which the IPCC recommends as a very cost-effective way of reducing GHG emissions) will inevitably lead to increased competition, between food and biofuels, for the remaining land. This may also act to push food prices higher.

As a result of the uncertainty regarding the GHG impacts of first-generation biofuels, on 17 October 2012 the European Commission issued a proposal for a 5% limit on the use of biofuels from food crops allowed in transport through to 2020, and the ending of all public subsidies for crop-based biofuels after the current legislation expires in 2020 (European Commission, 2012d).

Since Europe has already achieved about a 4.7% share of renewable energy in the transport sector, mostly through use of crop-based biofuels, this limits any further expansion of production and may result in financial losses to the biofuel industry.

The Commission will also investigate ILUC impacts, with the aim of including them in sustainability criteria – but not until at least 2021. It is hoped that these changes will encourage production of 'next-generation' biofuels with no, or low, ILUC emissions. These are being developed from non-crop-based biomass such as woody crops, agricultural and municipal residues or waste, and algae.

2.2.4 Biofuel compatibility

Existing fuel sold by filling stations already contains up to 5% biofuel blends, and is compatible with vehicles without any need for modification. However, use of high-percentage-biofuel blends requires that engines, and fuel and exhaust systems, are suitably designed and specified, otherwise problems may arise. Biofuels can have substantially different characteristics to standard mineral fuels with regard to volatility, viscosity and stability over time. With biodiesel, the characteristics can also vary depending on the feedstock and processes used to produce it, making it particularly difficult for vehicle manufacturers to ensure that their new vehicle test and development procedures cover all potential issues. However, ACEA, the European Automobile Manufacturers' Association ('Association des Constructeurs Européens d'Automobiles'), has supported measures to increase biofuels, and manufacturers have worked to ensure that their vehicles are compatible with the E10 petrol and B7 diesel that has become available on the market in accordance with the Fuel Quality Directive. All new diesel cars are compatible with B7 diesel fuel, and the vast majority of petrol models are compatible with E10 (ACEA, 2012b). Many next-generation biofuels do not suffer from these compatibility issues, as the production processes used result in fuels which have almost identical characteristics to conventional mineral fuels. These are known as 'drop-in' fuels since they can act as direct replacements.

2.3 Existing UK policy framework

When the DfT published its low-carbon transport strategy (DfT, 2009), it identified three main themes for carbon reduction:

- supporting a shift to new technologies and cleaner fuels;
- promoting lower-carbon choices; and
- using market mechanisms to encourage a shift to lower-carbon transport.

The first of these themes was expected to deliver over 91% of the total carbon reduction, primarily through European legislation – the regulations on new car and van CO_2 reduction and renewable transport fuels described in section 2.2. These have been transcribed into legislation in the UK and remain the most significant factor in reducing carbon emissions from passenger cars.

The UK Transport Carbon Reduction Delivery Plan (DfT, 2010b) reviews each of the key actions which are being taken to achieve these reductions, identifying how and when they are implemented, at the same time establishing measures to track progress. The actual tracking of progress is carried out by the CCC, which publishes annual progress reports.

2.3.1 Tailpipe CO_2-related policies

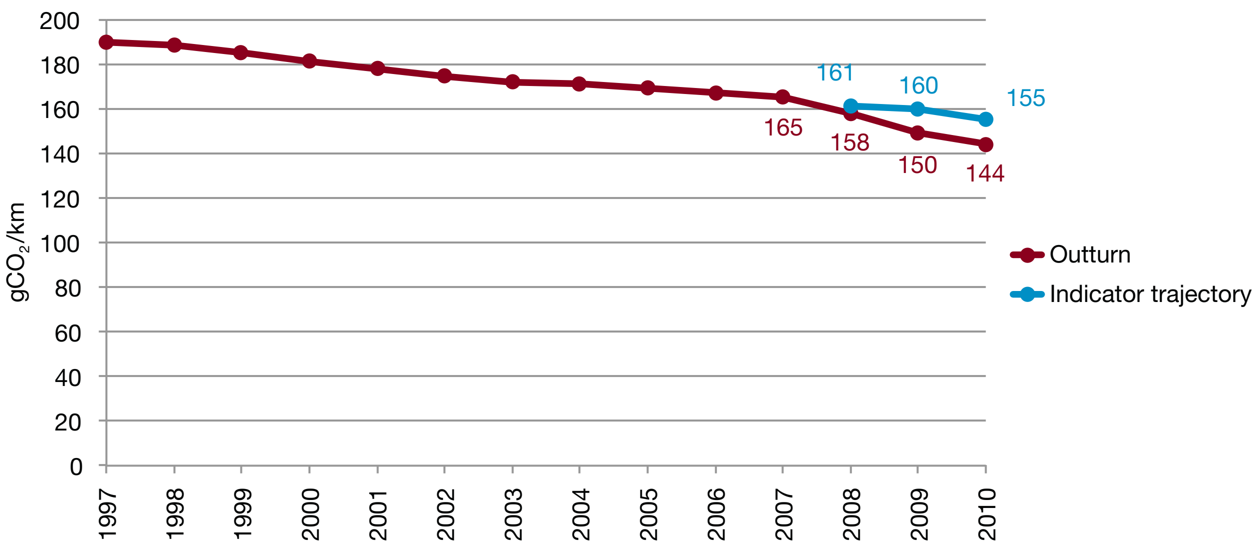
The introduction of tailpipe targets for the average CO_2 emissions from new sales of cars and vans has been a fundamental mechanism for the introduction of new vehicle technologies and fuels which aim to reduce carbon emissions.

As can be seen in Figure 2.1, since the European Commission set out the legislative framework for this policy in 2007, the pace of reductions has increased such that UK new car CO_2 emissions are ahead of the target trajectory.

The CO_2 intensity of new vans has also fallen from slightly, from 196 g/km in 2010 to 195 g/km in 2011. This is significantly higher than the 2020 target for vans of 147 g/km; however, the pace of reduction is expected to increase now that the legislation is in place.

Despite the good progress in new car CO_2 reduction, the 2020 target is still described by ACEA (2012a) as "extremely challenging".

Figure 2.1: Average UK new car tailpipe CO_2 emissions



Source: CCC (2012)

2.3.2 Vehicle Excise Duty

Vehicle Excise Duty (VED) has been based on CO_2 emissions since 2001. The system has been gradually reformed to increase incentives for the purchase and manufacture of lower-carbon cars since then. The 2012 budget raised VED rates again in April 2012 for all cars in emissions band D and above, as shown in Table 2.3.

Table 2.3: Vehicle Excise Duty for cars registered on or after 1 March 2001

Band	CO_2 emissions	2012/3	2012/3 6 months	2012/3 first-year rate*
A	up to 100 g/km	0	-	0
B	101–110 g/km	£20	-	0
C	111–120 g/km	£30	-	0
D	121–130 g/km	£100	£55.00	0
E	131–140 g/km	£120	£66.00	£120
F	141–150 g/km	£135	£74.25	£135
G	151–160 g/km	£170	£93.50	£170
H	161–170 g/km	£195	£107.25	£275
I	171–180 g/km	£215	£118.25	£325
J	181–200 g/km	£250	£137.50	£460
K**	201–225 g/km	£270	£148.50	£600
L	226–255 g/km	£460	£253.00	£815
M	over 255g/km	£475	£261.25	£1,030

Source: DVLA (2012)

* First-year rates: From 1 April 2010, anyone buying a new car will pay a different rate of vehicle tax for the first tax disc. From the second tax disc onwards, the standard rate of vehicle tax will apply.

** Band K includes cars that have a CO_2 emissions figure over 225 g/km but were registered before 23 March 2006.

While the proportions of vehicles in each VED band have shifted considerably towards the low-emissions bands since CO_2-based rates were introduced, the Institute of Fiscal Studies (IFS) stated that “there is no evidence of the role played by differential VED rates in this” (IFS, 2011). Indeed, a survey conducted by the RAC Foundation found that annual costs would have to increase by at least £1,100 before private car drivers would consider switching to a smaller-engined car or an alternative fuel (Energy Saving Trust, 2007).

First-year rates – a more effective tool

The King Review highlighted evidence that consumers give much more weight to the purchase price of a vehicle than to future running costs (King, 2007). Motorists also tend to underestimate running costs by a factor of two (RAC, 2004).

Recognising the greater influence of costs at the point of sale, a new first-year rate of VED was introduced in April 2010, to provide a stronger signal at the point of purchase. These rates were increased in April 2011 and again in April 2012. Consumers purchasing a car emitting under 130 gCO_2/km pay nothing in the first year, whereas for those emitting over 255 gCO_2/km the rate is now £1,030 (see Table 2.3).

Vehicle Excise Duty reform

The 2012 budget also announced that the government is considering "whether to reform VED over the medium term to ensure all motorists continue to make a fair contribution to the sustainability of the public finances, to reflect continuing improvements in vehicle fuel efficiency, and seek the views of motoring groups on this issue" (Hansard, 2012a). According to press reports, options under consideration may include:

- replacement of VED with a one-off upfront charge on new vehicles (BBC, 2012);
- a two-tier VED system, with the first charge giving access to local roads and most A-roads, then a second charge for use of major A-roads and the motorway network (Chapman, 2012).

2.3.3 Fuel economy label

European legislation has required that the fuel consumption of a vehicle is shown on a label at the point of sale since 2001.[3] However, the prescribed format did not make it easy for consumers to interpret the information. In 2005 the UK launched a label with colour-coded CO_2 bands aligned with the VED bandings, to help make it easier for consumers to choose more fuel-efficient models when purchasing a new vehicle. The label also includes estimated annual fuel costs and the VED cost. In 2009, labelling was expanded to include some of the used-car market when a system was made available to allow car dealerships selling nearly new vehicles to download fuel economy labels for free from the Vehicle Certification Agency website.

When surveyed, 71% of car buyers who were aware of the label said that it was important in helping them choose the make and model of car (LowCVP, 2009).

The fuel economy label is thus an important tool in helping to increase market demand for more fuel-efficient low-carbon vehicles.

2.3.4 Company car tax – including recent budget changes

In 2011 almost 60% of new cars registered in Great Britain were registered to companies, compared to 47% in 2001 (DfT, 2012b). Given that most of these vehicles will still be on the road in 2020, influencing company car purchasing decisions is a very important element of reducing carbon emissions from the

3 Directive 1999/94/EC relating to the availability of consumer information on fuel economy and CO_2 emissions in respect of the marketing of new passenger cars: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:012:0016:0023:EN:PDF.

overall car fleet. Although company car mileage has reduced substantially over the last decade or so (Le Vine & Jones, 2012), the vast majority of the mileage that these vehicles will cover in their lifetimes will be as privately owned used vehicles.

Company car tax in the UK has been based on CO_2 emissions since 2002, with the emissions level determining the cash equivalent of the benefit in kind on which tax is due. This is determined on the basis of a percentage of the new list price. For example, in 2012 a vehicle with 170 g/km emissions would be subject to an 'appropriate percentage' of 25%, whereas one with 120 g/km emissions would be subject to 15%. If the list price was £25,000, this amounts to a £2,500 difference in the benefit in kind, which for someone in the 40% tax bracket, would be a £1,000 difference in tax payable.

The policy offers complete exemption from company car tax for zero-emission vehicles, and a low rate of 5% for any vehicle under 76 gCO_2/km.

The same emissions-dependent percentage figure is used to calculate the benefit of free fuel provided for the private use of a company car user.

The policy has thus provided a strong incentive towards low-CO_2 vehicles. The result has been a significant shift towards diesel cars. In 2002 only 30% of company cars were diesel, but the figure now stands at over 60%. It has also resulted in a substantial reduction in the annual mileage of company cars, with distance travelled falling 45% between 1997 and 2009 (Potter & Atchulo, 2012).

Company car tax policy has been very effective in reducing CO_2 emissions

This policy has been one of the most effective measures in reducing carbon emissions from the UK car fleet. The combined effect of lower-emission vehicles and reduced distances travelled has resulted in savings of 25,000–35,000 tonnes of carbon each year from the company car fleet alone, representing 0.5% of all CO_2 emissions from road transport in the UK (ibid.). HMRC (HM Revenue & Customs) calculates that carbon reduction levels may reach a maximum of around 0.4–0.9 MtC (million metric tonnes of carbon) savings per year towards 2020 (HMRC, 2006).

As vehicle manufacturers have reduced average CO_2 emissions levels, so the company car tax bands have been shifted to ensure that the policy continues to provide sufficient incentive. However, the budget of April 2012 announced more substantial changes. The previous band from 76–120 gCO_2/km has been split into five bands, with only those under 100 gCO_2/km being eligible for the low 10% rate, and from 2015/6 zero-emission vehicles are to lose their exemption from company car tax and will pay 9% of the vehicle's list price, (HMRC, 2012b).

Despite the substantial tax concessions offered for ultra-low-carbon technologies, the policy has so far done little to promote their uptake. This is perhaps because currently available BEVs do not meet business usage requirements, given the longer distances covered.

The recent changes may be expected to benefit hybrid electric vehicles (HEVs) and PHEVs most, given that some recently launched models now achieve significantly lower CO_2 emissions than conventional diesel equivalents, while having only slightly higher list prices (Potter & Atchulo, 2012). As an example, Volvo has stated that it expects 80% of total sales for its V60 PHEV to be to the company car market (Volvo, 2011).

2.3.5 Fuel duty

Fuel duty provides by far the largest component of taxation on motorists, generating some £27 billion revenue in 2011/12, in comparison to £5.8 billion for VED (Hansard, 2012b).

Currently, duty rates for unleaded petrol, diesel, biodiesel and bioethanol are all set at the same level of £0.5795 per litre, with a planned 3.02p rise to £0.6097 in September 2013. Natural gas and biogas are set at 0.247 £/kg which provides a significant incentive for their use.

Biofuels (biodiesel and bioethanol) produced from biomass or waste cooking oil that were intended for use as road fuel had previously received a 20 pence per litre reduction on the fuel duty rate. This reduction was stopped for biomass-derived fuels on 1 April 2010, and for biodiesel from waste cooking oil on 31 March 2012 (HMRC, 2012a).

Box 2.2: Effect of fuel duty rebate on biodiesel from used cooking oil

Biodiesel from used cooking oil

Used cooking oil can be processed to create biodiesel. This is an effective way of diverting what would otherwise be a waste stream to produce a low-carbon fuel. The oil might otherwise be poured down the drain, causing blockages and increased costs to utility companies.

Recognising this, a 20 pence per litre reduction on the fuel duty rate was put in place. As a result, several businesses invested heavily in processing and refuelling infrastructure to support collection of used cooking oil from businesses and its conversion into biodiesel.

Data collected by the DfT on biofuel feedstocks showed that production volumes of biodiesel from used cooking oil increased dramatically, and it jumped from being the seventh most common feedstock in 2009/10 to the largest single feedstock accounting for 30% of total biofuel supply in 2010/11 (DfT, 2011). While this increased demand was met partly by diverting UK waste oil streams, it also resulted in a substantial increase in imported waste oil. Figures for the first quarter of 2012/13 show used cooking oil from the USA as the most widely reported source for biodiesel (DfT, 2012e). Removal of the 20 pence duty reduction in April 2012 may mean that biodiesel suppliers who use this feedstock find it harder to attract customers. Figures obtained from one UK producer show a 60% drop in production volumes since the change. However, under the UK's Renewable Transport Fuels Obligation, biofuels from waste count double (see section 2.3.6), and if the European Commission caps use of crop-based biofuels then this may increase demand for biodiesel from used cooking oil.

Since the amount of fuel duty paid will increase with both increased distance travelled and increased fuel consumption per mile, it is often argued that fuel duty is a fair and effective way of taxing motoring. More fuel burned means more carbon emissions, and more air pollution, but also higher tax paid, aligning with the principle of 'the polluter pays'.

However, there are other negative social impacts, or 'externalities', such as congestion, road deaths and injuries, noise and so on, which have a much weaker link to fuel use.

Increases in the price of fuel have been shown to result in a modest reduction in its consumption (Glaister & Graham, 2000). It can thus be expected that increases in fuel duty, and hence in pump prices, would tend to result in reduced total vehicle distances travelled.

Fuel duty escalator – attempting to give a clearer long-term signal

The concept of a fuel duty escalator – a system by which fuel duty is planned to be increased at a rate higher than general inflation – was introduced by the Conservative government in 1993. It aimed to reduce pollution from road transport to help tackle climate change. It also gave a clear indicator and created more certainty about the rising costs of road transport in the future. It was set at an annual increase of 3% ahead of inflation, later rising to 5%. The Labour government increased the rate to 6% in 1997. However, following large-scale protests regarding the price of fuel in 2000, the policy was scrapped.

One of the problems of the policy was that it did not take into account fluctuations in the price of oil. Recognising this, the coalition government introduced the concept of a 'fair fuel stabiliser' system in the 2011 budget. Under this system, fuel duty is set to rise by RPI (Retail Prices Index) inflation plus one penny per litre each year until 2014/5, but if oil prices are high, then the rise is by RPI only. The system came into effect in March 2012 with a 'trigger' price for oil of £45 (US$75) per barrel.

However, the policy has again met with widespread criticism and has been politically difficult to maintain. For example a 3 pence per litre rise in fuel duty was announced in autumn 2011 for 1 January 2012. This was then deferred to 1 August 2012, and then in June 2012 another deferral was announced, this time to 1 January 2013. The chancellor's Autumn Statement on 5 December 2012 announced that the rise would be pushed back again to 1 September 2013 (HM Treasury, 2012).

Fuel duty is not an environmental tax

In 2010 the government promised to increase the share of total revenues coming from environmental taxes. However, in order to assess this, it was first necessary to define what is and is not an environmental tax. In July 2012, the government published its definition, classifying environmental taxes as "those that meet all of the following three principles:

1. the tax is explicitly linked to the government's environmental objectives; and
2. the primary objective of the tax is to encourage environmentally positive behaviour change; and
3. the tax is structured in relation to environmental objectives – for example, the more polluting the behaviour, the greater the tax levied" (Hansard, 2012b).

It also specified which taxes are considered to meet these principles. Fuel duty was not included, nor was VED, although it was accepted that both have secondary environmental benefits.

Research conducted by the IFS for the RAC Foundation suggests that the setting of fuel duty rates is a politicised process in which there has been significant inconsistency, with announced future changes frequently delayed or cancelled (Johnson et al., 2012).

This uncertainty can cause difficulties both for consumers and businesses when making new vehicle purchase decisions. While future fuel prices can never be certain, owing to fluctuations in oil price, additional uncertainty due to government policy on fuel duty makes it harder to calculate the benefits of paying a higher purchase price for a more fuel-efficient vehicle.

2.3.6 Biofuels

In the UK, the 2003 European Biofuels Directive[4] eventually led to the introduction of the Renewable Transport Fuels Obligation (RTFO) which came into force in 2008. This obligates fossil fuel suppliers to produce evidence demonstrating that a target percentage of the fuel supplied for road transport in the UK comes from renewable sources and is sustainable. If this target is not met, a substitute amount of money must be paid.

Following the RED, the target is now for biofuel supply to reach 5% of total road transport fuel supplied by volume by April 2013. Because of ongoing uncertainty as to the volumes of biofuels that might be sourced sustainably, there are currently no plans for further UK targets. The RTFO was amended to implement the sustainability criteria for biofuels specified in the RED in December 2011. These include minimum GHG savings of 35% initially, rising to 50% in 2017 and 60% in 2018. These figures may change in the future following the European Commission's proposals published on 17 October 2012 mentioned in section 2.2.3 above. Fuel suppliers are also required to demonstrate that the cultivation of feedstock for their fuels does not damage areas of high carbon stocks or high biodiversity. Renewable Transport Fuel Certificates (RTFCs) are awarded once data has been independently verified. One RTFC is awarded per litre of biofuel, or kilogram of biomethane, supplied. Biofuels made from waste products such as cooking oil are given double rewards, as are fuels derived from lignocellulosic and non-edible cellulosic material. RTFCs may be traded between scheme participants, but at the end of the year suppliers must redeem the appropriate amount of RTFCs or pay a 'buy-out' price per litre of obligation (DfT, 2012f).

2.3.7 Ultra-low-emission vehicles

In 2009 the DfT established the Office for Low Emission Vehicles (OLEV) to support work to encourage people to buy and drive ultra-low-emission vehicles.

4 Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:123:0042:0042:EN:PDF.

Over £400 million has been used to fund actions to progress this, allocated to:

- the Plug-in Car and Van Grants;
- the Plugged-in Places (PIP) scheme;
- *Making the Connection* – the government's plug-in vehicle infrastructure strategy (OLEV, 2011); and
- Low-carbon vehicle industry support.

Each of these is reviewed in more detail here.

The Plug-in Car and Van Grants

Since January 2011, motorists purchasing an ultra-low emissions car have been eligible to receive a grant of 25% towards the cost, up to a maximum of £5,000, provided it meets set criteria. These include direct emissions below 75 gCO_2/km and a minimum range of 10 miles for a PHEV and 70 miles for a pure electric vehicle (EV). The full list of criteria is published on the UK government website under Plug-in Car Grant guidance (DfT, 2010a). As of 31 December 2012, there were eleven models of car which met these criteria, and 3,021 people had claimed grants.

The Plug-in Van Grant was introduced in February 2012. Van buyers purchasing a qualifying ultra-low emissions van can receive a grant of 20% towards the cost of the vehicle, up to a maximum of £8,000. The vehicle must have a gross weight of 3.5 tonnes or less, and emissions of below 75 gCO_2/km. Fully electric vans must have a minimum range of 60 miles between charges; PHEVs must be able to travel 10 miles.

As of 31 December 2012, there were seven models of van available through the scheme and 215 claims had been made.

The Plugged-in Places scheme

The PIP scheme has made available £30 million of match-funding to consortia of businesses and public sector partners to install EV charging points. It is operating in eight areas:

- East England
- Greater Manchester
- London
- Midlands
- Milton Keynes
- North East England
- Northern Ireland
- Scotland

The PIP scheme is expected to help raise the profile of low-carbon transport amongst local transport providers, encourage private-sector involvement with infrastructure installation, and help test recharging equipment. It also aims to create a better understanding of how people use EVs, including when and where they charge them. By the end of 2012, the scheme had installed over 2,800 charge points, primarily in London and the North East.

However, many private organisations are also installing charge points and it has been estimated that when these are included, there may be a total of over 3,000 across the UK (ibid.).

The plug-in vehicle infrastructure strategy

The plug-in vehicle infrastructure strategy, *Making the Connection*, was launched in June 2011. It set out the framework for the development of recharging infrastructure to support plug-in vehicle owners and industry in the UK. It predicts tens of thousands of plug-in vehicles on the roads in the UK by 2015, and highlights that independent forecasts suggest hundreds of thousands of plug-in vehicles could be on the road by 2020. (To put this in context, it should be noted that even 300,000 vehicles would still only represent just over 1% of the total UK car fleet.)

The strategy focuses on enabling recharging facilities to be established in three key areas:

Recharging at home – where the majority of plug-in vehicle recharging is expected to take place.

Recharging at work – particularly useful for employees for whom home recharging is not practical or sufficient.

Recharging in public places – targeted at key destinations such as supermarkets, retail centres and car parks, together with some on-street infrastructure, particularly for residents without off-street parking.

The strategy also included the introduction of the National Charge Point Registry – a system to allow charging point manufacturers and operators to make information on their infrastructure, including location, available in one place.

Both the Plug-in Car Grant and the PIP policy have come under scrutiny from the Transport Select Committee. In September 2012 it published a report which concluded that government must do more to show that its plug-in vehicle strategy represents good use of public money. It pointed out that only a small number of motorists had so far benefited from the schemes, and that there is a risk that the government is subsidising second cars for affluent households (House of Commons Transport Committee, 2012).

An update to the plug-in vehicle infrastructure strategy is expected in 2013, which will include a wider assessment of the market take-up (OLEV, 2011).

Low-carbon vehicle industry support

Support for R&D into low-carbon vehicle technologies is provided through the Technology Strategy Board's (TSB) **Low Carbon Vehicles Innovation Platform**. The platform was launched in September 2007 and delivers a wide range of research projects targeted at low- and ultra-low-carbon vehicle technologies. It is designed to promote low-carbon vehicle research, design, development and demonstration in the UK.

The **Low Carbon Vehicle Public Procurement Programme (LCVPPP)** was set up in 2007 to help stimulate the market for lower-carbon vehicles. The LCVPPP provides funding to support the trial of over 200 electric and low-emission vans in a range of public fleets. In November 2011, a second phase of the programme was announced with further funding of up to £1.7 million being made available for any public fleet buyers to purchase a further 500 low-carbon vans from the procurement framework.

The **Ultra Low Carbon Vehicle Demonstrator Programme (ULCVDP)** was launched in 2009 by the TSB with £25 million funding being made available for business-led demonstration projects of vehicles with tailpipe emissions of 50 gCO_2/km or less and a significant zero-tailpipe-emissions-only range. It includes 19 vehicle manufacturers, between them supplying 340 ultra-low-carbon vehicles, and is believed to be Europe's largest coordinated real-world trial of low-carbon vehicles.

In September 2011 a report was published summarising the findings to date (TSB, 2011). The results showed participants quickly feeling at ease with the vehicles, and concerns about – the fear of running out of battery charge and being stranded – falling substantially after only three months. Despite the majority feeling that the vehicles meet their daily needs, increased range is still a key desire.

In addition, a new government and cross-industry programme, **UKH2Mobility**, was launched in January 2012. The programme aims to evaluate the potential for hydrogen as a fuel for ultra-low-carbon vehicles in the UK, developing an action plan for an anticipated rollout to consumers from 2015 (ITM Power, 2013).

2.3.8 Policy trade-offs and synergies

Low-carbon cars and air quality

In general it might be thought that policies to promote low-carbon cars and fuels would naturally have air quality benefits and vice versa. However, the relationship can be more complex.

Policies such as company car tax and VED have resulted in a markedly higher market share for diesel vehicles. In 2011 diesel cars outsold petrol for the first time in the UK, accounting for 50.3% of new car sales; 31% of the total parc is now diesel. While this has led to reductions in CO_2 emissions, it has increased NO_x, NO_2 and particulate emissions relative to the situation before this shift, where petrol cars represented a larger share of the fleet. The increasing use of diesel vehicles has been described as an important factor contributing to the air quality challenges faced by many cities in Europe (European Environment Agency, 2012). However, it should be noted that diesel-powered heavy duty vehicles contribute disproportionately more to overall air pollution levels than passenger cars do.

Equally, measures to reduce air pollution, such as diesel particulate filters, can also negatively impact fuel consumption, increasing CO_2 emissions (AQEG, 2005). Meeting Euro VI emissions limits may also increase fuel consumption of heavy duty vehicles.

BEVs could substantially improve local urban air quality in areas where they achieve a high fleet penetration. However, in the short term at least, total emissions of NO_x, SO_2 and particulate matter can be increased overall if the electricity is generated using coal power plants, although most of these emissions will occur away from highly populated areas where negative impacts are greatest. This effect will also decline with the introduction of newer and cleaner plants, and emissions of air pollutants will generally decrease as the switch to renewable energy sources gains momentum. Uptake of vehicles that incorporate regenerative braking, such as hybrid and pure electric vehicles, will also reduce non-exhaust emissions relating to tyre and brake wear (AEA/TNO/CE Delft, 2012).

The problem of falling motoring taxation revenues

Reducing real-world CO_2 emissions from passenger cars means reducing the amount of petrol and diesel used, which in turn reduces fuel duty revenues. Moreover, since VED is based on CO_2 emissions, revenues from this, too, will fall unless there are further increases in the rates charged.

As vehicle fuel efficiency improves, it has been calculated that total revenue from motoring taxation (fuel duty and VED) is set to drop by £13 billion a year by 2029 (to £25 billion, from £38 billion in 2010) (Johnson et al., 2012).

In the longer term if there is a wide-scale switch to BEVs, this raises the question of how fuel duty should be replaced. Electricity prices will include an implicit carbon charge, but they do not include any duty relating to other motoring externalities.

While the amount of fuel duty paid increases with increased car use, there exists only a very weak link between this increase and one of the principle 'externalities' of motoring, namely congestion. EVs contribute to congestion in exactly the same way as conventional ones – in fact, their higher purchase price, combined with their much lower fuel costs, and incentives such as free parking and reserved recharging bays, may act to encourage increased car usage.

Road pricing – a solution to the problem of falling fuel duty and rising congestion?

Many economists have argued over a number of years that a national system of road pricing should be introduced. This is a view which is supported by the RAC Foundation itself – see, for example, *Keeping the Nation Moving* (RAC Foundation, 2011). If charges could be varied according to time of day and location, they could then be applied directly to tackle congestion regardless of the vehicle technology.

The IFS wrote:

> "The Committee on Climate Change (2008) has estimated that additional action to improve vehicle fuel efficiency could reduce revenues from fuel duty by £2.5 billion annually by 2020, on top of reductions to be expected anyway as cars become more efficient. The Committee envisages a future after that in which technology drives petrol and diesel cars off the roads almost entirely. In that world, no tax will be levied on driving, yet the main externality—congestion—will remain, and indeed is likely to grow. In addition, governments are unlikely to view the loss of £27 billion of fuel duty revenues with equanimity. Developing other forms of charging, preferably congestion charging, is a matter not just of economic efficiency. It is also likely to be viewed as a matter of fiscal necessity" (IFS, 2011).

If a road pricing scheme were to be introduced, then it would be important to ensure that incentives for the use of the most efficient vehicle technologies and fuels remained. For example, if such a scheme replaced some or all of the existing fuel duty and VED charges, then the charges for use of the road network would need to be lower for more efficient vehicles in order to maintain an equivalent incentive for their purchase.

However, while the coalition government has introduced a charge for lorries to use the UK road network (DfT, 2012d), it has specifically ruled out tolls or road user charges on existing roads at least for this parliament. The DfT is, however, consulting on how barrier-free or 'free-flow' road user charging schemes can be enforced (DfT, 2012g).

Other sources of funding for road networks are being investigated

In March 2012, the Prime Minister asked the DfT and HM Treasury to carry out a feasibility study to review new ownership and financing models for the strategic road network. This review is considering a range of options on how best to secure investment in the network to increase capacity and boost economic growth.

The study was expected to publish a consultation by the end of 2012; however, this has yet to appear as at the time of writing. It remains to be seen whether these investigations will result in any major changes to the current taxes and charges which motorists pay.

2.4 Future policy changes

Looking to the near future there are a number of policy landscape changes which will impact the future of low-carbon cars and fuels. Many of these are at a European level and revolve around the future targets for reducing CO_2 emissions and how these should be set and measured.

2.4.1 Post-2020 CO_2 targets

In order to provide certainty for vehicle manufacturers, the European Commission recognises the need for longer-term targets to be set out. In this way vehicle manufacturers are able to plan their R&D accordingly. In its proposal to amend existing regulations on CO_2 emissions from LDVs of July 2012, the Commission notes: "As industry benefits from indications of the regulatory regime that would apply beyond 2020, the proposal includes a further review to take place by, at the latest, 31 December 2014" (European Commission, 2012e).

The Commission has said it intends to issue a communication in 2013 in order to carry out a consultation on the form and stringency of post-2020 CO_2 targets for LDVs. The date for a future target is expected to be 2025. The European Commission has announced it will explore a level of 70 gCO_2/km by 2025 and is expected to seek stakeholders' views on post-2020 emissions targets for new cars and vans during 2013.

The feasibility of a 70 gCO_2/km target for passenger cars will be explored in the conclusion of this report – see Chapter 6.

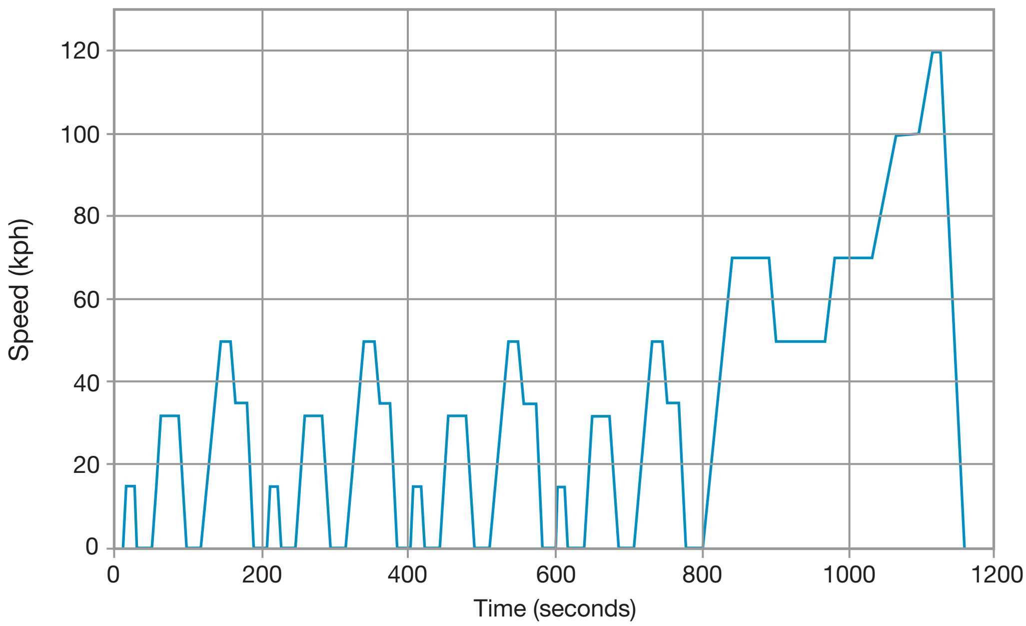
2.4.2 Changing the vehicle test cycle

The existing test

The current test cycle used for establishing the approved emissions and fuel economy figures for production vehicles is the New European Drive Cycle (NEDC), which was first introduced in its current form in 1990.

The cycle lasts just under 20 minutes (1,180 seconds) and consists of four repeated urban drive cycles each lasting 195 seconds, followed by one 'extra-urban' section lasting 400 seconds. Urban drive cycles have an average speed of 12 mph (approximately; the speeds are specified in kph), reaching a maximum speed of 31 mph (50 kph) for 12 seconds. The extra-urban section averages 39 mph, reaching a maximum speed of 75 mph (120 kph) for 10 seconds – see Figure 2.2. The test is performed using a 'cold' vehicle at a temperature of 20–30°C, and all ancillary loads are turned off (air conditioning, lights, rear window heater and so on).

Figure 2.2: New European Drive Cycle



Source: JRC-IES (2010)

Criticism of the existing test

Since the NEDC test is used to assess both the emissions and fuel economy performance of all passenger cars against the legislated limits, it is crucial that it produces results which are representative of real-world driving conditions. However, real-world driving tends to involve far more changes in speed, and faster accelerations; moreover, ambient temperatures will often be lower than 20–30°C, and drivers may be using lights, power-steering, heating or air conditioning. There are also a number of flexibilities in the exact test set-up available to manufacturers.

Real-world fuel consumption and CO_2 emissions can be over 20% higher

As a result of these differences between real-world vehicle usage and the formal test procedure, drivers may find their real-world fuel consumption to be significantly higher than the official figures. Research indicates that for 2001 model year vehicles, real-world fuel consumption figures averaged about 8% higher, but for 2010 model year vehicles, this figure had increased to 21%. The researchers also noted that the gap appeared to have widened particularly rapidly since 2007 (ICCT, 2012).

The issue of this difference between the official type-approval fuel economy figure and what drivers are likely to see in the real world has also been reported in magazine testing, where road test results have sometimes shown even larger differences (What Car?, 2006; Auto Express, 2008).

Some of the 'greenest' cars are furthest from their official CO_2 figures

Significantly, some of the largest differences are those for the vehicles with the lowest official CO_2 figures, meaning that consumers who opt for what is often marketed as the most 'environmentally friendly' option may be the most disappointed by the vehicle's actual fuel economy. For example, *Autocar* test results reported in a study by Ricardo showed hybrids as having 32–35% higher CO_2 emissions in realistic driving than the official figures (Ricardo, 2011).

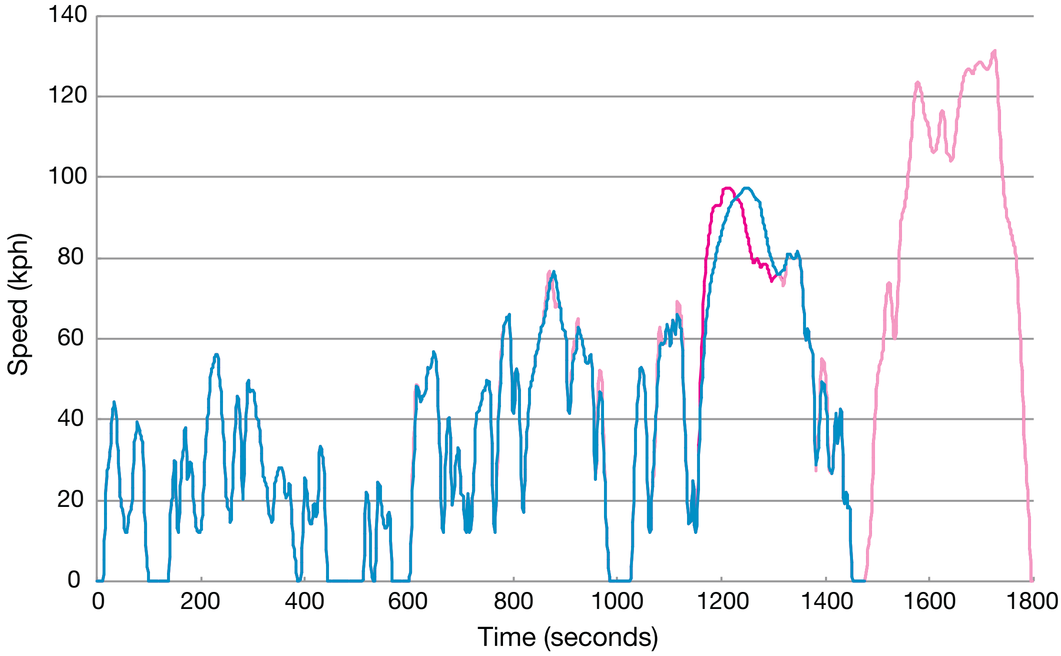
As a result, motorists are increasingly resorting to online websites which provide alternative fuel consumption figures based on magazine testing or owners' own reported figures.

There is evidence that other important emissions for both climate change and air pollution such as NO_x are also occurring at higher levels under real-world conditions than type-approval test results would suggest (JRC-IE, 2011).

A new worldwide test cycle

A new worldwide test procedure is currently being developed which will replace the NEDC (as well as test procedures currently used in Japan and the USA). The work is being conducted under guidelines from the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations. Known as the 'Worldwide harmonized Light vehicles Test Cycle' (WLTC), it is expected to be finalised in 2013–14.

Figure 2.3: Worldwide harmonized Light vehicle Test Cycle



Source: UNECE (2013)

As can be seen in Figure 2.3, the proposed test cycle has much more 'transient' operation, with more aggressive acceleration and more time spent at higher speeds.

New test procedures

In addition to using a new test cycle, the European Commission is currently examining two alternative test procedures for LDVs aimed at making results more representative of real-world driving. The aim is for these to be applicable from the mandatory Euro 6 dates (2014–15) onwards for type-approval and in-service conformity testing. The two alternative approaches are an on-road emissions test using a portable emissions measurement system and a laboratory procedure based on a randomised cycle derived from components of the WLTC. A choice between these two different approaches is expected to be made in 2013.

The Commission is also expected to propose a statistical model to weigh measured real-world emissions data and assess it against limit values (i.e. maximum permitted emission levels) used for type-approval.

It has also been reported that manufacturers may have to publish two fuel consumption figures – a best case, based on a vehicle with no passengers or ancillary loads, and a worst case, based on a fully occupied vehicle and with all ancillaries being used (Yarrow, 2012).

2.4.3 Moving to a life cycle emissions approach

While the use of a new test cycle and procedures to ensure that type-approval fuel economy and emissions are more representative of real-world conditions is important, there is a further issue.

Current legislation is focused on tailpipe emissions and does not take into account the 'life cycle' environmental impacts of vehicle use. These include the:

- manufacture of the vehicle;
- disposal of the vehicle; and
- generation and supply of the fuel.

As tailpipe CO_2 reduces, the importance of moving to a life cycle approach increases

As vehicle fuel economy and efficiency improves, the importance of these life cycle impacts becomes proportionally greater. Traditionally for conventional vehicles, manufacture and disposal has been estimated to account for 15% of total life cycle CO_2 emissions, while 85% is attributed to the 'in-use' tailpipe emissions (SMMT, 2013d). However, these proportions are changing for newer vehicles, and differences in the assumptions about the boundaries used to define life cycle calculations can introduce further variations.

As fuel consumption improves, the in-use proportion naturally declines, especially if the fuel consumption improvements are being achieved through the use of additional technologies which increase the manufacturing impacts.

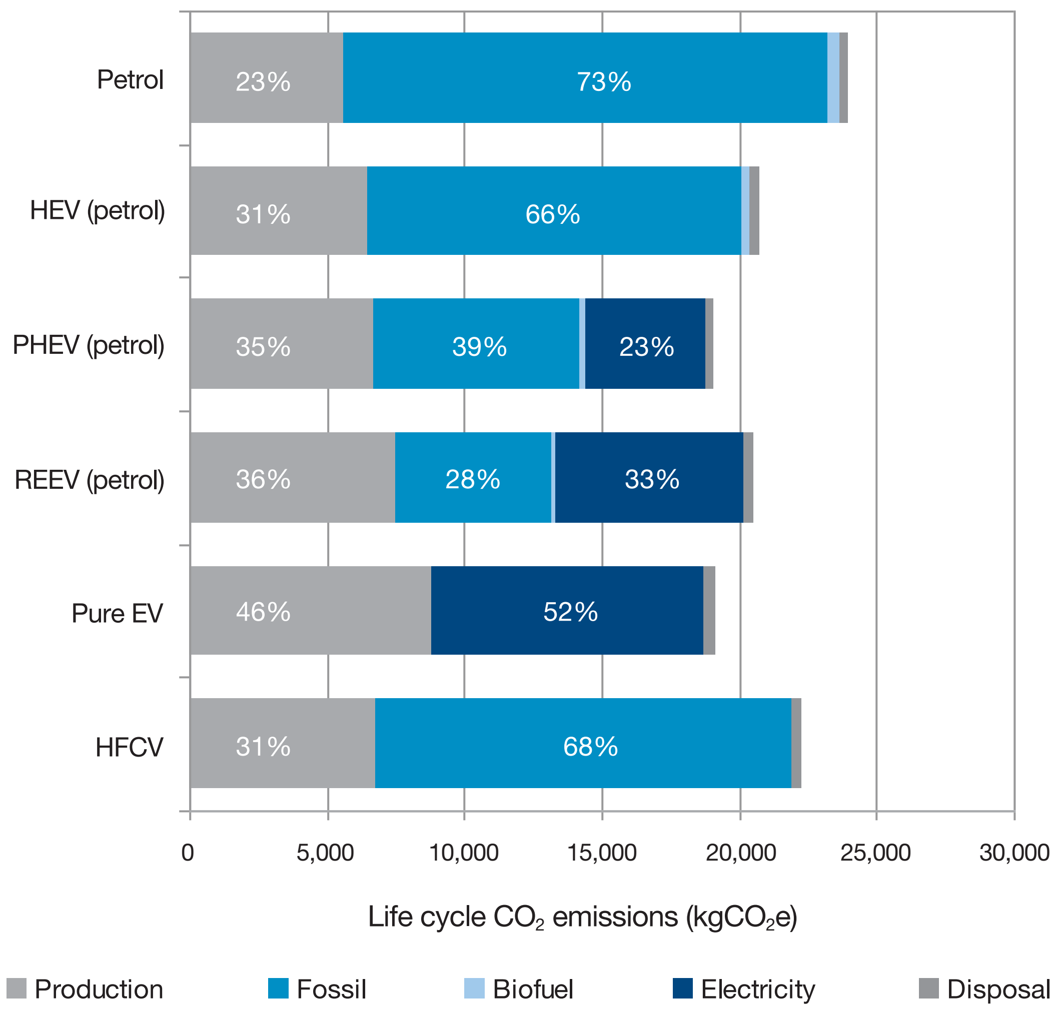
For BEVs it does not make sense for legislation to relate solely to tailpipe emissions, as there are none. However, there are certainly emissions associated with the production of the electricity needed to power the vehicle. Equally, EVs' manufacturing emissions are calculated to be significantly higher than those for a conventional vehicle (owing primarily to the batteries).

Despite this, new technologies such as HEVs, PHEVs and BEVs are calculated to have significantly lower overall life cycle GHG emissions than a conventional petrol vehicle. In Figure 2.4 it can be seen that for the baseline petrol vehicle, the in-use fossil fuel usage is calculated to contribute 73% of the total life cycle emissions. For a petrol PHEV, this figure has reduced to 39%, while the production phase has increased from 23% to 35% of the total. Nevertheless, its overall life cycle emissions amount to only around 80% of the baseline petrol vehicle.

The recommendations of the study from which this figure was taken were that a new CO_2 metric based on the GHG emissions emitted during vehicle production should be considered, together with targets aimed at reducing life cycle CO_2. These targets could include:

- a cap on production CO_2, dependent on vehicle segment;
- a reduction target for production or life cycle CO_2, compared to an appropriate baseline; and
- a maximum 'payback period' for trading increased embedded emissions against reductions in tailpipe/well-to-wheel CO_2 emissions.

Figure 2.4: Life cycle CO_2e emissions for various medium-sized vehicle technologies in 2015



Source: Ricardo (2011)

Notes: Vehicle specifications are based on Ricardo roadmap projections for 2015. Assumed lifetime mileage is 150,000 km and assumed fuels are E10 and B7. Electricity carbon intensity is assumed to be 500 gCO_2/kWh. Assumed industry hydrogen carbon intensity is 99.7 gCO_2e/MJ_{fuel}. Further detail on assumptions is provided in Appendix 2 of the original report. 'CO_2e' refers to CO_2 equivalent, a measure to express the global warming potential of non-CO_2 greenhouse gases (such as methane) relative to CO_2.

The European Commission has funded research to support the process of assessing the environmental impact of each life cycle phase of electric vehicles. The eLCAr (E-Mobility Life Cycle Assessment Recommendations) supplies tailored guidelines derived from the ILCD (International Reference Life Cycle Data System) Handbook from the European Joint Research Centre.[5]

The IEA has also recognised the importance of establishing an agreed methodology and task 19 of their Hybrid and Electric vehicle implementing agreement is Life Cycle Assessment of EVs (IEA, 2013).

2.5 Conclusions

It is clear that policies have been put in place aimed at promoting the uptake of low-carbon cars and fuels. Largely as a result of this, total CO_2 emissions from cars in the UK have been falling gradually since 2004. However, the current trajectories of these reductions are not sufficient to meet UK carbon budget commitments.

It is also reasonable to believe that the reductions made so far are likely to have been achieved through easier, lower-cost actions, and that continuing this rate of progress will become progressively more difficult and expensive.

Policymakers are therefore continuing to develop a policy framework and set targets intended to maintain or increase rates of progress. The next two chapters examine which fuels and vehicle technologies are available to manufacturers to meet these targets.

5 www.elcar-project.eu


BioDiesel
BioDiesel

3. Future Fuels

3.1 Introduction

Currently, motoring is dominated by the use of mineral oil in the form of petrol and diesel. Indeed, 95% of all our transport is fuelled by oil (European Commission, 2011b). It is perhaps useful to recall that this was not always the case. For example, in the USA in 1899–1900, electric cars outsold the two main competing technologies – steam-driven cars and petrol-powered ICE vehicles. Electric cars were quieter, smoother, less polluting, and easier to drive and use than their rivals as they did not require gear changes or hand-cranking to start (Kendall, 2008). In London, in 1907–9, the London Electrobus Company ran a fleet of 20 electric buses, with batteries which could be swapped out and replaced with fresh ones at the depot in three minutes (The Economist, 2007).

However, superior range and lower costs – particularly with Henry Ford's introduction of the mass production line – soon led to the dominance of the ICE for motor vehicles. Even then the use of oil-derived fuel was only one of the options being explored. Henry Ford had plans for his Model-T cars to run on ethanol made from corn, and Rudolf Diesel's new 'Diesel engine' was demonstrated at the 1900 Paris Exposition running on peanut oil.

Today, after more than a century of dominance by oil-derived petrol and diesel, our entire road transport system and refuelling infrastructure has developed around this paradigm. However, the need to reduce carbon emissions and air pollution, as well as the desire for increased energy security/resilience, is driving an exploration of the alternatives once again.

This chapter will review the fuels which are expected to be the most commonly used in our cars in the years through to 2025 and beyond. Starting with conventional petrol and diesel, but also covering biofuels, liquefied petroleum gas (LPG), compressed natural gas (CNG), electricity and hydrogen, each option is examined to assess its potential to contribute to a low-carbon motoring future (which also depends on the powertrain technology used), with a description of its advantages, disadvantages, infrastructure requirements and availability. Finally, the different options are compared side by side.

The following definitions are used throughout this chapter in relation to the emissions resulting from the use of different transport fuels and other energy carriers.

Direct emissions	Direct emissions are also referred to as 'tank-to-wheel' (TTW) or 'tailpipe' emissions. They refer to the emissions generated directly from the use of the fuel in the vehicle, i.e. in its combustion stage.
Indirect emissions	Indirect emissions are also referred to as 'well-to-tank' (WTT) emissions, or 'upstream' emissions. These are the total emissions generated in the various stages of the life cycle of the fuel prior to combustion, i.e. from extraction of the primary fuel (e.g. oil), fuel production/refining and distribution.

Life cycle emissions	In relation to fuels, life cycle emissions are the total emissions generated in all of the various stages of the life cycle of the fuel, including extraction, production, distribution and combustion. Fuel life cycle emissions are therefore equal to the sum of direct (TTW) and indirect (WTT) emissions, and are also known as 'well-to-wheel' (WTW) emissions. In relation to vehicle technologies, life cycle emissions not only include direct and indirect emissions from fuel use, but also emissions associated with manufacturing and scrapping. However, as discussed in section 2.4.3, there is no agreed approach to measuring these additional emissions. In this report, the term 'life cycle' is therefore limited in scope to fuel life cycle emissions and used interchangeably with 'well-to-wheel' (WTW) emissions.

Note that for biofuels, direct emissions of CO_2 are defined as being zero for biofuels as the same amount of CO_2 is absorbed in the growth of the feedstock from which the biofuel is produced (Defra/DECC, 2012).

3.2 Review of fuels

The following tables provide a review of the key fuels (or energy carriers) expected to be used in future vehicles in the years through to 2050. Each fuel is considered in turn, providing summary information on key aspects, including energy density, GHG reduction potential, advantages/disadvantages, and any infrastructure or availability considerations.

Figures for fossil fuel properties and CO_2 savings potential, as well as projections for future figures, are based on published data from the UK government (Defra/DECC, 2012; DECC, 2011a).

For electricity, these are based on current factors for electricity from Defra/DECC (2012) including upstream emissions, projected forward using DECC projections for UK electricity grid decarbonisation (DECC, 2012a). These result in life cycle grid carbon intensity figures as shown in Table 3.1. These figures include transmission losses and upstream emissions from the production of primary fuels used in electricity generation (i.e. coal, natural gas, oil, etc.). Losses from charging are also factored separately into the final emission factors for vehicles using grid electricity (cf. AEA, 2012).

Table 3.1: UK grid electricity life cycle carbon intensity assumptions

	2010	2015	2020	2025	2030	2040	2050
gCO_2/MJ	155.5	152.4	68.4	61.0	37.1	17.5	8.3
gCO_2/kWh	560	549	246	220	134	63	30

Since 'direct emissions' for biofuels are defined as zero, only life cycle GHG emissions figures are given. These are presented as ranges based on both 'typical' and 'default' figures from European Commission RED

Annex V (European Commission, 2009). ILUC figures are those published by the European Commission in October 2012 (European Commission, 2012d). Reduction potentials for biofuels are calculated by comparing emissions to UK values for petrol or diesel.

Where comparisons are provided between different fuels and powertrain types, these are based on the overall vehicle technology assessment summarised in section 4.2.

Future time series projections on how the GHG emissions performance of different fuels might evolve to 2025 and to 2050 are presented as comparisons in section 3.3.

3.2.1 Petrol

Fuel:	Petrol
Description:	Petrol (or gasoline) is a refined hydrocarbon that is produced from the fractional distillation of crude oil. It is the primary fuel used in spark-ignition engines. Note that unleaded petrol at UK filling stations is blended with up to 5% bioethanol. From 2013 it is expected that regulations will permit up to 10%. However, the figures presented here are for pure petrol.
Compatibility:	Petrol can be used in conventional spark-ignition ICEs.
GHG reduction potential:	Reductions in direct emissions from use of petrol can only be achieved by blending with biofuels. Limited improvements in indirect emissions from upstream activities could be made (e.g. reductions in gas flaring from oil rigs).
Energy density:	44.7 MJ/kg or 32.9 MJ/litre
Advantages:	• Petrol is one of the two dominant fuels currently being used by cars in the UK. It has a high energy density, meaning that many miles can be covered on one tank full, and it is widely accepted by the general public. • In comparison to diesel, combustion of petrol produces lower NO_x and particulate emissions.
Disadvantages:	• The only scope for reducing GHG emissions is through reduction of indirect emissions from fuel processing. • Exhaust emissions from combustion of petrol contribute to poor air quality. • Extraction of crude oil can be environmentally damaging, and in the longer term there is concern that supplies may be constrained.
Infrastructure:	Petrol is currently refined worldwide to meet today's transportation needs. It has been, and still is, the default fuel for spark-ignition engines in the UK. Refuelling infrastructure is widespread, with over 9,000 refuelling stations in the UK.
Availability:	The continuing availability of petrol is dependent on the availability and refining of crude oil, both in the UK and abroad.
GHG emissions:	Direct: 70.4 gCO_2e/MJ or 2.31 $kgCO_2e$/litre Indirect: 14.1 gCO_2e/MJ or 0.46 $kgCO_2e$/litre Total life cycle: 84.5 gCO_2e/MJ or 2.78 $kgCO_2e$/litre

3.2.2 Diesel

Fuel:	Diesel
Description:	Diesel fuel is a refined hydrocarbon that is produced from the fractional distillation of crude oil. It is the primary fuel used in compression ignition engines. Note that diesel at UK filling stations is blended with up to 7% biodiesel.
Compatibility:	Diesel can be used in conventional compression ignition ICEs.
GHG reduction potential:	Diesel offers about a 14% reduction in life cycle GHG emissions per km compared to the equivalent petrol vehicle, because of the higher efficiency of compression ignition engines. Limited improvements are also possible in upstream fuel production activities.
Energy density:	42.9 MJ/kg or 35.0 MJ/litre
Advantages:	Diesel fuel is the second of the dominant fuels currently being used by cars in the UK. It has slightly more energy per litre than petrol, and diesel engines are generally more efficient than petrol engines, so diesel can provide a longer range for a given fuel tank size.
Disadvantages:	• As the source of diesel fuel is crude oil, there is no scope to reduce direct emissions per unit energy, and the only scope for a reduction is via the indirect emissions from fuel processing. • Diesel engines also produce significantly more emissions of NO_x and particulate air pollutants than petrol engines, although particulate filters and after-treatment systems have reduced this. • Extraction of crude oil can be environmentally damaging, and in the longer term there is concern that supplies may be constrained.
Infrastructure:	Infrastructure currently exists to refine and deliver diesel fuel to over 9,000 public refuelling stations throughout the UK, and is expected to be in place for years to come.
Availability:	The continuing availability of diesel fuel is dependent on the availability and refining of crude oil, both in the UK and abroad.
GHG emissions:	Direct: 74.3 gCO_2e/MJ or 2.68 $kgCO_2e$/litre Indirect: 15.7 gCO_2e/MJ or 0.56 $kgCO_2e$/litre Total life cycle: 90.0 gCO_2e/MJ or 3.24 $kgCO_2e$/litre

3.2.3 Liquefied petroleum gas

Fuel:	Liquefied petroleum gas
Description:	LPG, or autogas as it is often known, is a mixture of liquefied propane and butane (*c.*95% propane in the UK; a lower proportion, and varying significantly, in other parts of Europe). Propane and butane are extracted from hydrocarbons such as natural gas, shale gas or crude oil. The fuel is stored on board the vehicle as a liquid in pressurised cylinders.
Compatibility:	LPG can be used in conventional spark-ignition ICEs. The additional space requirements for gas storage tanks mean it is unlikely it would be used for (plug-in) hybrids, as they must also package a battery and an electric powertrain.
GHG reduction potential:	LPG offers a 14% reduction in life cycle GHG emissions per km compared to the equivalent petrol vehicle, and roughly equivalent WTW GHG emissions to a diesel vehicle. This is mostly a result of the reduced proportion of carbon atoms for a given energy content, and fewer emissions resulting from refining processes, which means that LPG produces 14% less CO_2 per MJ than petrol and 20% less than diesel (Defra/DECC, 2012).
Energy density:	45.9 MJ/kg or 24.0 MJ/litre (somewhat lower when including the full fuel storage system)
Advantages:	LPG can help reduce air pollution as it produces very little soot and offers lower NO_x emissions than petrol. It has much lower NO_x and particulate emissions than diesel. However, recent improvements to conventional diesel and petrol vehicles have eroded this advantage.
Disadvantages:	The same quantity of energy in LPG takes up a larger volume than that of diesel or petrol. LPG also has to be stored within pressurised cylindrical tanks which are bigger and weigh more than conventional diesel or petrol tanks, and are more expensive. There are few vehicle manufacturers producing dedicated LPG vehicles within the UK. Aftermarket conversion costs range from £850 to £2,000, depending on the size of engine.
Infrastructure:	There is an existing LPG infrastructure within the UK with over 1,400 public LPG refuelling sites, mostly housed within existing refuelling forecourts (UK LPG, 2012). This corresponds to approximately 15% of public refuelling stations in the UK. The cost of individual filling station installations ranges from about £16,000 for a basic unit with dispenser to £100,000 for a station with remote underground tanks and a dispenser incorporated in a petrol forecourt (Autogas-Network, 2011).
Availability:	LPG for automotive use represents approximately 6% of the total butane and propane consumption within the UK (DECC, 2012d). Given that the fuel is produced as a by-product of natural gas (including shale gas) and crude oil extraction, this fuel will continue to be available while these sources are extracted.
GHG emissions:	Direct: 63.8 gCO_2e/MJ or 1.53 $kgCO_2e$/litre Indirect: 7.99 gCO_2e/MJ or 0.19 $kgCO_2e$/litre Total life cycle: 71.8 gCO_2e/MJ or 1.72 $kgCO_2e$/litre

3.2.4 Compressed natural gas

Fuel:	Compressed natural gas
Description:	Natural gas is a naturally occurring hydrocarbon gas that consists mainly of fossil-fuel-derived methane produced as a byproduct of crude oil or extracted directly from natural gas fields. Typically the fuel is stored on board the vehicle as CNG at 200 bar (2,900 p.s.i.) in pressurised cylinders.
Compatibility:	CNG can be used in conventional spark-ignition ICEs. The additional space requirements for gas storage tanks mean it is unlikely it would be used for (plug-in) hybrids, as they must also package a battery and an electric powertrain.
GHG reduction potential:	WTW CO_2 emissions are up to 24% lower than for a comparable petrol car and could be up to 7% lower than for a diesel Euro 5 car (European Commission, 2011c).
Energy density:	47.7 MJ/kg, or 8.3 MJ/litre at 200 bar (2,900 p.s.i.) pressure (somewhat lower when including the full fuel storage system)
Advantages:	• Natural gas can be used in spark-ignition engines with modifications of a minor nature. Apart from the GHG reduction potential, using CNG has air quality benefits due to very low NO_x and practically zero particulate matter emissions. • The technology for using CNG in cars is mature, with countries across Europe using them already – notably Italy, which has over 785,000 CNG cars and vans on the road (NGVA, 2012).
Disadvantages:	• CNG has a high energy content per kilogram, but a low energy content per litre. Even with high compression levels, CNG vehicles require cylindrical storage tanks that can weigh four times as much as an equivalent full diesel storage tank (AEA, 2009). • Because CNG is a fossil fuel, there is no further potential for reduction in direct GHG emissions beyond current levels.
Infrastructure:	The UK already has a widely distributed piped natural gas infrastructure servicing residential and commercial properties, but there is minimal specific refuelling infrastructure for the use of CNG in automotive applications. CNG refuelling infrastructure could either use the existing piped natural gas network if appropriate, or fuelling stations could receive liquefied natural gas (LNG) via a road tanker which can then be regasified. The UK currently has very few publicly accessible CNG refuelling stations (CNG Services, 2012). One alternative is to have a slow-fill system installed at home.
Availability:	Although existing automotive CNG refuelling facilities are minimal, natural gas itself is a widely available fuel within the UK and is the primary fuel for residential heating and electricity generation. Looking to the future, developments with LNG and unconventional gas sources such as shale gas have opened up new sources of supply that will help to ensure security of supply for many years. The exact impact of shale gas is still unclear owing to the early stage of production, but it has been estimated that UK shale gas reserves could supply 10% of UK demand for over a hundred years (Institute of Directors, 2012). However, if use of CNG in road vehicles were to increase substantially, this could create competition for the resource with other sectors.
GHG emissions:	Direct: 57.1 gCO_2e/MJ or 2.72 $kgCO_2e$/kg Indirect: 8.9 gCO_2e/MJ or 0.42 $kgCO_2e$/kg Total life cycle: 65.9 gCO_2e/MJ or 3.15 $kgCO_2e$/kg

3.2.5 Biomethane/biogas

Fuel:	Biomethane (as bio-CNG)
Description:	Biomethane is methane gas that is produced by biological means, such as sewage treatment, the anaerobic digestion of organic feedstock, or the gasification of lignocellulosic biomass. Sources can include slurry or manure, food waste, industrial food processing and specific energy crops (such as silage). The term biomethane is generally used to distinguish the purified product (up to 98% methane) used for transport (or other) applications from biogas (e.g. from landfill or sewage treatment), which can typically contain 40% CO_2. Biomethane is chemically similar to fossil natural gas (though usually with a much higher proportion of methane) and can be either used directly or injected into the natural gas grid for distribution.
Compatibility:	Biomethane can be used in conventional spark-ignition ICEs. The additional space requirements for gas storage tanks mean it is unlikely it would be used for (plug-in) hybrids, as they must also package a battery and an electric powertrain.
GHG reduction potential:	GHG savings from the use of biomethane can be high – typically between 73% and 86% as compared to petrol. It is often produced from waste biomass or manure, meaning there are little or no land-use change emissions (see Box 2.1), and the collection and use of biomass/manure as a fuel can reduce methane emissions.
Energy density:	49.0 MJ/kg, or 8.3 MJ/litre at 200 bar (2,900 p.s.i.) pressure (somewhat lower when including the full fuel storage system)
Advantages:	• Because biomethane is produced from renewable sources such as food waste and manure, it can achieve substantial GHG savings compared with petrol and diesel fuels. • Use of biomethane in transport creates little or no land-use change emissions and does not compete with food production. • Biomethane can be used in spark-ignition engines with only minor modifications.
Disadvantages:	• Biomethane's disadvantages are much the same as for CNG (except those associated with being a fossil fuel). It has low energy content per litre, and vehicles require cylindrical storage tanks that can weigh four times as much as an equivalent full diesel storage tank (AEA, 2009).
Infrastructure:	There are three approaches to use of biomethane in transport: 1. provide biomethane refuelling facilities at the location of its production (however, for anaerobic digestion, this is often in rural areas); 2. inject biomethane into the national gas grid and refuel vehicles from grid-connected refuelling facilities; however, a 'green gas certification scheme' is needed to claim the 65–77% GHG savings, as the vehicle is refuelled using standard gas from the national grid (Renewable Energy Association, 2012); and 3. liquefy the biomethane and distribute to refuelling facilities via tanker lorries; this results in somewhat reduced GHG savings due to the liquefaction and transportation energy requirements. Currently, owing to limited supplies, the liquid biomethane is mixed with LNG. All three approaches are currently in use for commercial vehicles. If biomethane use increases, facilities may become available for private motorists.

Fuel:	Biomethane (as bio-CNG)
Availability:	National Grid has estimated that biomethane production in 2020 could reach 56 TWh per year (terawatt-hours per year), equivalent to 5% of the total UK gas demand, and up to 18% on the basis of an idealised 'stretch' scenario (National Grid, 2009) It is estimated that anaerobic digestion alone could provide up to 37 TWh per year by 2030 (DECC, 2011a).
GHG emissions:	Emissions vary according to feedstock and production process. Emissions excluding ILUC: 12–23 gCO_2e/MJ (0.6–1.1 kgCO_2e/kg) ILUC emissions: 0 gCO_2e/MJ (0 kgCO_2e/kg) Total life cycle: 12–23 gCO_2e/MJ (0.6–1.1 kgCO_2e/kg)

3.2.6 Bioethanol

Fuel:	Bioethanol
Description:	Bioethanol is ethanol that is produced from crops such as corn or sugar cane through conventional fermentation processes. In this case it is a first-generation, crop-based biofuel. However, advanced or next-generation 'cellulosic bioethanol' can be produced from feedstocks such as miscanthus, switchgrass, and forestry and agricultural residues through cellulolysis or gasification processes. Bioethanol can be used as a fuel in its pure form (E100) but is more commonly blended with petrol in blends of 5% (E5), 10% (E10) and up to 85% (E85, which requires a 'flex-fuel' vehicle). Bioethanol is chemically identical to ethanol produced by other means (about 5% of world ethanol production is not bioethanol, instead it is petroleum derived – through catalytic hydration of ethylene). Current UK unleaded petrol contains up to 5% bioethanol.
Compatibility:	Bioethanol can be used in conventional spark-ignition ICEs.
GHG reduction potential:	The GHG reduction potential of first-generation crop-based bioethanol will vary significantly depending on the feedstock and the production process. Savings can range from 3% to 56% when ILUC is included (17% to 72% if excluded). Typically sugar beet or sugar cane crops give the highest savings, but most UK-produced bioethanol is from wheat, which can still generate savings of up to 55% if the most efficient production processes are used. Next-generation cellulosic bioethanol yields significantly higher GHG savings, the exact amount depending on which feedstock is used: savings range from 70% for farmed wood to 87% for straw. These feedstocks are thought to have no or low ILUC effects.
Energy density:	26.8 MJ/kg or 21.3 MJ/litre (pure bioethanol, E100)
Advantages:	• For low blends of bioethanol with petrol, there is no requirement for additional infrastructure or vehicle changes. • The feedstocks for next-generation cellulosic bioethanol do not generally require land that would otherwise be used for food. • High-blend bioethanol has a higher octane rating than petrol and a high heat of vaporisation, allowing higher boost in turbocharged or supercharged engines, or a higher compression ratio in a dedicated E85 application. As a result, higher specific power can be achieved. It is therefore well suited to downsized turbo direct-injection engines.

Fuel:	Bioethanol
Disadvantages:	• Higher strength blends of bioethanol (e.g. E85) require a specific flex-fuel vehicle with a modified engine control system. • Pipeline transportation of the fuel is problematic as a result of its corrosive nature and propensity to absorb water and impurities. • Bioethanol has a 33% lower energy density than petrol, which will result in reduced driving range and potentially higher fuel bills at higher percentage blends. • The effect of ILUC can significantly reduce the GHG savings of bioethanol, and the large amount of arable land required to grow the crops could decrease biodiversity through the destruction of natural habitats. • There are concerns that the use of bioethanol produced from food crops, or on land that could otherwise be used for food, could result in increased global food prices.
Infrastructure:	Low-blend strengths of bioethanol can be dispensed via the current refuelling infrastructure without modifications, but adding new E85 dispensing capacity to a refuelling station can cost £95,000–£120,000 (AEA, 2011a). It also requires facilities to supply and distribute this fuel alongside the unleaded 95 and super unleaded petrol grades. To date there are very few high-blend bioethanol dispensing stations in the UK.
Availability:	By 2020, bioethanol availability could potentially allow for a 10% blend in petrol fuel (by volume) (AEA, 2011b). The supply of such higher blends is already allowed under EU law and available in some countries. The British Standards Institute (BSI) is expected to publish a revised petrol specification (BS EN 228) in early 2013 which will allow fuel suppliers to sell up to 10% ethanol-blended (E10) petrol in the UK. Cellulosic bioethanol currently makes up only a small proportion of total bioethanol production.
GHG emissions:	Emissions vary according to feedstock and production process. First-generation crop-based bioethanol Emissions excluding ILUC: 24–70 gCO_2e/MJ (0.5–1.5 $kgCO_2e/litre$) ILUC emissions: 12–13 gCO_2e/MJ (0.26–0.28 $kgCO_2e/litre$) Total life cycle: 36–83 gCO_2e/MJ (0.8–1.8 $kgCO_2e/litre$) Next-generation cellulosic ethanol Total life cycle: 11–25 gCO_2e/MJ (0.23–0.53 $kgCO_2e/litre$)

3.2.7 Biodiesel (first-generation FAME)

Fuel:	First-generation biodiesel
Description:	First-generation biodiesel (FAME – fatty acid methyl ester) can be produced through esterification of a wide variety of vegetable oils and animal fats such as rapeseed oil, palm oil, soybean oil and tallow. Biodiesel is generally blended with a crude-oil-derived diesel and is sold as a blend, such as B7 or B30 – which represent biodiesel blends with a maximum of 7% and 30% ester respectively. Current UK diesel already contains up to 7% biodiesel.
Compatibility:	Biodiesel can be used in conventional compression ignition ICEs without modification in low blends. Higher blends up to 100% may be used, but can cause problems, particularly for newer/more sophisticated engine systems.

Fuel:	First-generation biodiesel
GHG reduction potential:	If FAME biodiesel is produced from waste vegetable oils such as used cooking oil, GHG savings are very high – up to 89% – mainly because there are no ILUC impacts. However, crop-based first-generation FAME biodiesel actually results in higher GHG emissions than use of fossil diesel when ILUC impacts are taken into account, unless methane capture is used at the oil mill. Savings are at best 3%, and at worst palm oil biodiesel can result in 37% higher GHG emissions. (This range would become savings of 24% to 64% if the ILUC impact were to be excluded.)
Energy density:	37.2 MJ/kg or 33.1 MJ/litre
Advantages:	• Biodiesel made from used cooking oil diverts a waste stream which can otherwise cause disposal problems, and results in very high GHG savings. • Blends of up to 7% biodiesel can be used directly by vehicles without any modification to the refuelling infrastructure or vehicle engines. • Biodiesel is biodegradable, non-toxic and free of sulphur and aromatics.
Disadvantages:	• The impacts of ILUC result in crop-based first-generation biodiesel having higher GHG emissions than fossil diesel (unless methane capture processes are used, in which case small savings may be obtained). • The large amount of arable land required to grow crops could decrease biodiversity through the destruction of natural habitats. • There are concerns that first-generation biodiesel produced from food crops, or on land that could otherwise be used for food (e.g. palm oil), could result in increased global food prices. • First-generation biodiesel is mildly corrosive and can degrade while in storage tanks. When this degraded fuel is burned in an engine, it can corrode engine parts and leave deposits that plug pumps and other mechanisms.
Infrastructure:	No new infrastructure is required for low blends of biodiesel, for example 7%, but adding new B30 refuelling stations could cost £75,000–£100,000 each (AEA, 2011a).
Availability:	By 2020, there is the potential for first-generation biodiesel to provide a B7 blend in diesel fuel. This would use 70% of the biodiesel supply, leaving the rest to be used for depot refuelling of captive fleets, such as trucks or buses (AEA, 2011b).
GHG emissions:	Emissions vary according to feedstock and production process. <u>Crop-based biodiesel</u> Emissions excluding ILUC: 32–68 gCO_2e/MJ (1.1–2.3 kgCO_2e/litre). ILUC emissions: 55 gCO_2e/MJ (1.8 kgCO_2e/litre) Total life cycle: 87–123 gCO_2e/MJ (2.9–4.1 kgCO_2e/litre) <u>Biodiesel from waste vegetable oil</u> Total life cycle: 10–14 gCO_2e/MJ (0.33–0.46 kgCO_2e/litre)

3.2.8 Next-generation biodiesels

Fuel:	Next-generation biodiesels (e.g. HVO and FT-BTL Diesel)
Description:	Next-generation – or so-called ‘advanced’ second- and third-generation – biodiesels can be produced using two very different processes and a variety of feedstocks. They result in fuels which have properties much closer to conventional mineral diesel than first-generation FAME biodiesel. For this reason they are often referred to as ‘renewable diesel fuels’ to distinguish them. Hydrotreated vegetable oil (HVO) is produced using a process which can be applied to oils from a wide variety of feedstocks – from food crops such as rape, sunflower and palm to waste animal fats, jatropha and algae oils. (Algal biofuels are sometimes known as ‘third generation’.) HVO is currently the most common process for next-generation biodiesel production. The Fischer–Tropsch process is a series of chemical reactions which can be used to convert biomass to liquid diesel (both the process and the resultant diesel being referred to as ‘FT-BTL’). Feedstocks can be woody energy crops, waste wood or forestry residues.
Compatibility:	Next-generation biodiesel can be used in conventional compression ignition ICEs in up to 100% blend strengths.
GHG reduction potential:	The GHG reduction potential of next-generation biodiesel will vary significantly depending on the feedstock and the production process. Using the Fischer–Tropsch process on farmed or waste wood results in GHG savings of 93–96%. HVO can result in a much wider range of savings. When using food oils such as rape, sunflower and palm, the savings are somewhat better than for FAME biodiesel, but can still result in higher GHG emissions than fossil diesel when ILUC is accounted for. At best, sunflower oil achieves 3–7% savings, and palm oil with use of methane capture can result in 9% savings. However, some palm oil processes can result in 30% higher GHG emissions than fossil diesel. Figures for HVO from Jatropha, animal fats and algae are not available from the European Commission RED Annex V. However, they might be expected to be significantly better.
Energy density:	44.0 MJ/kg or 34.3 MJ/litre
Advantages:	• Next-generation biodiesel fuels are drop-in replacements for diesel fuel, i.e. compatible up to 100% blends with current diesel engines. This removes the need for changes to the refuelling infrastructure and vehicles. • There are no specific storage stability issues or deposit formation problems. • Next-generation biodiesel production processes can use feedstocks which can substantially reduce ILUC impacts and competition with food crops.
Disadvantages:	• Next-generation biodiesel production processes are more expensive than those for first-generation biodiesel. • While HVO is now in commercial production, volumes are low compared to first-generation biodiesel. • The FT-BTL technology is currently at the pre-commercialisation stage, and it is unlikely that this method will produce significant quantities of fuel until the 2020s (AEA, 2011b).

Fuel:	Next-generation biodiesels (e.g. HVO and FT-BTL Diesel)
Infrastructure:	As both HVO and FT-BTL diesel are drop-in fuels, there is no requirement for the vehicle fleet or the refuelling infrastructure to be modified to accommodate the biofuel.
Availability:	Next-generation biodiesel produced from advanced feedstocks will only start to come into production over the next five years, and is unlikely to make an impact until the 2020s (ibid.). However, smaller quantities of HVO produced from conventional feedstocks are already being sold.
GHG emissions:	Emissions vary according to feedstock and production process. Fischer–Tropsch process using waste or farmed wood Total life cycle: 4–6 gCO_2e/MJ (0.1–0.2 $kgCO_2$/litre) HVO from vegetable oils Emissions excluding ILUC: 27–62 gCO_2e/MJ (0.9–2.1 $kgCO_2e$/litre) ILUC emissions: 55 gCO_2e/MJ (1.9 $kgCO_2e$/litre) Total life cycle: 82–117 gCO_2e/MJ (2.8–4.0 $kgCO_2e$/litre) HVO from non-food feedstocks is expected to result in significantly lower GHG emissions.

3.2.9 Electricity

Fuel:	Electricity
Description:	Grid electricity can be used as an energy source to charge on-board batteries of PHEVs and pure BEVs.
Compatibility:	Electricity can be used in PHEVs, REEVs and pure BEVs.
GHG reduction potential:	Using electricity to provide motive power in a vehicle will produce a 100% reduction in direct GHG emissions during the use phase. Factoring in life cycle emissions from the electricity's generation and transmission (using 2010 grid average figures of 0.560 $kgCO_2e/kWh$), a 54% GHG reduction is currently possible on a per-kilometre-travelled basis. With the anticipated levels of decarbonisation of future grid electricity, this could increase to 75% in 2020 and 83% by 2030 (DECC, 2012a; AEA, 2012). The actual performance will depend on the marginal emissions factor for electricity, which will in turn depend on the time of day the vehicle is charged. Emissions will likely be lower at night-time when surplus wind or nuclear-generated electricity is available, and higher at peak demand when natural gas or coal powered generation will most likely be used to meet additional demand. The current and near-future average marginal electricity emission factor is somewhat below the grid average according to DECC (2012a).
Energy density:	The latest lithium–ion batteries still only have an energy density of about 2% of petroleum fuels (European Commission, 2011c). However, this density might increase substantially in the future, for example as a result of R&D currently being undertaken into advanced battery chemistries such as lithium–air and lithium–sulphur.

Fuel:	Electricity
Advantages:	• There are no direct emissions of air pollutants – particularly important in urban areas, where these emissions are most harmful. • Electricity offers energy security and diversification, since it can be generated from a wide range of possible primary energy sources. • There exists the potential for extremely low GHG emissions per unit of energy through the decarbonisation of grid electricity. This is anticipated to be achieved by increasing uptake of renewable energy sources, nuclear energy, and the use of carbon capture and storage (CCS) with fossil-fuelled power stations. • Off-peak vehicle charging has the potential to make use of surplus low-carbon electricity (e.g. from wind at night) using existing generating capacity. • Electricity offers a large reduction in noise at lower speeds (although this may pose a risk for pedestrians and cyclists).
Disadvantages:	• The current technology for the charging of batteries is considerably slower than the equivalent hydrocarbon refuelling. For instance, slow-charging of a Nissan LEAF via a home unit could take six to ten hours (for a full charge), and even quick charging (up to 80% to protect the battery) could take 30 minutes (Nissan, 2012). • Owners of vehicles without access to off-street parking will have to rely on public charging infrastructure, which could be problematic during the early stages of EV deployment because of the scarcity of public charging stations.
Infrastructure:	The existing UK electricity infrastructure provides users with a very efficient system for generation, transmission and distribution of electricity to consumers. However, some local distribution grids would need upgrading in the case of a significant switch to EVs. Additional infrastructure is also required to install charging points at the home of BEV or PHEV owners, as well as public charging stations. Smart grid infrastructure would need to be created to manage the large numbers of EVs that might be charging, to balance the timing of a range of demands on the grid in an efficient way. Currently it is not completely clear what the optimal mix of slow-charging (for example in residential areas or workplaces), fast-charging (for example at conventional refuelling stations), or contactless charging and battery-swap stations will be. This will be determined by practical considerations, such as the rate of technical improvement in battery technology (leading, for example, to range improvements), but also aspects such as range anxiety and changes to the way the public use transport. Frequently fast-charging the battery will also reduce its effective lifetime in the case of most typical/conventional lithium–ion battery technologies.
Availability:	Electricity is widely available across the UK and can be produced from a wide variety of increasingly renewable sources. However, there will increasingly be competition for low-carbon electricity from other sectors as they become increasingly electrified.
GHG emissions:	Direct: zero emissions Indirect: Current emissions from power generation are approximately 155 gCO_2e/MJ (560 gCO_2e/kWh); however, this is anticipated to reduce to 68 gCO_2e/MJ (245 gCO_2e/kWh) by 2020, and to 37 gCO_2e/MJ (133 gCO_2e/kWh) by 2030 (DECC, 2012a). Emissions resulting from the use in the vehicle will also be somewhat higher due to recharging losses, which are currently estimated at around 13%, but may reduce to as little as 8% by 2050 (AEA, 2012). Note that these figures are averages. Actual GHG emissions will vary according to the mix of generation technologies being used by the grid at the time of vehicle charging (i.e. the marginal emissions factor).

3.2.10 Hydrogen

Fuel:	Hydrogen
Description:	Hydrogen is the simplest chemical element and a universal energy carrier that can be used as a fuel for transport. Naturally occurring hydrogen gas (H_2) is rare; the element is most commonly present in water molecules (as H_2O). To produce hydrogen for automotive use, the two most common methods are by separating it from oxygen via the electrolysis of water, or via steam reformation of natural gas. There are also other potential routes for hydrogen production available or under development, such as the gasification of either coal or biomass into hydrogen and CO_2, or various biological routes. As hydrogen has a very low energy density per unit volume, it is typically compressed to a pressure of 350 or 700 bar (*c.*5,000 or *c.*10,000 p.s.i. respectively) to provide the vehicle with sufficient on-board storage. Although hydrogen can be used in modified ICEs, it is principally being investigated for future use in highly efficient fuel cell vehicles (FCVs).
Compatibility:	Hydrogen can be used in dedicated spark-ignition ICEs and FCVs.
GHG reduction potential:	There is a 100% GHG reduction at the point of use of hydrogen, but factoring in the full life cycle emissions from its production and distribution, then using hydrogen could reduce emissions by 44% (on the basis of production from natural gas). As grid electricity is decarbonised and hydrogen production shifts towards electrolysis, this figure could rise to 52% by 2020 and 59% by 2030 (assuming 40% of production from electricity).[93]
Energy density:	120.1 MJ/kg, or 2.1 MJ/litre when compressed to 350 bar / *c.*5,000 p.s.i. or 3.2 MJ/litre at 700 bar / *c.*10,000 p.s.i. (somewhat lower when including the full fuel storage system) (Argonne National Laboratory, 2010)
Advantages:	• There are no direct emissions of air pollutants when used in an FCV, with only water vapour being emitted. This is particularly important in urban areas, where air pollutant emissions are most harmful. • Hydrogen offers energy security and diversification, since it can be produced from a wide range of possible energy sources/pathways. • When hydrogen is produced from low-carbon electricity, or derived from natural gas with CCS, then significant GHG reduction can be achieved. • With 700 bar (*c.*5,000 p.s.i.) compression a vehicle can have a range that is comparable with an ICE, and refuelling takes only a few minutes (BOC, 2012). • There is significant maturity in the technology, with over 80,000 fuelling procedures having already taken place (European Commission, 2012c). • Hydrogen offers a large reduction in noise at lower speeds when used with an FCV (although this may pose a risk for pedestrians and cyclists).
Disadvantages:	• There is a high cost associated with producing hydrogen from steam reformation or hydrolysis, and additional costs due to the compression or liquefaction. • The overall energy chain for hydrogen production and use in vehicles is much less efficient than using electricity directly (in BEVs or PHEVs) – i.e. greater total primary energy is needed (potentially around twice as much) to make hydrogen and use it in vehicles.

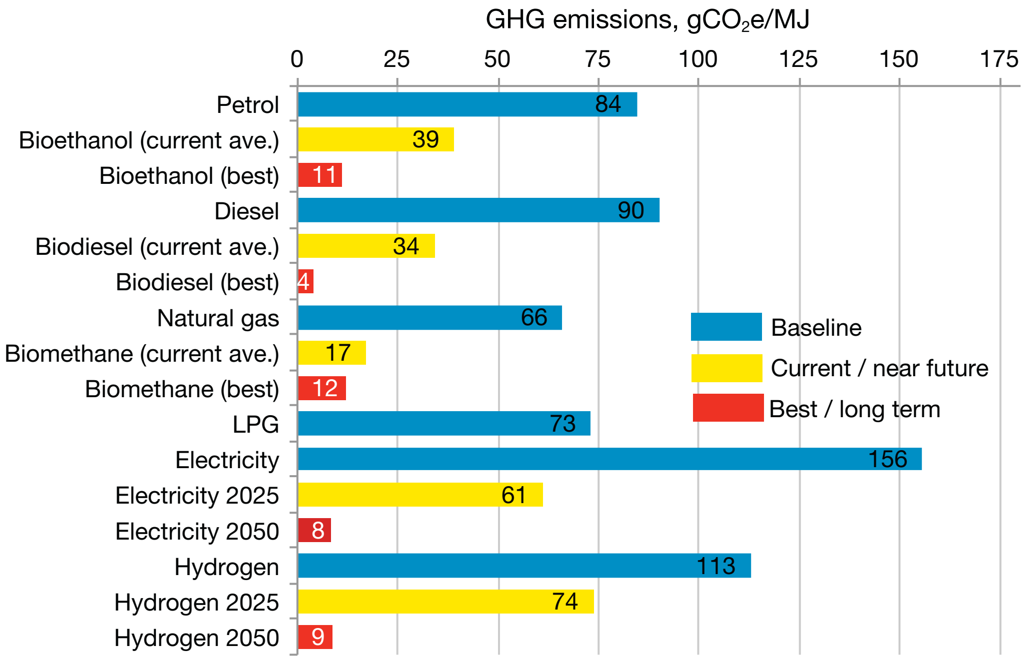
Fuel:	Biomethane (as bio-CNG)
Infrastructure:	Hydrogen is already produced and distributed in large quantities by petrochemical plants, and is used primarily by industry. This existing infrastructure may be utilised during the early stages of hydrogen for FCVs. It has been estimated that the cost of installing hydrogen infrastructure could be approximately €1,000–€2,000 (£800–£1,600) per car (European Commission, 2011a).
Availability:	Currently there is only one public access hydrogen refuelling station within the UK (BOC, 2012), but there are 200 hydrogen filling stations expected across Europe by 2015 (EEGFTF, 2011). Hydrogen can be produced from a number of sources using proven technologies, which could therefore ramp up production to meet the demand.
GHG emissions:	Direct: zero GHG emissions Indirect: 112.7 gCO_2e/MJ (or 13.54 $kgCO_2e/kg$), on the basis of 100% natural gas reformation) but potentially decreasing to 73.7 gCO_2e/MJ (8.85 $kgCO_2e/kg$) by 2025 (on the basis of hydrogen sourced from 60% natural gas reformation and 40% electrolysis).[6] If hydrogen is produced from electrolysis using purely renewable electricity then indirect emissions are essentially zero.

3.3 Comparison of fuels

The previous section has provided a summary review of each fuel in turn. In Figure 3.1, comparisons are presented of the current and potential future full fuel life cycle – the WTW GHG performance of fuels. The GHG reduction potential of biofuels is strongly dependent on the feedstock, production process and any direct or ILUC impacts. The figures presented in the preceding section exclude or assume minimal potential ILUC impacts; however, GHG savings may be substantially reduced where ILUC effects are significant. There is still considerable uncertainty as to how much biofuel can be provided sustainably, and what the overall GHG savings performance might be once ILUC is factored in (DECC, 2012e). Even beyond considerations such as competition with food production and other bioenergy applications, there are other sectors also increasingly competing for biomass (e.g. those requiring biomaterials and chemicals). Furthermore, there is increasing consensus that for transport applications, sustainable biofuels may be most effectively prioritised for aviation and shipping in the medium to long term, as in these cases there are fewer technical alternatives enabling GHG reduction, and fleets take much longer to turn over owing to long aircraft and ship operational lifetimes (DECC, 2012c). For electricity (and also to some extent hydrogen), the emissions factors presented are based on UK electricity grid averages (Defra/DECC, 2012) and projections on the future changes in these (DECC, 2012a). As has been discussed earlier, the actual marginal emissions due to the use of electricity for cars will vary depending to a significant degree on the time of day that the vehicle is recharged.

6 Ricardo-AEA analysis

Figure 3.1: Comparison of life cycle GHG emissions of various fuels (well-to-wheel)



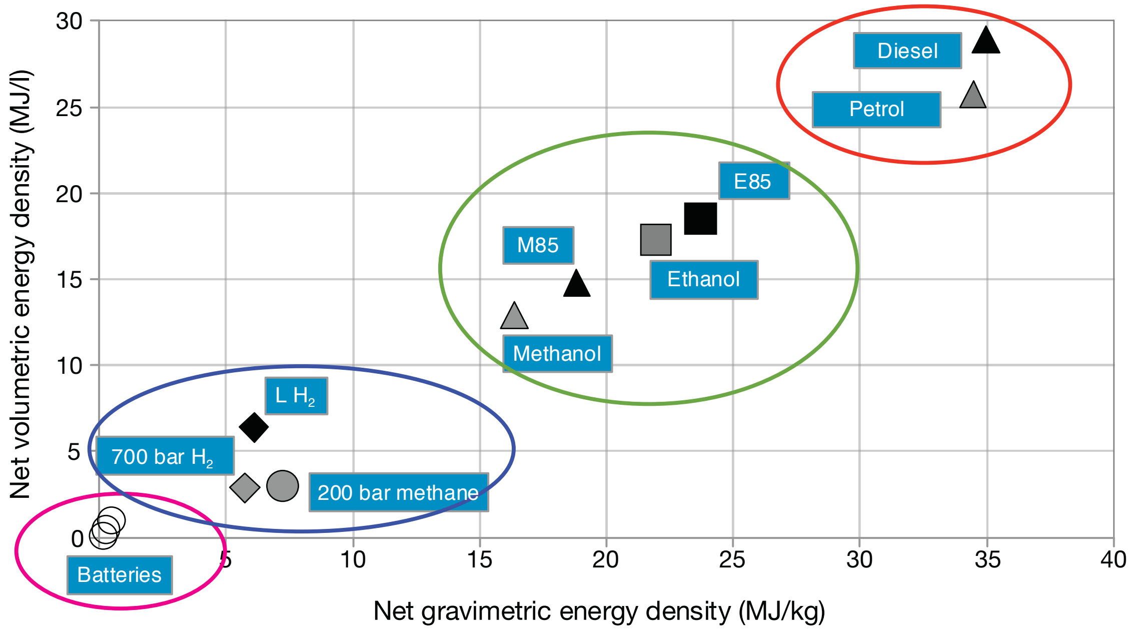
Source: Ricardo-AEA analysis

Notes: The GHG reduction potential of biofuels is strongly dependent on the feedstock, production process and any direct or ILUC impacts. The figures presented here are for the best case with minimal ILUC, but GHG savings may be substantially reduced where ILUC effects are significant. Emission factors for electricity exclude charging losses, which have been estimated to be around 13% in 2010, but may reduce to as little as 8% by 2050 (AEA, 2012). Emission factors for electricity are also dependent on source, the time of day for recharging (for example, it will be higher at times of peak demand when gas or coal generation will be used to meet marginal demand, and lower at night when surplus wind or nuclear electricity is available) – the current and future forecast UK grid averages are presented here.

From a practical perspective, Figure 3.2 also provides a comparison of the energy densities of different fuels once their respective onboard storage systems are taken into account. This illustrates the challenge facing alternative fuels such as hydrogen and electricity, even factoring in the significantly higher inherent efficiency of EVs and FCVs (i.e. taking into account that they are two to three times more efficient than conventional petrol and diesel cars). For gaseous fuels, the larger, heavier storage tanks required in comparison to diesel and petrol are a significant handicap. For hydrogen, a technology breakthrough is also needed to reduce the cost of the storage system.

Finally, Table 3.1 provides a semi-quantitative summary assessment of the relative strengths and weaknesses of different fuels against key criteria.

Figure 3.2: Comparison of on-board energy density for various transport fuels including storage system



Source: Pearson et al. (2010)

Table 3.1: Summary comparison of the relative performance of various transport fuels against key criteria

Fuel	Energy density	GHG saving* (now /future)	Air quality	Infra-structure	Availability (current)	Future resources**
Petrol	+++	---	--	+++	+++	--
Diesel	+++	--	---	+++	+++	--
Natural gas	-	-	+	-	+	-
LPG	-	--	-	++	++	-
Electricity	---	++ / +++	+++	+	--	+++
Hydrogen	--	+ / +++	+++	---	---	++
Biodiesel (first-gen.)	+++	+	---	++	+	-
Biodiesel (advanced)	+++	++	---	+++	--	+
Bioethanol	++	+ / ++	--	++	+	+
Biomethane	-	++	-	+	-	+

Source: Ricardo-AEA

Notes:

+++ highly positive;---highly negative

* Factoring in the much higher relative efficiency of electric powertrains.

** Considering both future long-term resource availability/sustainability (including competition with other sectors) and overall energy chain efficiency.

4. Future Vehicles

In this chapter the vehicle technologies which are expected to be the most important in the years through to 2025 and beyond are reviewed. There are still many things that can be done to further improve the efficiency of petrol and diesel powertrains, and to ensure, through the use of lightweight construction, reduced aerodynamic drag and improved rolling resistance, that future cars need less energy to propel them. Then there is the potential for further development of hybrid technology and the recently introduced plug-in hybrid options. Electric vehicles, sometimes incorporating small range-extending internal-combustion engines, are covered; and ultimately there are fuel cell vehicles.

In section 4.2 each option is examined to assess its potential to contribute to a low-carbon motoring future, and a description is provided of its costs, advantages/disadvantages, any risks or dependences relevant to the effective introduction of the technology into the marketplace, applications, GHG reduction potential, and availability. Finally the different options are compared side by side, and the key area of battery technology is explored in depth. However, the big question – to which everyone would like to know the answer – is: which of these technologies and fuels will prove to be the most successful in the marketplace and when?

Since the King Review was published in 2007, there has been a wealth of literature published on this subject. Opinions, estimates and modelling of the likely future mix of technologies have resulted in widely differing conclusions. Section 4.1 provides an initial look at the likely technology pathways for future cars. However, the predicted market shares for different technologies, the sensitivities which may affect market shares and timings, and the likely resulting fuel mix are explored later, in Chapter 5.

4.1 Overview

While there may be widely differing views on the speed of market take-up for different technologies, an analysis of the literature suggests there is a general consensus regarding the technology pathways themselves.

The UK Automotive Council consulted with OEMs operating in the UK and produced a commonly agreed technology roadmap, shown in Figure 4.1. Alongside the roadmap, the Automotive Council has also developed a useful summary of the R&D activities that are needed to deliver these technologies in the short, medium and long term (Figure 4.2).

Uncertainty over timeframes due to the energy storage breakthroughs required

As the roadmap highlights, the pathway of powertrain electrification – moving from full hybrid technologies, to plug-in hybrid, and onwards to mass-market BEVs and FCVs – will require breakthroughs in the area of energy storage in terms of both cost and performance.

The primary reason for the wide variation in estimates for the speed of market uptake of these technologies is uncertainty regarding when – and, indeed, whether – these breakthroughs can be achieved.

Nevertheless, there is widespread agreement, not just from the Automotive Council roadmap but from other sources too, that future technology development will fall into three key areas:

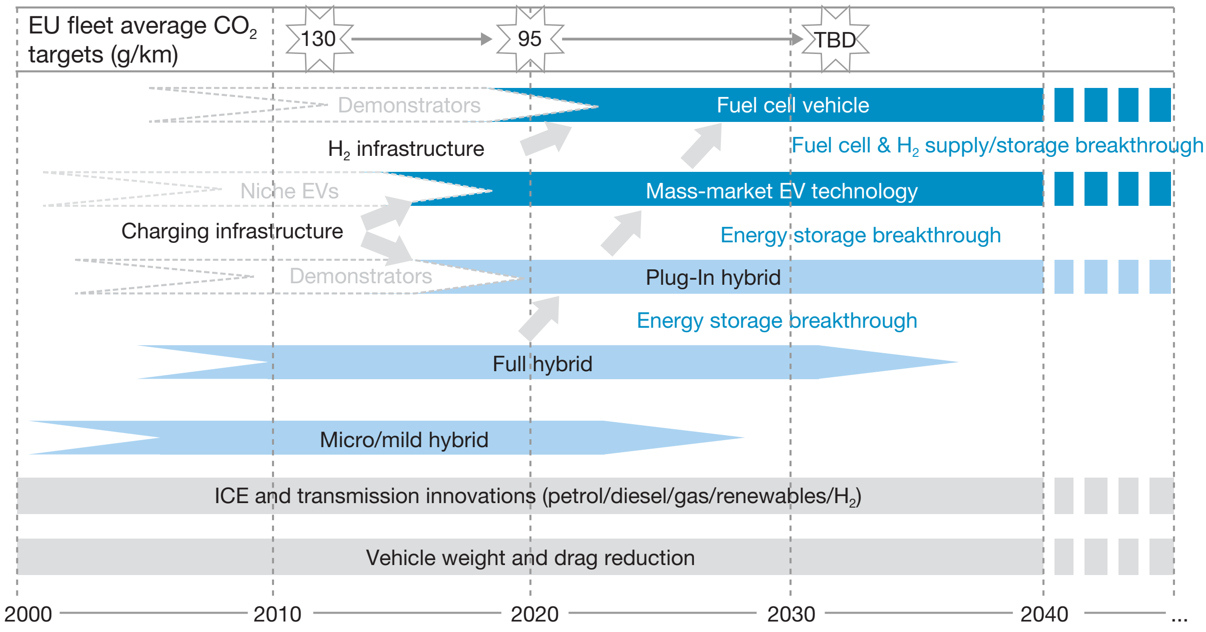
1. further improving ICE and transmission technology;

2. weight, drag and rolling resistance reduction; and

3. powertrain electrification.

Each of these three areas will be reviewed in turn, and the likely timeframes for developments in each summarised in sections 4.3 to 4.5 of this chapter; section 4.6 then looks at emissions in the real world and the impact of driving style. First, however, section 4.2 provides overall summary information on each of the main car powertrain options.

Figure 4.1: Automotive Council UK OEM Consensus Passenger Car Technology Roadmap



Source: Automotive Council (2011)

Figure 4.2: Automotive Council common research agenda

	SHORT TERM 5–10 years from production	MEDIUM TERM 7–15 years from production	LONG TERM 10–20 years from production
	INDUSTRY		UNIVERSITIES
Propulsion	• ICE optimisation • Boost systems for downsizing • Flexible valve/actuation for engines/transmissions • Low-cost compact e-motors	• Higher efficiency ICEs • Capacitive boost systems • All electric actuation systems • Optimised range extender engine • Lower cost e-motor • Heat energy recovery (e.g E-turbine)	• Super high-efficiency motors (superconducting) • New ICE with 70%+ thermal efficiency • Advanced heat energy recovery (e.g. thermoelectric) • Motor/fuel cell materials
Energy storage	• Improved quality / durability 200+ Wh/kg & $800/kWh cost battery systems • Low-cost power electronics	• Next gen batteries 300+ Wh/kg and $500/kWh cost • Flexible power elec. modules • Other forms of energy recovery (mechanical/chemical etc)	• 3rd gen batteries 400+ Wh/kg & $200/kWh cost • New low-cost solid state power conversion systems • Hydrogen storage technology
Vehicle Efficiency	• Lightweight structures and interiors • Low rolling resistance tyres / brakes	• New vehicle classes and configurations • Comination of function to reduce weight / cost • Minimised weight / losses	• Flexible re-configurable multi-utility vehicle concepts • 50% weight reduction from 2008 • Advanced aerodynamic concepts
System Control	• Information enabled control (Topology, V2V, V21, traffic etc.) • Optimised vehicle energy mgmt. • Intelligent thermal management	• Advanced information enabled control • Intelligent P/T and HVAC mgmt.	• Autonomous P/T and vehicle control interated with active safety
Energy + Fuel Supply	• Optimised 1st gen biofuels processes • New 2nd gen biofuel processes	• Intelligent energy / re-fuelling infrastructure (e.g. fast charge) • Industrial scale demonstration of new 2nd gen biofuel processes	• 3rd gen biofuel processes • 2nd gen industrial scale biofuel production infrastructure
Processes + Tools	• Process + delivery tool development and connectivity	• Auto-optimisation methods using virtual systems	• Artificial intelligence to deliver complex multi-criteria system optimisation

Source: TSB (2010)

4.2 Review of vehicle technologies

The following tables provide a review of the key technologies expected to be used in future vehicles in the years through to 2050. Each technology is considered in turn, providing summary information on key aspects including costs, advantages/disadvantages, any risks or dependences relevant to the effective introduction of the technology into the marketplace, applications, GHG reduction potential, and availability.

In general, figures used for cost and expected CO_2 savings potential are based on a version of the *Road Vehicle Cost and Efficiency Calculation Framework* produced by AEA Technology for CCC (AEA, 2012), that has been further developed and updated with more recent information by Ricardo-AEA. This ensures that figures are comparable across different technologies, and represent nominal vehicles of equivalent size/performance.

In general, costs and performance are presented for the current situation in the tables below. Future projections on how these figures might evolve to 2025 and to 2050 (owing, for example, to increased production volumes, technology improvements, or changes in materials costs) are presented as comparisons across different powertrain types at the end of section 4.7.

4.2.1 Further development of internal-combustion engine technologies

Technology:	Further development of internal-combustion engine powertrain technologies
Description:	Technologies to improve the efficiency of spark and compression ignition engines and transmissions, and hence decrease the energy consumption per km: stop–start; downsizing and turbocharging; petrol direct-injection; dual-clutch transmissions and variable valve actuation and lift – these are some of the technologies that can offer the greatest GHG reduction potential.
Cost:	The cost will vary between the different technologies, and will also vary for different engine sizes. However, the following are 2010 cost estimates for a implementing the technologies on a medium-sized car (European Commission, 2011e): • stop–start – £170 (£320 for systems with regenerative braking); • strong downsizing (45% cylinder reduction) with turbocharging – £480; • petrol direct-injection (stratified charge) – £400; • petrol variable value actuation and lift – £224. According to several recent studies, the average extra cost per vehicle (compared to costs in 2010) for achieving the European new car CO_2 target for 2020 of 95 g/km using primarily advanced ICE powertrain technologies has been estimated to be up to £800 (€1,000) (ibid.).
Fuel cost/km (for an average-sized car):	£0.107/km for petrol (£1,605 p.a., based on 15,000 km p.a.) £0.083/km for diesel (£1,245 p.a., based on 15,000 km p.a.) £0.071/km for LPG (£1,065 p.a., based on 15,000 km p.a.) £0.049/km for CNG (£735 p.a., based on 15,000 km p.a.) (Ricardo-AEA, 2012)

Technology:	Further development of internal-combustion engine powertrain technologies
Advantages:	• Implementing engine technologies can be some of the most cost-effective reduction measures and can be achieved in the short term. • These technologies do not require any additional changes to the refuelling infrastructure, and can be implemented on many existing vehicles' models. • The ICE is an established technology with consumers, who are comfortable purchasing the product.
Disadvantages:	• Although combining these engine technologies delivers significant emissions reductions, to achieve the very substantial long-term emissions reduction targets, supplementary vehicle technologies and low-carbon fuels will be required.
Risks:	–
Dependences:	–
Applications:	These ICE technologies can be applied to the whole fleet of standard spark and compression ignition engined cars, as well as to (plug-in) hybrids.
GHG reduction:	The GHG reduction potential varies according to the particular engine technology, but the some of the major technology options are: • stop–start – 5–10% reduction (higher value for systems with regenerative braking); • strong downsizing (45% cylinder reduction) with turbocharging – 16% reduction; • petrol variable valve actuation and lift – 10% reduction; • petrol direct-injection (stratified charge) – 9% reduction. Calculations based on known technological options in combination could achieve a reduction of up to 71% for petrol engines (to 69 gCO_2/km for the average-sized car, excluding biofuel) and 66% (to 67 gCO_2/km excluding biofuel) for diesel engines on a real-world basis (Ricardo-AEA, 2012). Emissions can also potentially be further reduced through the use of sustainable biofuels, as discussed in Chapter 3.
Availability:	Most of these technologies are ready for deployment now; however, others are still under development (e.g. HCCI – homogenous charge compression ignition) but are expected to be ready for market deployment in the next ten to fifteen years.
Examples:	The Audi A3 1.2 TFSI S tronic has implemented downsizing, petrol direct-injection, and variable valve actuation and lift (European Commission, 2011e). The 2012 Ford Focus 1.0 EcoBoost, a direct-injection, turbocharged engine, is an example of the potential for downsizing, with the lower power version achieving 109 gCO_2km on the official test cycle (Ford, 2012).

4.2.2 Non-powertrain technologies

Technology:	Non-powertrain technologies (e.g. lightweighting, aerodynamics and rolling resistance)
Description:	Non-powertrain technologies consist mainly of weight reduction, reducing aerodynamic drag, and lowering rolling resistance.

Technology:	Non-powertrain technologies (e.g. lightweighting, aerodynamics and rolling resistance)
Cost:	The costs of these technologies will vary according to the specific vehicle, but current cost estimates are (European Commission, 2011e): • weight reduction: 10% – £130; 20% – £320; 30% – £800; • improved aerodynamics – £40; • active aerodynamics – £50; • low rolling resistance tyres – £30.
Fuel cost/km:	N/A
Advantages:	• Non-powertrain technologies can be implemented for all vehicle types, spreading cost and risk of development across a greater number of vehicles, and reducing unit costs. For example, Lotus has concluded that by 2020, a 38% weight reduction might be achieved with only a 3% increase in production cost (World Economic Forum, 2011). • Such technologies are particularly beneficial for BEVs and FCVs. Given that drag and rolling resistance represent the great majority of the energy losses, these technologies provide further opportunities to downsize batteries/fuel cells and reduce costs.
Disadvantages:	• These technologies will assist in reducing GHG emissions, but by themselves will not enable cars to achieve their GHG reduction targets. Supplemental vehicle technologies, such as biofuels and/or electric drive, need to be implemented.
Risks:	The low (or negative) cost of a significant proportion of the potential for weight reduction is dependent on smart design. Material substitution is a significantly higher-cost alternative, in which there is more limited potential owing to aesthetic and other limitations. Weight reduction must not impair safety. Increasing the typical difference in weight between difference classes of vehicles (e.g. HGVs and cars) may increase safety risks.
Dependences:	–
Applications:	These technologies can be applied to cars with various powertrains, but are particularly beneficial for BEVs and FCVs, where drag and rolling resistance represent much higher proportions of overall energy losses.
GHG reduction:	10% weight reduction ≡2% GHG reduction 20% weight reduction ≡6% GHG reduction 30% weight reduction ≡12% GHG reduction Improved aerodynamics ≡2% GHG reduction Advanced aerodynamics ≡an additional 1% GHG reduction Low rolling resistance tyres ≡3% GHG reduction (European Commission, 2011e)
Availability:	These technologies are already being applied by manufacturers to a certain extent in some vehicle models. Higher degrees of weight reduction will require the use of currently expensive materials substitution and advanced design processes that may take ten to twenty years or longer to become cost-effective in mainstream vehicles compared to alternatives.
Examples:	Lightweight: smart fortwo (*c.*750 kg); Citroën C1 (800 kg); Toyota iQ (*c.*845 kg) Low drag coefficient: Mercedes E220 Coupé (0.24); Toyota Prius (0.25); Peugeot 508 (0.26)

4.2.3 Hybrid electric vehicles

Technology:	Mild & full hybrid electric vehicles
Description:	Mild hybrid vehicles include a small electric motor and a battery larger than the standard one used in a regular vehicle. The motor can provide extra power during acceleration and recover energy during braking, but is not sufficiently powerful to enable the vehicle to be driven under electric power alone. Full hybrids have a larger battery and motor than mild hybrids, thus enabling the vehicle to be driven for a few miles using electric power alone if required. The greater flexibility of a full hybrid allows the vehicle more scope to operate its engine only when that is the most efficient method of powering the vehicle (Hybrid Center, 2010).
Cost:	The current cost premiums for a medium-sized HEV are: mild hybrid *c.*£1,000; full hybrid *c.*£2,400 (European Commission, 2011e). The majority of the additional cost is due to the battery, which is expected to halve in cost in the next ten years.
Fuel cost/km (for an average-sized car):	£0.078/km for a full petrol hybrid and £0.066/km for full diesel hybrid (£1,170 and £990 p.a. respectively, based on 15,000 km p.a.) (Ricardo-AEA, 2012)
Advantages:	• HEVs can offer significant increases in fuel efficiency and decreases in GHG emissions, particularly when used in urban environments, where they can also reduce emissions of other air pollutants compared to conventional vehicles. • HEVs can reduce the noise levels within urban environments.
Disadvantages:	• HEVs have an increased environmental footprint resulting from the production of the electric motor and battery. This reduces to a small degree some of the emissions savings that arise from improved fuel efficiency.
Risks:	There are potential resource risks for the rare earth elements that are required for the electric motors, and materials for batteries.
Dependences:	–
Applications:	Mild and full hybrid technologies can be implemented on all car sizes, but they are best suited to cars operating in the urban environment, and packaging is more challenging on smaller cars.
GHG reduction:	Mild hybrids can reduce emissions typically by 15% and full hybrids by 25% (European Commission, 2011e). Emissions can also potentially be further reduced through the use of sustainable biofuels, as discussed in Chapter 3.
Availability:	There are an increasing number of mild and full hybrid vehicle models available and on the road today, with a number of OEMs looking to produce more models.
Examples:	Toyota Prius, Honda Insight, Honda Jazz Hybrid, Lexus CT 200h, Porsche Cayenne S Hybrid, Peugeot 508 HYbrid4, Mercedes E300 BlueTEC Hybrid (Lucas, 2008)

4.2.4 Plug-in (i.e. parallel) hybrid electric vehicles

Technology:	Plug-in (i.e. parallel) hybrid electric vehicles
Description:	A PHEV is a vehicle with a plug-in battery-powered electric motor and an ICE, arranged such that either can provide power to the wheels. A larger battery allows electric-only operation for shorter journeys (typically of around 10 miles). When the battery is depleted, the vehicle switches back to ICE operation but retains the benefits of full hybrid capability. Typically up to 30% of an average UK driver's annual mileage can be in full battery electric mode for vehicles of this type.
Cost:	Approximately £7,800 manufacturing cost premium over a conventional ICE, with this anticipated to reduce to £3,000 by 2020 (Ricardo-AEA, 2012).
Fuel cost/km (for an average-sized car):	£0.063/km for petrol and £0.054/km for diesel (£945 and £810 p.a. respectively, based on 15,000 km p.a.)
Advantages:	• PHEVs can combine the benefit of running on electric mode for short distances (e.g. the daily commute), while also having the range and short refuelling benefits of a petrol or diesel vehicle. • While the car is operating in electric mode, it produces no direct air quality pollutants and reduces noise pollution. • When used in conjunction with low-carbon electricity, PHEVs can lead to a high GHG emissions reduction.
Disadvantages:	• PHEV purchase prices are significantly more than those of equivalent ICEs. • PHEVs can be heavier than conventional vehicles because of the requirement to house the ICE, an electric motor and a large battery. This can lead to reduced cabin or load capacity within the vehicle and can increase vehicle energy consumption. • PHEVs have an increased emissions footprint, due primarily to the production of the larger battery. However, net overall emissions over the entire life of the vehicle are still significantly reduced.
Risks:	There are potential resource risks for the rare earth elements that are required for the electric motors, and materials for batteries.
Dependences:	• Many households do not have off-street parking, so additional on-street residential or workplace recharging infrastructure would be required to facilitate uptake in these cases. • There is a need for reducing battery cost (and weight) through technology innovation, to bring prices closer to alternatives and improve performance.
Applications:	These vehicles are suitable for most drivers who undertake a significant number of shorter trips (such as a daily commute), but who also need the range and utility of a conventional ICE car.
GHG reduction:	The potential for petrol PHEVs is for up to 33% net life cycle emissions reduction, which could rise to 37% reduction in 2020 as a result of the decarbonisation of electricity (Ricardo-AEA, 2012). Emissions can potentially be further reduced through the use of sustainable biofuels, as discussed in Chapter 3.
Availability:	These vehicles are currently available to purchase from some of the mainstream OEMs.
Examples:	Volvo V60, Toyota Prius Plug-in Hybrid

4.2.5 Range-extended (i.e. series) hybrid electric vehicles

Technology:	Range-extended electric vehicles
Description:	A REEV receives its drive exclusively from an electric motor (of which there may be more than one), but has an ICE-powered generator on board capable of continuously recharging the battery. The battery alone can typically provide a range of 25–50 miles. After that the ICE can generally provide a range equivalent to a conventional ICE vehicle. This arrangement is sometimes known as a ‘series PHEV’. Typically up to 60% of an average UK drivers’ mileage can be in full battery electric mode for vehicles of this type.
Cost:	An additional £11,000 manufacturing cost compared with a conventional ICE, with this premium reducing to £4,500 by 2020.
Fuel cost/km (for an average-sized car):	£0.048/km for petrol and £0.043/km for diesel (£715 and £645 p.a. respectively, based on 15,000 km p.a.)
Advantages:	• REEVs have significant all-electric range that will allow for most of a regular motorist’s mileage (typically over 60%) to be electric, and also share the benefits of longer range when running on petrol or diesel vehicle beyond this. • While the car is operating in electric mode, it produces no direct air quality pollutants and reduces noise pollution at low speeds. • When used in conjunction with low-carbon electricity and biofuels, a large GHG reduction can be achieved.
Disadvantages:	• The upfront purchase price is high compared with ICE cars. • A REEV can have embedded GHG emissions from manufacturing that are as much as 34% higher than its ICE equivalent (Ricardo, 2011), due primarily to the battery. However, net overall emissions over the entire life of the vehicle are still significantly reduced.
Risks:	There are potential resource risks for the rare earth elements that are required for the electric motors, and materials for batteries.
Dependences:	There is a need for reducing battery cost (and weight) through technology innovation, to bring prices closer to alternatives and improve performance.
Applications:	The longer all-electric range of REEVs, combined with the petrol or diesel extender, make such vehicles ideally suited to regular everyday use on shorter journeys, as well as giving them the range and utility of a conventional ICE car for longer journeys when needed.
GHG reduction:	REEVs can exhibit a 43% GHG reduction compared with conventional ICEs, which will increase to 47% by 2020 with the decarbonisation of electricity (Ricardo-AEA, 2012). Emissions can also potentially be further reduced through the use of sustainable biofuels, as discussed in Chapter 3.
Availability:	REEVs are now available from General Motors and Fisker, with other OEMs also planning to provide these types of vehicles.
Examples:	Vauxhall Ampera / Chevrolet Volt, Fisker Karma

4.2.6 Pure battery electric vehicles

Technology:	Pure battery electric vehicles
Description:	A BEV is powered solely by a battery charged from mains electricity. Alternative descriptions include: all-electric, fully electric or simply electric vehicle.
Cost:	Medium-sized BEVs (such as the Nissan LEAF) can cost £14,000 more than their petrol or diesel equivalent, with the majority of this additional cost being due to the battery. As a result of technical innovation and increases in production volumes, the cost premium of BEVs is likely to decrease over time to £5,600 by 2020 and to £2,700 by 2030 (Ricardo-AEA, 2012).
Fuel cost/km (for an average-sized car):	Approximately £0.033/km (£500 p.a., based on 15,000 km p.a.)
Advantages:	• BEVs emit zero tailpipe GHGs and air quality pollutants. • They reduce noise pollution. • They have simpler driver controls (typically no gear-shifting is required). • At a national level, large deployment of BEVs could reduce the UK's dependency on imported energy. • When used in conjunction with low-carbon electricity, a large reduction in GHG emissions is possible. • BEVs have low per-kilometre running costs. • BEVs require less costly maintenance than ICE cars, owing to the reduction in moving parts, the reduced needs for fluid changes, and less brake wear.
Disadvantages:	• The large purchase cost of a BEV compared to petrol, diesel or hybrid vehicles is the biggest disadvantage of this technology. • Compared with petrol or diesel vehicles, current BEVs currently have a limited range (typically 100 miles, but ranging from 50–250 before recharging is required). This range can be even more limited in extreme hot or cold conditions. • The embedded GHG emissions as a result of the vehicle manufacture can be twice those of a conventional ICE vehicle (Ricardo, 2011). However, net overall emissions over the entire life of the vehicle are still significantly reduced. • Actual real-world battery durability over the lifetime of the vehicle is a relative unknown. However, to qualify for the Plug-in Car Grant, vehicles must have a three-year battery and electric drivetrain warranty, with an option to extend the battery warranty for an extra two years. • Emergency response personnel need to be trained to understand the potential risks in dealing with an EV associated with the possibility of high current discharges.
Risks:	There are potential resource risks for the rare earth elements that are required for the electric motors, and materials for batteries.
Dependences:	To encourage wide-scale uptake of BEVs by consumers, a large network of public charging infrastructure is required to ensure that drivers can (and also reassure them that they can) charge their vehicles away from their homes. The infrastructure actually required will depend on the EVs' range and what users expect from them. Smart vehicle charging needs to be enabled to ensure that BEVs can plug into the grid without negatively impacting grid capacity. Decarbonisation of the electricity grid is required to ensure that BEVs can achieve extremely low WTW emissions.

Technology:	Pure battery electric vehicles
Applications:	Currently, BEVs are best suited to urban environments, where shorter journeys are experienced in stop–start conditions, and drivers have convenient access to charging infrastructure. However, in the future it is expected that manufacturers will introduce BEVs with a greater driving range that will enable a wider range of applications.
GHG reduction:	Compared to current petrol equivalents, BEVs yield a 100% reduction in TTW emissions, but factoring in WTW emissions the figure is a 56% reduction, based on the grid average. This could rise to 67% by 2020 as a result of electricity decarbonisation. Depending on the time of day for EV charging (and mix of generation capacity), the GHG savings may be higher or lower depending on the marginal generation type (i.e. for the electricity used to provide the additional energy needed for EVs). Overnight charging is likely to lead to greater GHG savings (owing to surplus renewable wind electricity generation or nuclear base-load). However, charging nearer peak demand hours in the daytime is likely to result in significantly reduced savings, as gas or coal power stations are used more.
Availability:	BEVs are starting to come into the marketplace from the major OEMs, but limitations in available models, high purchase prices and range concerns are likely to result in relatively low deployment levels over the next ten years.
Examples:	Nissan LEAF, Mitsubishi i-MiEV / Peugeot iOn / Citroën C-Zero, Renault Fluence Z.E., Renault ZOE, smart fortwo electric drive

4.2.7 Fuel cell vehicles

Technology:	Fuel cell vehicles
Description:	FCVs are powered by electrical energy obtained from stored hydrogen, methane or methanol which is converted into electricity using a fuel cell. Most commentators are expecting hydrogen polymer electrolyte membrane fuel cells to be the focus, therefore the following assessment focuses on HFCVs.
Cost:	FCVs are not in production at present, and the current premium over an ICE car is estimated at *c.*£70,000. However, this cost premium is due to reduce over time, with an estimate of just £3,000 premium by 2030 (AEA, 2011; Ricardo-AEA, 2012).
Fuel cost/km (for an average-sized car):	£0.033/km (£500 p.a., based on 15,000 km p.a.; estimate based on hydrogen produced from natural gas)
Advantages:	• No air quality pollutants are emitted during the use phase, with water vapour being the only product of the reaction. • FCVs produce little noise pollution at slow speeds. • When hydrogen is produced from electrolysis of renewable energy, FCVs have the potential to produce ultra-low life cycle emissions.
Disadvantages:	• FCVs are not currently being mass manufactured by OEMs, and modelling shows that these vehicles are not going to be cost-competitive at the point of purchase for another twenty to thirty years (AEA, 2011; Ricardo-AEA, 2012). • On-board hydrogen storage in highly compressed fuel tanks (or other means) is still significantly heavier / larger in volume than conventional fuel storage.

Technology:	Fuel cell vehicles
Risks:	The main risk is the lack of breakthroughs to reduce the cost of the fuel cell. There are also potential resource risks for the rare earth elements that are required for the electric motors.
Dependences:	To encourage wide-scale uptake of FCVs by consumers, a large network of hydrogen refuelling infrastructure is required to ensure that drivers can refuel their vehicles without inconvenience. Innovation is also required in the fuel cell to reduce the required amount of platinum. Decarbonisation of the electricity grid is required to ensure that hydrogen can achieve low WTW emissions.
Applications:	Because of the short refuelling time and their large range, FCVs are suited to vehicles that are required to operate regularly over long distances.
GHG reduction:	FCVs exhibit a 100% reduction in TTW emissions. In terms of WTW emissions, FCVs can achieve a 58% reduction in 2020 (assuming hydrogen sourced from 80% natural gas reformation and 20% electrolysis using grid electricity), and 68% reduction in 2030 (assuming 60% gas reformation and 40% electrolysis).
Availability:	There are currently no production HFCVs available to purchase, but Honda has leased some vehicles and Hyundai started limited production in February 2013 for lease to public and private fleets. Toyota has stated that it is to launch a saloon-sized fuel cell car by 2015, and some other manufacturers have similar expectations (Reed, 2012).
Examples:	No FCVs are currently in production; however, Honda has produced a limited run of 200 FCX Clarity FCVs available for lease in California. Hyundai expects to build 1,000 vehicles for lease by 2015.

4.3 Further improving internal-combustion engine and transmission technology

The following sections provide additional information, further elaborating on that summarised in the technology boxes in the previous section.

In previous research conducted by Ricardo-AEA involving interviews with very senior R&D decision-makers from the automotive industry, there was a strong message that the short to medium term would continue to be dominated by further improvements to ICE technology (JRC-IPTS, 2012).

This is confirmed by technology roadmaps from various organisations including the Automotive Council UK and EUCAR, the European Council for Automotive R&D (Automotive Council, 2011; EUCAR, 2011). The 2012 position paper of EARPA (the European Automotive Research Partners Association) on advanced ICEs and fuels states:

> “In 2030 more than 65% of all road transport vehicles will still be powered by ICE running on liquid fuels, therefore engines have to become thermodynamically more efficient” (EARPA, 2012).

In the longer term, high-efficiency ICEs are expected to remain important for use in PHEVs and REEVs.

Even in the IEA's BLUE Map scenario (which makes assumptions about light-duty powertrain technology splits on the basis of the need to achieve carbon reductions, rather than market trends), 55% of vehicle sales in 2050 will feature an ICE, although only 9% will be conventional petrol or diesel vehicles. The majority (34%) are forecast to be PHEVs, with a further 8% being conventional hybrids (IEA, 2010).

The World Energy Council has published scenarios for the make-up of the overall vehicle fleet in 2050, on the basis of two alternative policy options. In the 'Freeway' scenario pure free market forces are allowed to prevail, and in Western Europe as much as 61% of the light duty vehicle fleet remains conventional petrol and diesel vehicles. In the alternative 'Tollway' scenario of "a more regulated world where governments decide to intervene in markets to promote technology solutions and infrastructure development that puts common interests at the forefront", this figure falls to 19%, but with a further 44% still featuring an ICE, albeit 22% being plug-in hybrids (World Energy Council, 2011).

Table 4.1: World Energy Council scenarios for light duty vehicle fleet technology mix in 2050

	'Freeway' (free market)	'Tollway' (Intervention)
Conventional (petrol and diesel)	61%	19%
Hybrid (petrol and diesel)	19%	14%
Plug-in hybrid (liquid fuel)	1%	22%
Hydrogen hybrid ICE	0%	0%
CNG and LPG (ICE and hybrid)	17%	8%
Battery electric	1%	28%
Hydrogen fuel cell	0%	8%

Since the introduction of the European passenger car CO_2 emissions legislation, there has been a stronger focus on vehicle efficiency, and progress in reducing CO_2 has accelerated.

There remains much more which can be done to improve the efficiency of the ICE and transmission systems (Table 4.1).

Stop–start technology allows 5–10% reductions in CO_2

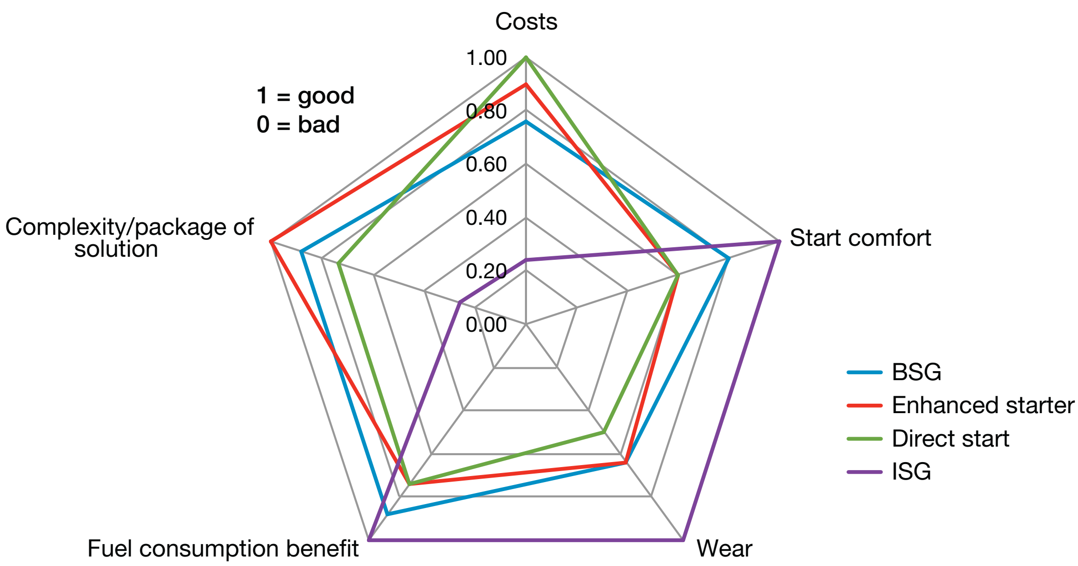
Stop–start technology is perhaps the most cost-effective way of achieving reductions of between 5–10% in CO_2 emissions (depending on whether the system is able to recapture braking energy). Ricardo estimated that the cost per gram of CO_2 reduction was about half that of improving the fuel efficiency of the ICE, and less than a quarter of that for hybridisation (Ricardo, 2012).

Currently low-cost belt-driven starter-generator systems (BSGs), and enhanced starter systems which eliminate the belt and use a modified starter motor, between them dominate the market. However, the technology is expected to progress to direct start systems which use the engine management system on direct-injection engines to allow the engine to instantly restart itself, and integrated crankshaft starter generators (ISGs – see Figure 4.3; note that for all parameters in the below radar chart, values closest to the centre represent very poor performance (e.g. high cost) and those reaching the outside edges represent very good performance (e.g. low cost); likewise a high figure for wear means low wear, and a highly complex system will score low on that axis of the radar chart).

High-efficiency stop–start systems require better energy storage technology

Improvements in stop–start technology enabling them to recapture energy are linked to improvements in energy storage technology. Technologies such as enhanced flooded batteries or valve regulated batteries have a much greater cycle life and capacity to accept charge, allowing better durability and energy recapture; these are now being fitted to some production vehicles (VARTA, 2013).

Figure 4.3: Comparison of stop–start technologies



Source: FEV (2011)

Ultimately ultra-capacitors offer unlimited cycle life and very high energy density. They provide much greater efficiency in regenerative braking systems, since they can charge and release energy at a vastly greater rate and at higher efficiency than battery technologies. At the moment existing battery-based regenerative systems only capture/release 33–50% overall of the energy from braking (this percentage increases with more gradual braking/acceleration), and are currently expensive.

Table 4.2: Internal-combustion engine and transmission system technologies and timeframes (excluding hybrid/electrification measures)

	Short/medium term (2012–17)	Longer term (2017–25)
Combustion engine technologies	Engine downsizing enabled by: • turbocharging • supercharging • direct-injection Fully variable valve actuation Improved fuel injection systems: • multi-strike injection • rate shaping • increased pressures Low speed torque assist: • variable geometry turbochargers • electric super/turbochargers Improved thermal management: • advanced coolant management • exhaust heat recovery Friction reduction	Advanced/alternative combustion systems: • high EGR (exhaust gas recirculation) stratified • lean stratified (with lean NO_x trap aftertreatment) • laser ignition systems • controlled auto-ignition • split cycle / Atkinson cycle / Miller cycle • micro-turbines and other concepts suited to range-extender applications / multi-fuel options Cylinder de-activation Variable compression ratio
Transmission technologies	Longer final drive ratios (‘down-speeding’) 6-to-8-speed gearboxes Dual-clutch transmissions	Planetary gearboxes

Source: Based on roadmap information from Ricardo-AEA (2012), EARPA (2012) and EUCAR (2011)

4.4 Weight, drag and rolling resistance reduction

All vehicles, regardless of powertrain type, can be made more efficient through reducing weight, aerodynamic drag and rolling resistance. However, the benefit of such improvements for electrically powered vehicles is particularly strong. Electric powertrains are highly efficient, and as a result weight, drag and rolling resistance account for a much larger proportion of the total efficiency losses. Reducing these losses may also allow the battery size to be reduced for a given range, in turn further reducing vehicle weight and cost.

4.4.1 Weight reduction

Weight reduction is the area with perhaps the greatest potential. As Gordon Murray, the ex-Formula 1 designer who is currently developing radical new city car concepts has said: “Lightweight is the most powerful tool we have in our armoury in the fight against emissions and fuel consumption.”

The average mass of new cars sold in Europe increased by nearly 9% between 2001 and 2007 (from 1,268 to 1,378 kg), but has, since 2007, remained relatively constant. It has been calculated that if mass had stayed constant at 2001 levels, new car average CO_2 emissions in 2010 would have been 5 gCO_2/km lower (ICCT, 2011). Reducing vehicle mass is important for all vehicles, but particularly for those used in areas with high levels of stop–start activity.

Initially, weight reductions are likely to be achieved through a greater focus on minimising vehicle weight in the design process in areas such as seating, glazing and interior components, in combination with further increases in the use of high-strength steels and aluminium in the vehicle body structures. Simplification of assemblies to reduce the number of components can also achieve weight reductions. The ‘aggregation of marginal gains’ – a phrase coined by David Brailsford, director of British Cycling – is as applicable to reducing automotive mass as it is to Olympic cycling.

However, the increased focus on improving fuel economy and reducing CO_2 emissions has led to further demand for lightweight materials innovation, with research focused on (European Commission, 2011d):

- carbon fibres, natural/glass fibres;
- high-strength steels and aluminium;
- magnesium technologies; and
- hybrid materials and bioplastics.

Carbon-fibre-reinforced plastics (CFRPs) are already starting to be introduced. CFRP is the planned material for body components on BMW’s forthcoming i3 battery electric and i8 hybrid vehicles, where it is reported to achieve a weight saving of 50% over steel and 30% over aluminium (Green Car Congress, 2011; BMW-i, 2013).

Other manufacturers are looking at alternatives to carbon fibre because of its cost and energy-intensive production processes. Audi is examining using basalt-fibre, and even waste plant-based fibres (Stanford, 2011).

The ultimate potential for weight reduction is likely to be seen in dedicated ultra-light city cars. The Renault Twizy gives a current production example of what is possible for a two-seater EV, weighing just 450 kg. Many other manufacturers have developed small, lightweight one-, two-, or three-seater prototypes to demonstrate the potential of these vehicles (see Table 4.3).

Gordon Murray's T.25 design is powered by a 660cc modified smart car engine, seats three, and has a range of 480 miles.[7] It weighs 550 kg, is reported to achieve 74 mpg / 86 gCO_2/km on the NEDC, and is estimated to cost £6,000. It won the inaugural RAC Future Car Challenge (FCC) in 2010, averaging 96 mpg, equivalent to 68 gCO_2/km.

His T.27 design, a battery electric version of the T.25, weighs 680 kg and provides a useful direct comparison between a highly efficient ICE design and a BEV. It won the RAC FCC in 2011 using 7 kWh for the 63-mile course. This equates to 69 Wh/km, which at an assumed UK grid average carbon intensity of 560 gCO_2/kWh and a recharging efficiency of 87% equates to 44 gCO_2/km. However, its estimated cost is £7,000, and the range obtainable from its 12 kWh battery is estimated at 100 miles on the NEDC (although at 69 Wh/km this would increase to 120 miles).

Table 4.3: Comparison of city car concepts

Concept	Seats	Weight (kg)	Powertrain technology	Range (miles)	Claimed tailpipe gCO_2/km	Life cycle gCO_2/km (from electricity production)*
Audi urban concept (1+1)	2	480	Electric	45	0	63
GM EN-V	2	400	Electric	25	0	51
Murray T.25	1+2	550	Petrol	480	86[8]	n/a
Murray T.27	1+2	680	Electric	100	0	48
Opel RAK e	2	380	Electric	62	0	32
Peugeot VéLV	1+2	650	Electric	62	0	55
Renault Twizy	2	450	Electric	43	0	56
Tata Megapixel	4	950?	REEV (petrol)	560 (54 EV)	22[9]	n/a
VW NILS	1	460	Electric	40	0	53
VW XL1	2	795	PHEV (diesel)	? (20 EV)	21[10]	n/a

Note: Figures for CO_2 from electricity consumption are calculated using the Department for Environment, Food and Rural Affairs (Defra)/DECC grid electricity consumption carbon intensity figure of 560 gCO_2e/kWh (including transmission losses), and a charging efficiency of 87% (Defra/DECC, 2012). Vehicle efficiency is calculated from stated battery capacity (kWh) and range. Note that the vehicle efficiency figures may be pessimistic, given that useable battery capacity is lower than stated capacity.

7 Assuming 30 litre fuel tank and 74 mpg (Autocar, 2012; Carfolio, 2010).
8 Cropley (2012)
9 Tisshaw (2012)
10 Volkswagen Media Services (2013)

The designers of the Edison2, winner of the Automotive X PRIZE (for “cars that achieved at least 100 MPGe in real-world driving”), initially assumed that they would use a hybrid or full electric powertrain. However, when designing a very light four-seater vehicle, they found that optimal energy efficiency was achieved with a conventional drivetrain rather than hybrid or electric, the benefits of regenerative braking being outweighed by the additional weight of the hybrid system’s battery and electric motor (Edison2, 2010). The vehicle weighs about 450 kg and has achieved fuel economy of 110 mpg-e (132 mpg in UK gallons) and emissions as low as 82.6 gCO_2 per mile (51 gCO_2/km) (Edison2, 2012).

The Automotive Council UK notes that the longer-term (ten to twenty years from production) potential for improving vehicle efficiency includes achieving a 50% weight reduction from 2008 levels, and the introduction of flexible re-configurable multi-utility vehicle concepts (TSB, 2010).

When considering lightweight materials, it should be noted that lighter weight materials such as aluminium and carbon fibre can have a significantly higher carbon footprint than steel. While it is very likely the increased manufacturing emissions would be more than compensated for by reduced in-use carbon emissions, this further reinforces the need to move to a full vehicle life cycle emissions approach.

4.4.2 Aerodynamic drag reduction

Some modern production cars are now being designed to achieve very low coefficients of aerodynamic drag. For example the Mercedes E220 Coupé has a drag coefficient of 0.24 – the lowest of any series production vehicle (Daimler, 2009). The Toyota Prius Plug-in achieves 0.25, as does the standard Prius (Toyota, 2011a; 2011b). Given the fuel economy benefits, it is likely that more manufacturers will increase their focus on achieving similarly low drag coefficients.

While achieving these figures can require expensive detailed wind tunnel test work, it is unlikely to mean a significant increase in vehicle retail prices. Relatively low-cost measures to reduce drag include reducing the ride height, smoothing the under body, and fitting smooth wheel covers. More expensive measures such as active grille shutters which close at higher speeds have been introduced on some Opel/Vauxhall[11] and Ford models, resulting in a claimed 2% reduction in CO_2 (Ford, 2011b). However, average passenger car frontal areas have increased approximately 10% between 1995 and 2010, which may have offset reductions in drag coefficient.

Ultimately drag factors as low as 0.15 are possible for a four-seater vehicle, as demonstrated by the design of the Automotive X PRIZE winner, Edison2; however, the compromises to conventional styling and packaging may be unacceptable to today's consumers.[12]

4.4.3 Rolling resistance reduction

The primary way in which rolling resistance can be reduced is through the use of low rolling resistance tyres kept at the correct tyre pressures. Recognising this, the European Commission has mandated the introduction of both low rolling resistance tyres and TPMS (tyre pressure monitoring systems) for all new passenger cars starting from 2014, as described in section 2.2.1. In the past there was a trade-off between fuel economy, safety, noise and longevity. However, according to manufacturers, low rolling resistance is often achieved through changes to the tyre wall and carcass, rather than the tread itself.

A TPMS alerts the driver if the tyre pressure falls below 80% of the normal value. According to the European Commission (2007), they are expected to achieve a 2.5% reduction in carbon emissions, while for passenger cars, low rolling resistance tyres are expected to achieve a further 3%. These figures are substantially lower than the DfT's estimate of up to 20% reductions in fuel consumption by 2020 (DfT, 2010b). The further European Commission regulation requiring tyre labelling should help consumers to purchase the most fuel-efficient tyres when replacements are needed, although it is yet to be seen how consumers will respond.

11 http://media.opel.com/media/intl/en/opel/news.detail.html/content/Pages/news/intl/en/2011/OPEL/01_12_astra_ecoFLEX_start-stop.html

12 Progresive Automotive X-Prize website available at www.progressiveautoxprize.org.

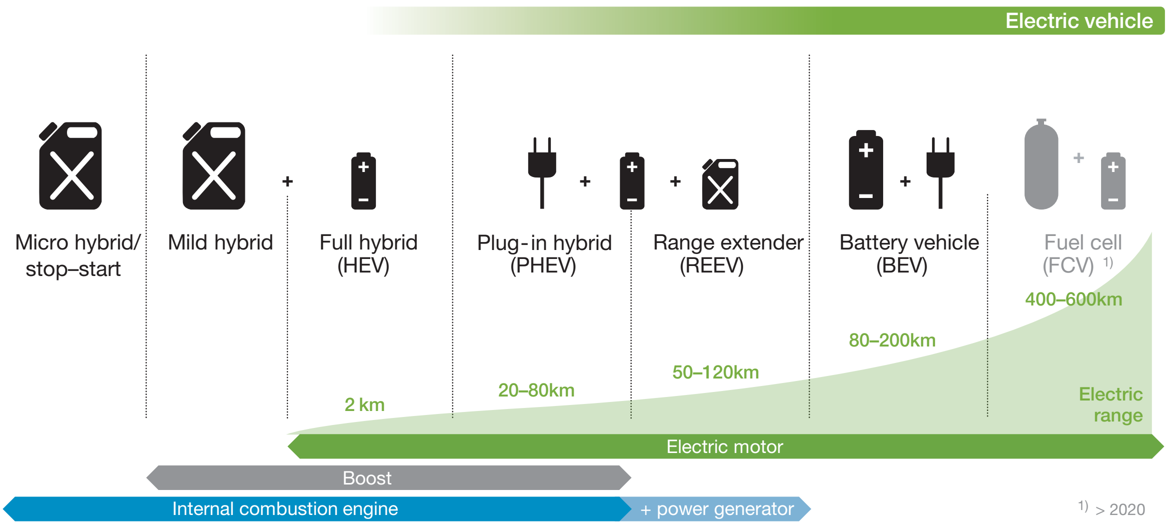
4.5 Powertrain electrification

Since the publication of the King Review in 2007, one area of low-carbon car technology has had more focus than any other – that of electrification. As ERTRAC states in the introduction to its electrification roadmap: "Within the last years electrified mobility has been given first priority in the US, Japan, China, Korea and EU" (ERTRAC, 2012).

It is important to recognise the various stages of powertrain electrification. EUCAR summarised these as shown in Figure 4.4.

This progression is in agreement with the Automotive Council's roadmap, and is widely accepted elsewhere. The contention is in the timing for these developments. As a recent report from the European Commission's Joint Research Council (JRC) stated, for EVs it is a "when-question, not if-question" (JRC-IPTS, 2010).

Figure 4.4: Electrification of the powertrain



Source: Steiger (2013)

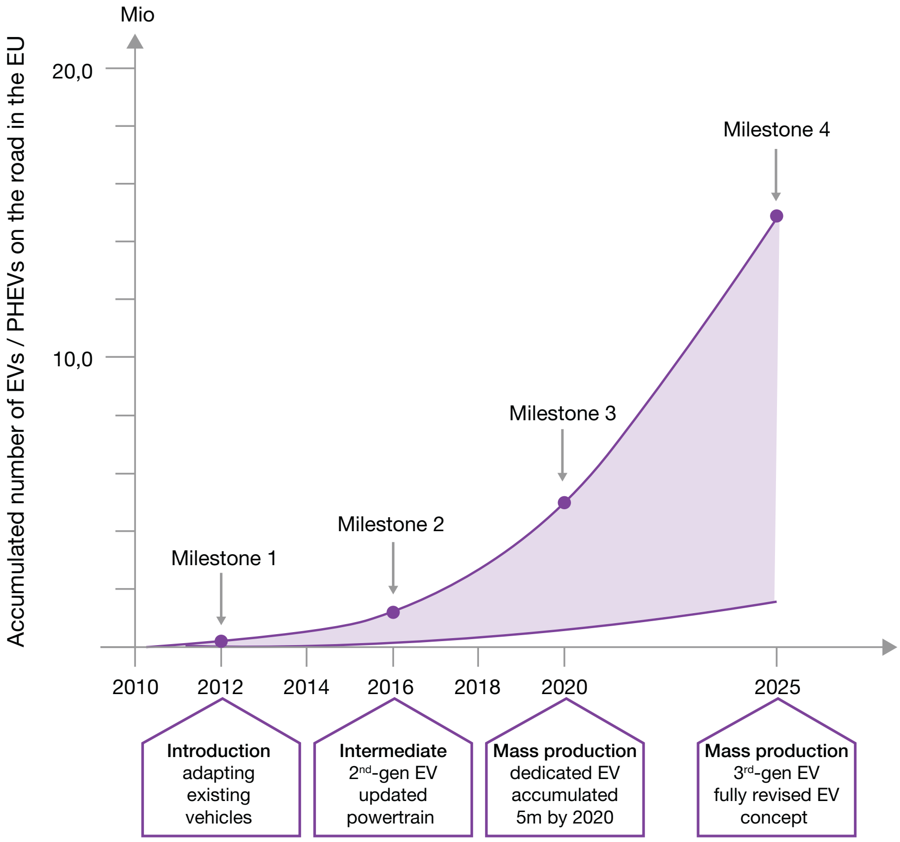
Note: 'Boost' refers to the ability of the electric powertrain components to boost the performance of the internal-combustion engine (which is not possible in a stop–start system).

ERTRAC's electrification roadmap identifies four key milestones as shown in Figure 4.5 These set out how the technology pathway is expected to progress over time, and are summarised as follows:

- ***Milestone 1: Introduction (2012):*** Adaptation and conversion of existing vehicle models into PHEV and electric cars, with the first vehicles often used in niche applications such as, for example: taxis, car-sharing systems, delivery services and other captive fleets.

- ***Milestone 2:** Intermediate (2016):* Dedicated second-generation EVs are developed, providing efficiency gains for all consumers, advanced system integration, and high-performance energy storage systems. An enlarged charging infrastructure linking various cities and regions will develop in parallel.
- ***Milestone 3:** Mass Production (2020):* Mass production of dedicated PHEV and EVs may be fully established in Europe. Batteries have approximately doubled lifetime and energy density compared to 2009 lithium–ion technology, at about 30% of the cost. Other systems need to be highly integrated and cheap, and on the market in high volumes to enable vehicle sales without subsidies. Grid integration providing advanced levels of convenience through, for example, contactless and quick charging at high efficiencies (and potentially also bidirectional energy flow between the vehicle and the grid).
- ***Milestone 4:** Fully Revised Electric Vehicle Concept (2025):* The exploitation of the full potential of electric cars requires total revision of the automobile concept. This will lead to step changes in energy efficiency and cost, and greatly contribute to the availability of EVs at the cost of an ICE vehicle without incentives. Third-generation EVs will be based on dedicated integrated platforms with distinctly improved energy recovery, and batteries with enhanced vehicle-to-grid, and fast-charging capabilities. Contactless charging may be widely available, with multi-fuel range extenders as a solution for enhancing the options provided by an EV. Full integration into the multimodal transport is required for establishing customer acceptance and new use cases.

Figure 4.5: Milestones for European electrification of road transport



Source: ERTRAC (2012)

4.5.1 Battery technology

The main factor determining the speed of progress for powertrain electrification is battery – or energy storage – technology. Battery technology is a key determinant of the overall cost and performance of plug-in vehicles. Improving battery technology and reducing cost is widely accepted as one of the most important, if not *the* most important factor in how speedily these vehicles gain market share. Breakthroughs are needed in four areas:

- reducing the cost;
- increasing the specific energy (enabling improved vehicle range/ performance for a given battery weight);
- improving usable operational lifetime; and
- reducing recharging times.

At the same time, manufacturers must ensure the highest levels of safety, as the potential damage to the image of EVs from a high-profile failure is substantial. This is a significant challenge, given the instability of many lithium–ion chemistries, which are the main focus for current plug-in vehicles (Canis, 2011). However, over the years many different types of battery have been used. Five of the most common alternatives to lithium–ion batteries are shown in Table 4.4.

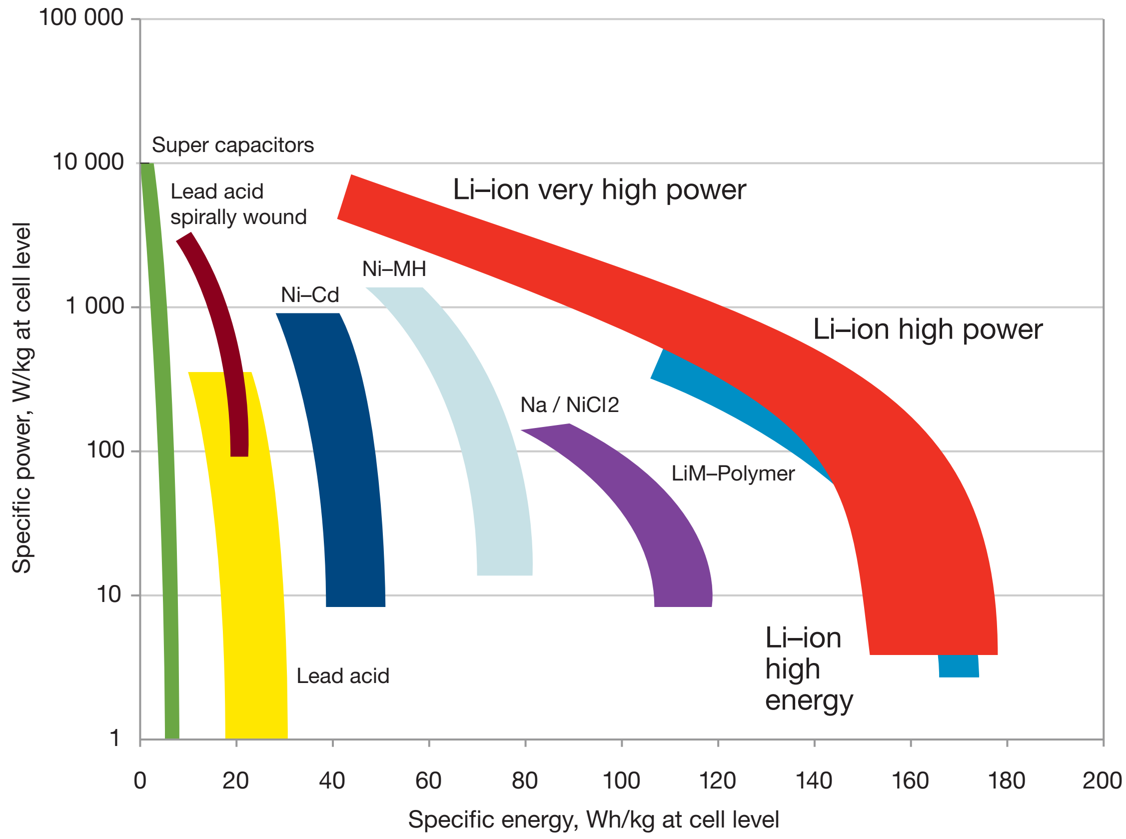
Table 4.4: Previously and currently used alternatives to lithium–ion

Chemistry	Principal advantages	Principal drawbacks	Car and van applications
Lead–acid	Low-cost, mature technology Very well-developed recovery and recycling systems Comparatively benign environmental impacts	Poor specific energy and power	Peugeot 106 Electrique (1995) and early Citroën vans; UK milk floats; advanced lead–acid batteries currently being developed for stop–start technology (LaMonica, 2012)
Zebra (molten $NaAlCl_4$ or $NaNiCl_2$)	Attractive specific energy Low material cost and plentiful supply	Relatively poor specific power High operating temperature (245°C) Low cycle efficiency	Modec van (2007), Th!nk City (2011), IVECO daily (2009)
Nickel–cadmium (NiCd)	Long cycle life Robust Withstand low temperatures	Lower specific energy than NiMH (see next row) Toxicity of cadmium	Trolleybuses / light rail; used by PSA Peugeot Citroën in the past
Nickel–metal hydride (NiMH)	High specific energy (compared with lead–acid) Long cycle life	High self-discharge Lower specific energy & power than lithium–ion	GM EV1, RAV-4 EV, Toyota Prius (1st, 2nd and 3rd generation)
Lithium– metal polymer (LMP or Li–poly)	(Similar to other lithium–ion performance) No liquid or gel Can be almost any shape Potential for fast recharging Safer than most other lithium–ion chemistries	Lower specific energy than best lithium–ion Greater life cycle degradation rate Require careful charging: high instability if overcharged	Ford Focus Electric, Pininfarina BLUECAR (used in Paris Autolib' scheme; also known as B0 or B Zero), Hyundai Sonata hybrid (Brown, 2011); used to set EV distance record in Audi A2 (Yoney, 2010)

Source: Ricardo-AEA

The relative characteristics of lead–acid, Zebra (labelled $NaNiCl_2$), NiCd, NiMH and LMP battery chemistries in comparison to lithium–ion are shown in Figure 4.6. This clearly illustrates the specific power and energy advantage that lithium–ion technologies possess in comparison to these other chemistries, helping to explain why this has become the dominant technology at present.

Figure 4.6: Specific power versus specific energy of various battery technologies



Source: IEA (2011)

Lithium–ion batteries

There are many different types of lithium–ion battery, depending on the exact combination of materials used for the anode and cathode. Different chemistries have different advantages and disadvantages, and no single one of them outperforms its rivals on all measures.

The most prevalent chemistry for electronic goods such as mobile phones, laptops and cameras is lithium cobalt oxide, owing to its high capacity. This chemistry was used in the Tesla Roadster; however, it is not generally used for automotive applications owing to inherent safety risks, especially if damaged (BCG, 2009). For the automotive sector, safety and cycle life are likely to be more important than absolute capacity.

Details of the advantages and disadvantages of different lithium–ion technologies, with examples of applications, are shown in Table 4.5.

Table 4.5: Lithium–ion battery chemistries

Chemistry	Principal advantages	Principal drawbacks	Current use
Lithium–nickel cobalt aluminium oxide (NCA)	• High specific power and energy • Excellent lifespan	• Expensive • Requires careful consideration of safety aspects	Tesla Model S (longest range of current EVs – 265 miles)
Lithium–nickel manganese cobalt oxide (NMC)	• High specific energy • Good specific power • The lowest self-heating rate of Li–ion chemistries	• Designing to increase specific power reduces specific energy and vice versa • Only average lifespan	Rolls-Royce Phantom Experimental Electric (Johnson Matthey, 2013)
Lithium–manganese oxide (LMO)	• Materials are low-cost • Materials are environmentally friendly • Similar performance levels to conventional lithium–ion	• Early versions showed poor cycle life, especially at high temperatures • Reports of battery degradation concerns due to high ambient temperatures from Nissan LEAF owners in Arizona (LeSage, 2010)	Nissan LEAF, Vauxhall Ampera / Chevrolet Volt, Renault Twizy / Zoe / Fluence / Kangoo (Edison, 2011)
Lithium–titanate oxide (LTO)	• Can be fast-charged • Excellent safety • Excellent lifespan • Low-discharge characteristics	• Lower specific energy than other lithium–ion chemistries • Expensive	Honda Fit EV, Mitsubishi i-MiEV / Peugeot iOn / Citroën C-Zero
Lithium–iron phosphate (LFP)	• Thermal/chemical stability • Longer cycle life • High current rating • Lower materials cost	• Lower specific energy than other lithium–ion chemistries • High self-discharge rates • Cold temperature reduces performance • Calendar life is poor above 30°C	Smith Electric Vehicles, Fisker Karma, CODA sedan (US EV model), BYD (Chinese OEM)

A number of new lithium–ion technologies are being researched. An overview of some of the possible battery chemistries which may come to market in the future are listed in Table 4.6, along with their advantages and disadvantages. Of these, lithium–sulphur holds perhaps the most promise in the short to medium term, with lithium–air having greater potential, but expected to be ten to twenty years from commercialisation (Battery University, 2011).

One technological development, which is helping to address some of the barriers faced in new battery chemistries, is nanotechnology. This can be used to increase the surface area of individual electrode particles, allowing battery charge and discharge rates to be improved. Nanotechnology could also be used to help reduce battery weight.

Another possible option to improve the performance of lithium–ion batteries is the use of semi-solid flow cells. Here, the anode and cathode are made up of particles suspended in a liquid electrolyte and separated by a thin porous membrane. By splitting storage and discharge functions into two separate physical structures, it is expected that the battery can be made more efficient. Researchers claim this new design could halve the size and cost of an EV battery. Semi-solid flow cells could also allow a battery to be recharged by pumping out the depleted liquid in exchange for a fully charged replacement (Chandler, 2011).

Ultra-capacitors

Ultra-capacitors (sometimes also referred to as super-capacitors) have the potential to allow manufacturers to use smaller, lighter and cheaper batteries. Ultra-capacitors perform well in terms of specific power and cycle life, but have very low energy density that limits storage to around 5% of the energy that lithium–ion batteries can hold. Alone, they are suitable for high-power, low-range duty cycles, for example in urban buses, which are able to take advantage of the rapid charging times (of the order of seconds). When fitted alongside a battery, they could extend the life cycle by up to five times by levelling out high power demands. Other advantages include reduced battery currents, reduced battery cycling range and lower cooling requirements (Pesaran et al., 2009). However, these systems require complex control strategies and need electronics for each installation.

Table 4.6: Possible future energy storage technologies

Chemistry	Principal advantages	Principal drawbacks
Lithium–ion with transition metal oxide (TMO) cathode	• Higher specific energy than conventional chemistries	• Chemistry imposes fundamental limit on specific energy that other technologies may surpass
Lithium–imide electrolyte (replacing LiPF6)	• Higher specific energy than lithium–ion • Significantly more robust to temperature and moisture • Longer cycle and calendar life	• Lithium–imide is highly corrosive to aluminium, commonly used as the cathode (however, this issue can be overcome)
Zinc–polymer	• Inexpensive materials • Lightweight materials • Environmentally friendly materials • Safe	• Still in research phase • Not as high theoretical energy density as other options
Zinc–air	• Very high specific energy (theoretical limit: 1,085 Wh/kg)	• Not electrically rechargeable – must be recharged mechanically by replacing zinc electrodes • Low specific power
Lithium–sulphur	• Very high specific energy (theoretical limit: 2,600 Wh/kg) • Abundant availability of sulphur	• Poor stability at high temperatures • Cycle life issues • More durable versions may be high-cost
Lithium–air	• Extremely high specific energy (theoretical limit: 5,200+ Wh/kg)	• Still in research phase • Recharging is currently the primary barrier • Peak power issues • (nanotechnology or the use of catalysts could help address these issues)

Battery costs

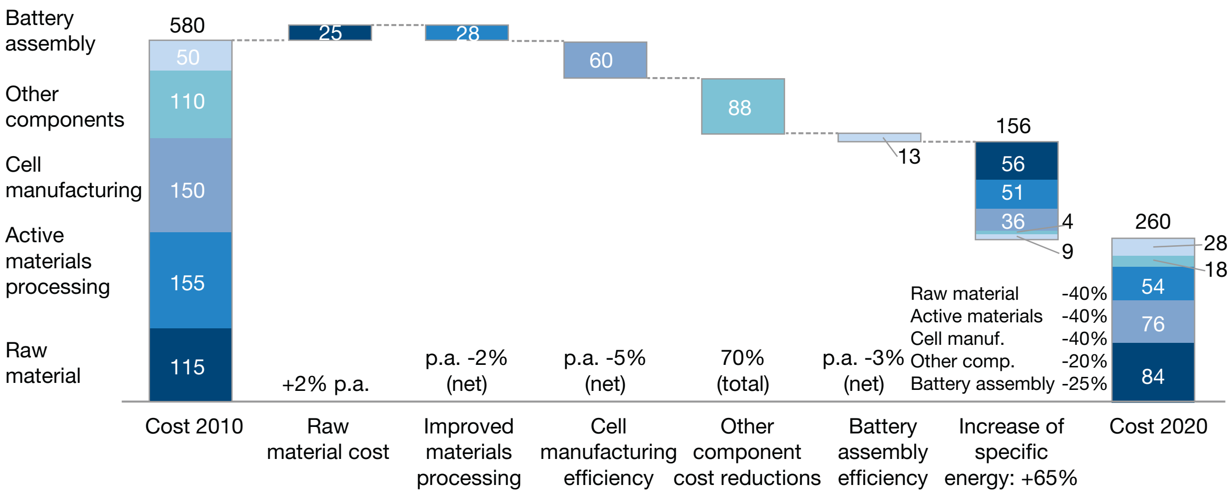
The battery of a plug-in EV is estimated to cost €6,000 to €16,000 (£4,800 to £12,800) (ACEA, 2011a) although this has been predicted to halve in the next decade, and in the longer term to decrease to around €3,000 to €4,000 (£2,400 to £3,200) (Reiner et al., 2009).

A more recent report for the CCC estimated current costs at *c.*US$800/kWh (£480/kWh). This is predicted to reduce to US$318/kWh (£*190*/kWh) by 2020 and US$212/kWh (£125/kWh) by 2030 for a medium-sized vehicle in the baseline scenario (Element Energy, 2012). This is within range of the IEA's reference value of US$300/kWh (£180/kWh) by 2020 to achieve its BLUE Map scenario.

The Association of European Storage Battery Manufacturers (EUROBAT) set out a 15-year R&D roadmap with an achievable goal for battery costs at the end of that programme. EUROBAT's target is for €200/kWh (£160/kWh) by 2020. The United States Advanced Battery Consortium has defined a "minimum goal for commercialisation" of US$150/kWh (£90/kWh); and the Japanese Ministry of Economy, Trade and Industry is reported to have a target of US$50/kWh (£30/kWh) (CCC, 2010).

Since a large percentage of the total battery cost is associated with the necessary raw materials and their required processing, achieving these cost reductions will be dependent primarily on finding ways of increasing the energy density achieved alongside other ways of achieving component cost reductions. Figure 4.7 suggests that energy density would need to increase by 65% to reduce costs to €260/kWh (£210/kWh). The CCC's estimate for €250/kWh (£200/kWh) by 2020 assumes that specific energy of battery packs increases from today's figures of around 100 Wh/kg to 150 Wh/kg in 2020 and 185 Wh/kg from 2025.

Figure 4.7: Battery pack costs in €/kWh



Source: Roland Berger (2010)

4.6 Real-world emissions and driving style

In section 2.4.2 the difference was highlighted between real-world fuel economy and CO_2 emissions, and the type-approval figures for the same. While some of this difference may be due to the regulations of the test cycle, driving style can also have a substantial impact on fuel economy and CO_2 emissions.

The test cycle features gentle acceleration and constant cruise speeds. Drivers who accelerate more aggressively, and brake more frequently will increase fuel consumption by as much as 37% (Wengraf, 2012). Studies suggest that adopting 'eco-driving' techniques typically reduces fuel consumption and CO_2

emissions by about 10%, although the figures obtained in research studies are highly variable and range from 2% to 35% (ibid.). It should also be noted that drivers who have been taught eco-driving techniques may well slip back into a less-efficient style of driving over time, with one study finding the benefit falling to 3% one year after an eco-driving course had been undertaken (European Commission, 2006).

Vehicle manufacturers can help drivers to maintain fuel-efficient driving styles by providing feedback through the instrument panel. For example, in 2012 it became mandatory for all new vehicles in Europe to be fitted with a gear shift indicator light.

While diesel vehicle fuel economy is less sensitive to driving style than petrol, vehicles running on electric energy are much more sensitive. This is due to the fact that electric drivetrains are so much more efficient than ICEs.

Electric vehicles are far more sensitive to driving style

Whereas driving style, if considered to range from very aggressive to very economical, may affect the range of an ICE vehicle by a factor of up to 50%, for a BEV this figure could be 1,000%. Ricardo Engineering's quarterly magazine stated in early 2009 that

> "an aggressive driving style and higher speeds can increase an EV's rate of energy consumption by a factor of up to ten, dramatically reducing the driving range available on each full charge of the batteries" (Ricardo, 2009).

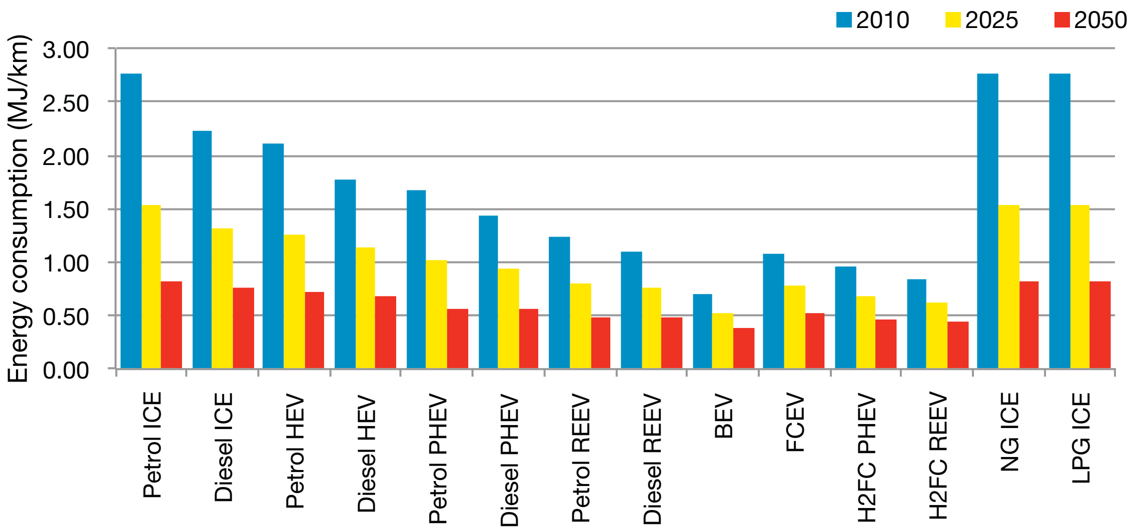
Equally, the use of auxiliary functions such as heating and cooling systems on EVs will have a proportionally much greater impact on available range as compared to conventional vehicles, in which drivers are often unaware that fuel consumption and range is affected at all.

4.7 Comparison of technologies

The previous section has reviewed each technology individually. In Figures 4.8 to 4.12, comparisons are presented of the current and potential future costs, energy consumption and GHG performance of different powertrain types. Future figures have been estimated on the basis of a combination of near-term objectives (e.g. the 95 gCO_2/km target for new cars in 2020), and the aim of maximising future CO_2 reductions from all powertrains in the medium to long term. The estimates for WTW emissions are based on the projected changes to different fuels, as summarised in section 3.2 above.

Figures 4.8 and Figure 4.10 illustrate the impact of factoring in both real-world effects (as discussed in section 4.6) and also account for emissions from the production and distribution of fuels (which is particularly important for electricity generation and hydrogen production). The figures show that there is still a very considerable potential for future improvement to conventional ICE cars (which include stop–start and regenerative braking technologies in the analysis, but not mild or full hybridisation). If motivated by strong targets for CO_2 reductions, levels might reach as low as 48 gCO_2/km by 2050 for petrol ICEs on a test-cycle basis (69 gCO_2/km on a real-world basis). However, in order to achieve long-term national GHG reduction objectives (of 80% by 2050), passenger cars will likely need to almost completely decarbonise, which will require the use of predominantly electrified powertrains (meaning that FCVs are also likely to be included). Figure 4.11 provides a summary comparison of estimated marginal manufacturing costs of different powertrains – i.e. how much more it will cost to make these vehicles compared to the cost of manufacturing a 2010-vintage petrol ICE car. This figure shows that the differential between ICEs and alternative powertrains is anticipated to reduce very significantly over the next decade, with the biggest differential potentially reducing to under £1,500 by 2050. In later periods these additional costs would be expected to be recovered within the first few years, even for moderate amounts of annual driving, through fuel cost savings – which are illustrated in Figure 4.12 (based on 15,000 km/9,300 miles p.a.).

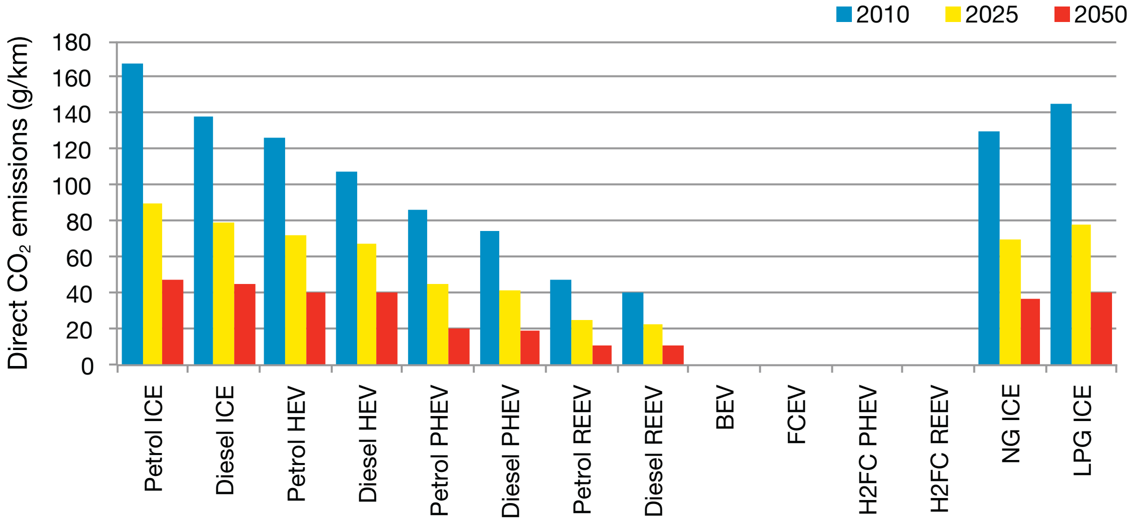
Figure 4.8: Comparison of estimated average energy consumption in real-world conditions for various powertrains from 2010 to 2050



Source: Ricardo-AEA (2012)

Notes: Estimates are based on an objective of maximising CO_2 reductions from new vehicles, with the setting of tighter new car CO_2 reduction targets beyond current 2020 objectives in the future.

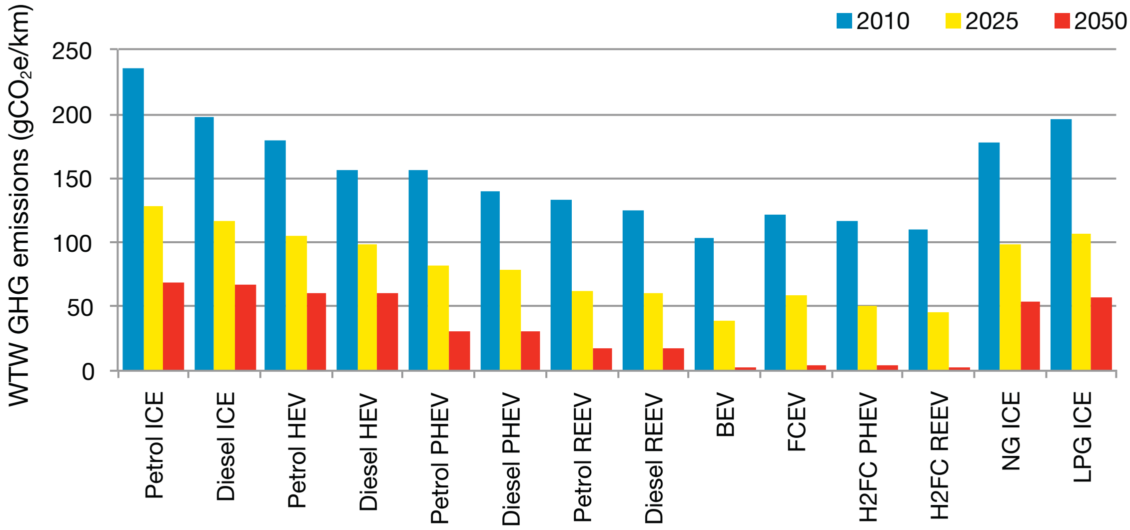
Figure 4.9: Comparison of estimated average regulatory test-cycle-based CO_2 emissions for various powertrains from 2010 to 2050



Source: Ricardo-AEA (2012)

Notes: Estimates are based on 0% biofuel content and an objective of maximising CO_2 reductions from new vehicles, with the setting of tighter new car CO_2 reduction targets beyond current 2020 objectives in the future.

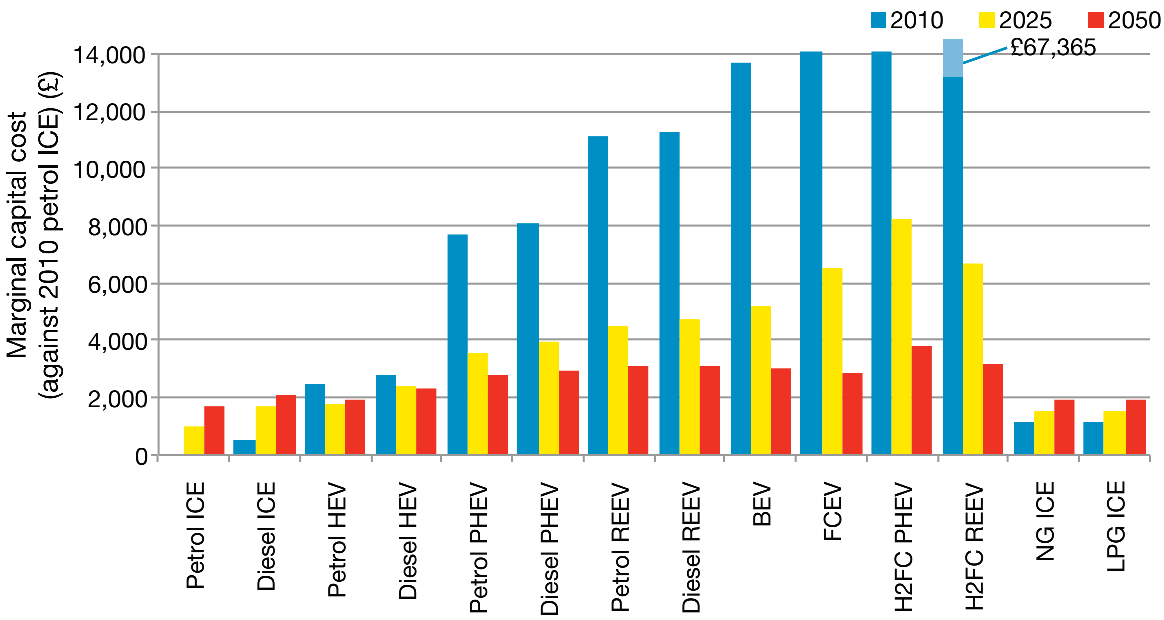
Figure 4.10: Comparison of estimated average well-to-wheel greenhouse gas emissions in real-world conditions for various powertrains from 2010 to 2050



Source: Ricardo-AEA (2012)

Notes: Estimates are based on 0% biofuel content and an objective of maximising CO_2 reductions from new vehicles, with the setting of tighter new car CO_2 reduction targets beyond current 2020 objectives in the future. Figures exclude potential savings for vehicles using biofuels owing to significant uncertainty in their performance and future volumes. Assumes average grid electricity (including upstream emissions from primary fuel production) at 0.590 $kgCO_2e/kWh$, 0.231 $kgCO_2e/kWh$ and 0.031 $kgCO_2e/kWh$ for 2010, 2025 and 2050, respectively.

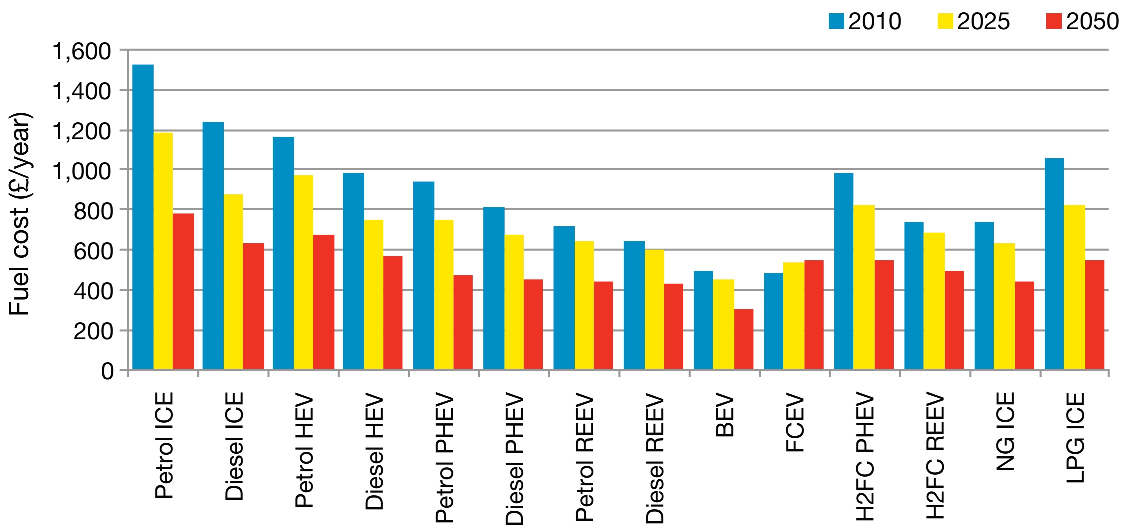
Figure 4.11: Comparison of estimated marginal manufacturing costs for various powertrains from 2010 to 2050, at 2010 prices



Source: Ricardo-AEA (2012)

Notes: Estimates are based on an objective of maximising CO_2 reductions from new vehicles, with the setting of tighter new car CO_2 reduction targets beyond current 2020 objectives in the future.

Figure 4.12: Comparison of estimated annual fuel costs for various powertrains from 2010 to 2050, at 2010 prices



Source: Ricardo-AEA (2012)

Notes: Estimates are based on an objective of maximising CO_2 reductions from new vehicles, with the setting of tighter new car CO_2 reduction targets beyond current 2020 objectives in the future.

5. Predicted Market Shares of Future Technologies and Fuels

When discussing the various different future market projections that are available in the literature, it is important to understand the different types of projection available. Widely differing results can be obtained according to the nature of the projections or forecasts, and the methods and assumptions used.

- **Future market demand forecasts**: These are generally produced by industry analysts, and are used by companies to help them plan and manage their product portfolio. They generally predict the market sales, share or size of different product types. There is a range of techniques which can be used to do this, but they rely principally on projecting existing trends into the future in combination with some expertise or detailed understanding of the existing marketplace. In relation to the automotive sector, forecasts are likely to be more accurate if they take account of underlying economic growth trends. Future market demand forecasts are commonly used to make projections five to ten years into the future.
- **Backcasting / scenario planning**: As the name suggests, 'backcasting' consists of starting from a desired future position and working backwards towards the current situation in order to establish what would need to happen in order for this to be achieved. Backcasting is more commonly used by governments and policymakers to establish what policy measures or programmes may be necessary to achieve future targets. Backcasting techniques are often used in relation to desirable future scenarios which may be twenty to fifty years away, and may also be known as scenario planning.

An example of backcasting is the IEA's BLUE Map scenario. This scenario reflects the IPCC targets for a reduction of energy-related CO_2 emissions to half their 2005 levels by 2050, with transport expected to contribute to this overall reduction by cutting CO_2 emissions levels in 2050 to 30% below 2005 levels.

Backcasting from this scenario, IEA has generated an EV Technology Roadmap (IEA, 2011) which recommends setting sales targets for EVs and PHEVs. It sets two targets:

- at least five million EV and PHEV combined global sales per year or more, if possible, by 2020; and
- a combined EV/PHEV sales share of at least 50% of LDV sales worldwide by 2050.

The roadmap goes on to recommend coordinated national strategies to make EVs cost-competitive and to introduce infrastructure rollout strategies. It also recognises the importance of a focus on improving battery technology. A key point made in this roadmap is that in order to reach the deployment targets set out, sales per model must rise rapidly to reach scale economies, but the number of models introduced must also rise rapidly.

However, almost all the other studies reviewed in this section (a list of which can be found in Table 5.1) were found to use a mixture of forecasting and backcasting. They generally attempt to forecast future market shares, but included in the assumptions are policy levers and other instruments which may be expected to be put in place with a view to achieving 2050 carbon reduction targets. The majority also use different scenarios to examine the influence of a range of factors.

Three of the studies are predictions for global market shares, but the majority are focused on Europe. Two look only at the German new car market, while only one is related specifically to the UK market.

Table 5.1: Sources for market share predictions, showing geographic region

Source	Title	Geographic region
ACEA (2010)	The Future of Electric Cars – The Automotive Industry Perspective (speech at San Sebastian at the Informal Competitiveness Council)	Europe
AEA (2009)	Market outlook to 2022 for battery electric vehicles and plug-in hybrid electric vehicles	UK
AT Kearney (2012)	Powertrain 2025 – A global study on the passenger car powertrain market towards 2025	Europe
CE Delft (2011)	Impact of Electric Vehicles	Europe
CLEPA (2012)	Member communication	Europe
European Commission (2012a)	Action plan for the EU automotive industry in 2020	Europe
IEA (2010)	Technology Roadmap – Electric and plug-in hybrid electric vehicles	Global
JRC-IPTS (2010)	Plug-in Hybrid and Battery Electric Vehicles – Market penetration scenarios of electric drive vehicles	Europe
McKinsey (2009)	Roads toward a low-carbon future: Reducing CO_2 emissions from passenger vehicles in the global road transportation system	Global
PRTM (2010)	Plugging Into the Electric Car Opportunity	Global
Oliver Wyman (2009)	Power play with electric cars	Europe
Roland Berger (2009–11)	Powertrain 2020 report: The Future Drives Electric (2009) Electro-mobility: Challenges and opportunities for Europe (2010) Automotive Landscape 2025: Opportunities and challenges ahead (2011)	Europe
Öko-Institut (2012)	Transport and Climate Change – Scenarios in the context of long-term environmental and energy policy objectives	Germany
Shell (2009)	Shell Passenger Car Scenarios up to 2030	Germany

In the following report sections, market share predictions from this wide range of sources are examined and compared. Section 5.3 analyses what the key sensitivities are which lead to variations in these forecasts.

To put the results of these studies in context, it is important to bear in mind the current mix of technologies in the UK new car market. Data from the SMMT (Society of Motor Manufacturers and Traders) for 2012 new car sales in the UK indicates that between them, conventional petrol and diesel cars account for 98.6% of the market (diesel market share is now 50.8%, with petrol at 47.8%) (SMMT, 2013a). HEVs accounted for 1.2% of the market, while vehicles eligible for the Plug-in Car Grant amounted to just 0.1%. The market share of cars powered by natural gas or biofuel actually fell from 0.05% in 2011 to 0.03% in 2012.

Comparing the figures for pure electric car sales to the number of vehicles which qualified for the government's Plug-in Car Grant indicates that almost half of all the qualifying plug-in vehicles were PHEVs/REEVs (SMMT, 2013b). Currently in the UK these are the Chevrolet Volt / Vauxhall Ampera and the Toyota Prius Plug-in. This is despite the Toyota only becoming available in July 2012 and the Volt/Ampera in April of the same year.

5.1 Predicted market shares of future technologies

For each technology, 'mainstream' estimates are provided. These are intended to give the reader the approximate range of the majority of estimates rounded to the nearest 5%, ignoring outliers that may result from more extreme assumptions.

5.1.1 Predicted market share of more efficient conventional ICE vehicles

When examining the technology pathways, it is clear that for the near future at least, there is still significant further potential for improving the efficiency of conventional ICE vehicles. Of course the market share of ICE vehicles (whether petrol-, diesel- or gas-powered) will be determined by whatever combined market share HEVs, PHEVs, REEVs and BEVs manage to achieve. Given the uncertainties over their growth rates, the predicted market share for ICEs is equally uncertain.

Stop–start systems are expected to be fitted to 50% of new cars in the near future

Sales of stop–start systems have been predicted to have a compound annual growth rate of 32% up to 2020, with global annual sales predicted to reach 37 million vehicles (almost 40% of the total market) (Pike Research, 2012a). In Europe it is predicted that more than 50% of new vehicles will have stop–start as standard after 2013 (FEV, 2011). One battery supplier predicts this figure to rise to 70% by 2015 (VARTA, 2012).

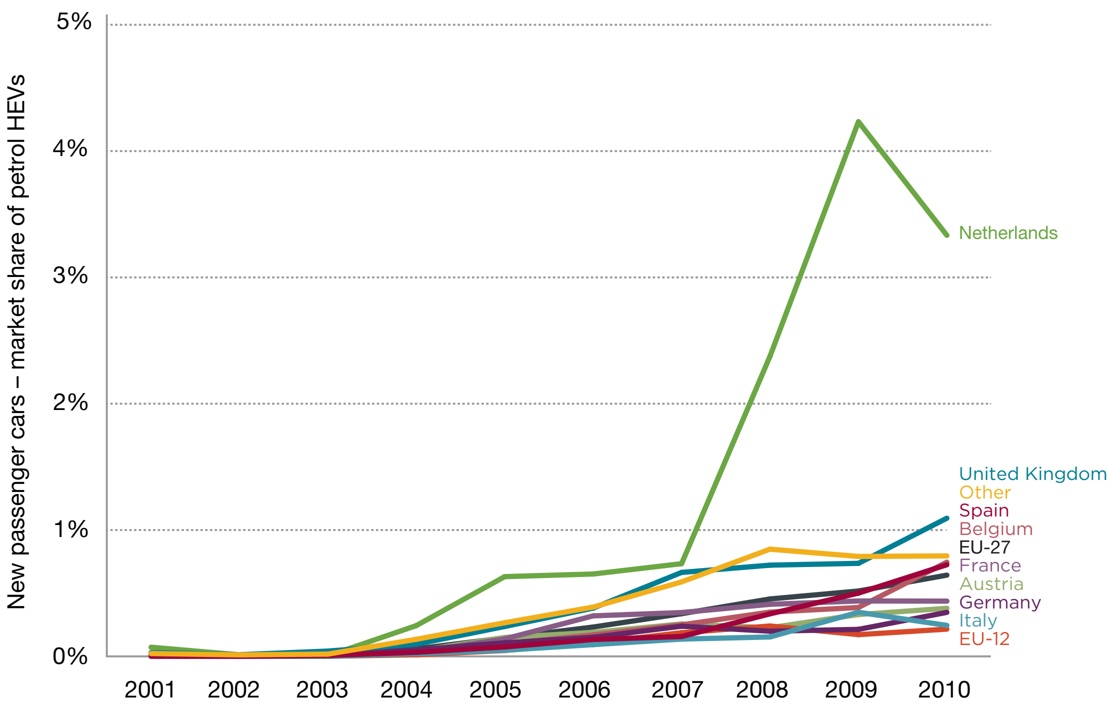
5.1.2 Predicted market share of hybrids

Mainstream estimates – hybrid electric vehicles	
2020	5% to 20%
2030	20% to 50%

First introduced into mass production by Toyota with the first-generation Prius in 1997, hybrid technology is now firmly established in the marketplace. In Japan, the Prius became the best-selling car in 2009, and hybrids have an 11% market share. In the first quarter of 2012 the Prius was reported to be the third best-selling car in the world (Ohnsman & Hagiwara, 2012). Globally, hybrid technology will achieve greater market share as it becomes available on a wider range of vehicle types. As well as bringing out upmarket Lexus hybrids and expanding the Prius range to include a seven-seater, Toyota has now introduced hybrid versions of the Auris and Yaris. In September 2012, Toyota announced it plans to launch 21 new hybrid models by the end of 2015, and that it expects annual sales of its hybrid vehicles to be at least one million units a year in the period 2013–15 (Toyota, 2012). This equates to about 15% of Toyota's car production.

In Europe, petrol HEVs' market shares are generally less than 1% (see Figure 5.1). The exception is the Netherlands, where hybrid vehicles qualify for a substantial bonus/registration tax reduction introduced in mid-2006, which has boosted sales (IEA, 2012). The UK has the second-largest hybrid market share at 1.2% of new car sales in 2011, equating to 23,047 vehicles (DfT, 2012b).

Figure 5.1: Petrol hybrid electric vehicles' market shares in European new car sales, by member state



Source: ICCT (2012)

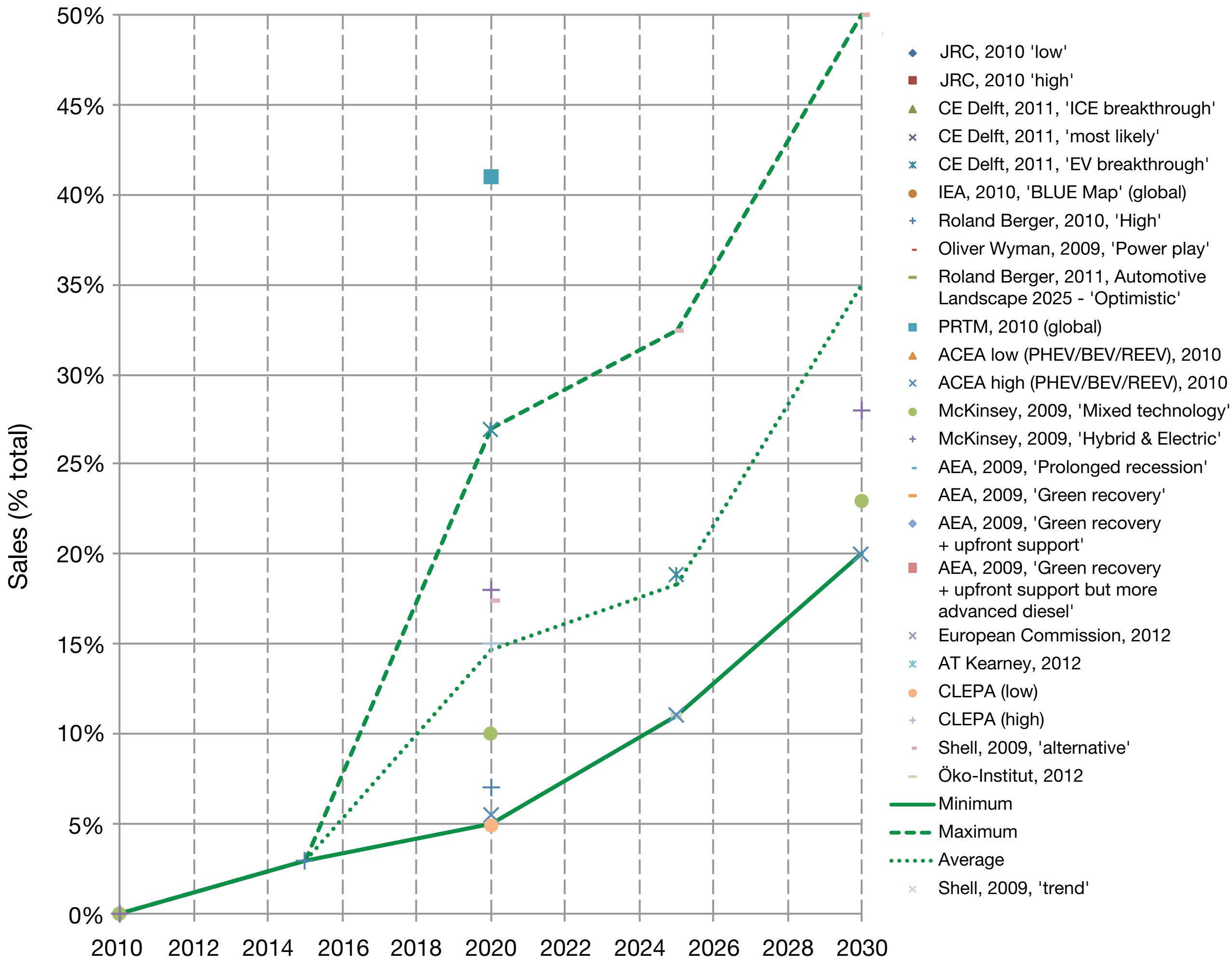
Perhaps because hybrid technology is already more established, there appears to be less literature available examining future market predictions than exists for plug-in EVs. Nevertheless, several private-sector analysts have published studies with figures for predicted market share – often giving a range according to different scenarios (see Figure 5.2).

For 2015, predictions are cautious, with 3% seen as a ‘high’ scenario. By 2020, AT Kearney suggests that ‘mild’ and ‘strong’ hybrids together will account for as much as 27% of sales in Europe. Their study makes the point that they expect this to decline to 19% by 2025 on the basis of their predictions for more advanced technologies such as PHEVs to gain market share.

PRTM (2010) suggests an even higher market share for hybrids in 2020, of 41%. This seems highly unlikely, especially as the figure is given as a global estimate, and the higher cost of hybrid technology in strong growth markets such as China and India is likely to limit market share. As a result, this has been shown as an outlier.

Other studies provide different scenarios illustrating the impact of different assumptions. This can be useful, although the ranges can be very wide. For example, one study gave three different scenarios with estimated hybrid global market shares in 2030 of 28%, 23% and less than 1% (McKinsey, 2009). This third scenario, in which ICE powertrains continue to maintain 99% market share through to 2030, resulted in global passenger car CO_2 emissions declining by only 11% in 2030 relative to 2006, and is not included here (or shown in the graph), as it was not considered realistic.

Figure 5.2: Predicted market shares for hybrid electric vehicles



The wide range of predictions illustrates the very large uncertainties involved and the importance of the underlying assumptions, which are explored in section 5.3. It should be noted that the 'maximum' figures for the years 2025 and 2030 presented in Figure 5.2 may be high, as they come from a study in which it is not clear whether PHEVs are being included in the general heading 'hybrids'.

5.1.3 Predicted market share of plug-in hybrids

Mainstream estimates – plug-in hybrid electric vehicles	
2020	1% to 5%
2030	15% to 30%

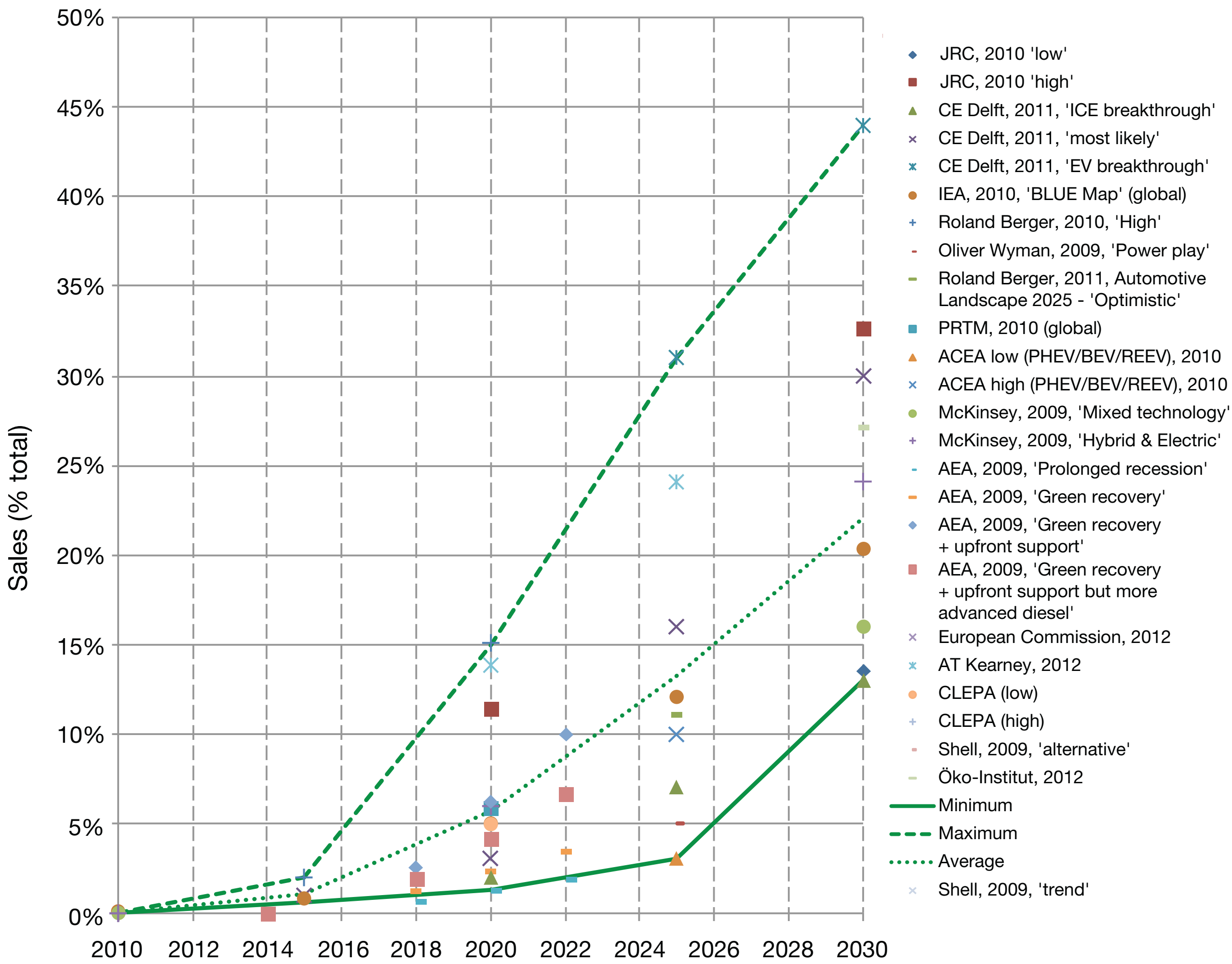
When discussing PHEVs it is important to note the distinction between 'parallel' plug-ins and 'series' plug-ins. For the purposes of this report, series PHEVs are referred to as 'range-extended electric vehicles' (REEVs). However, many of the sources for predicted market shares refer simply to PHEVs, making it unclear whether some of these figures include REEVs.

For PHEVs there is a much wider range of estimated market shares available, with no fewer than 16 different figures for the year 2020, originating from nine separate studies (cf. Figure 5.3).

All but three of these estimates lie in the range of 1–6% for the year 2020. The JRC's 'high' scenario predicts 11.4% on the basis of aggressive rollout of recharging infrastructure (ahead of existing national plans) in combination with fast reductions in battery costs (€200/kWh or *c*.£160/kWh by 2030). AT Kearney's study forecasts a 14% share on the basis of interviews with OEMs, suppliers and governments/associations, supported by total cost-of-ownership calculations and desk research. The study assumes a 75 gCO_2/km target for 2025 in Europe, tax exemptions for EVs and PHEVs, and some electric-drive only zones being put in place.

Roland Berger's 'The Future Drives Electric' scenario predicts a 15% market share for Western Europe assuming higher oil prices, accelerated reduction of battery cell costs to €200/kWh (£160/kWh), stronger government support, and a broader product range on offer from the OEMs.

Figure 5.3: Predicted market shares for plug-in hybrid electric vehicles



By 2030, the range of predictions has broadened substantially from as low as 13% to as high as 44%. Both these figures come from the CE Delft (2011) study for the European Commission. The low estimate comes from the ‘ICE breakthrough’ scenario, in which significant CO_2 efficiency improvements can be made to ICE technology at reasonable cost, while technological progress and cost reduction in battery technology is slower than expected. The high estimate, named ‘EV breakthrough’, envisages, from 2015 onwards, a rapid decrease of battery cost and increase of battery lifetime.

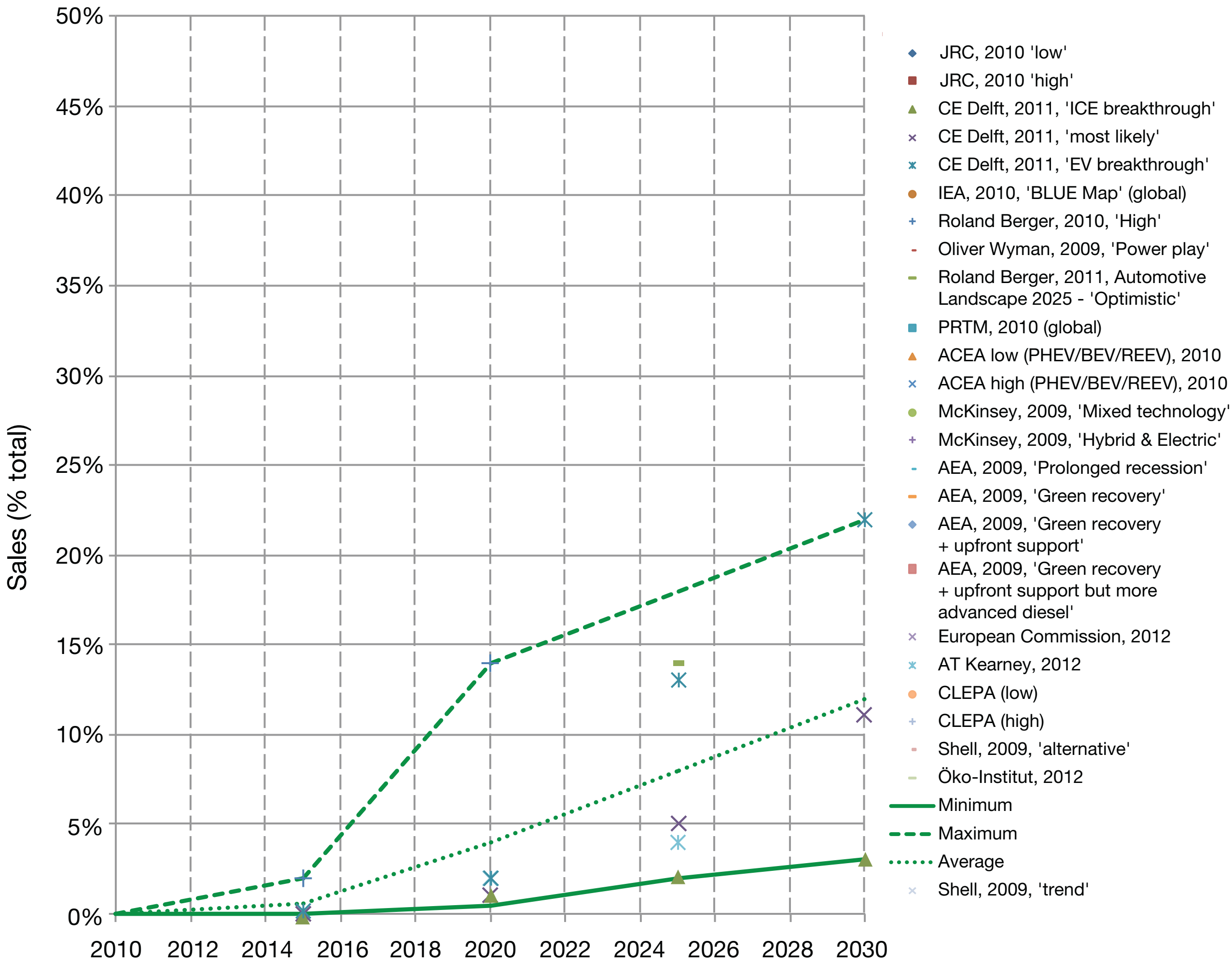
5.1.4 Predicted market share of range-extended electric vehicles

Mainstream estimates – range-extended electric vehicles	
2020	1% to 2%
2030	5% to 20%

Note: Only five studies specified figures specifically for REEVs.

As described in the previous section, some studies do not differentiate between PHEVs and REEVs. However, five studies did give figures specifically for REEVs (series PHEVs). In general, the predictions, shown in Figure 5.4, are significantly lower than those for PHEVs, and much more in line with those for BEVs.

Figure 5.4: Predicted market shares for range-extended electric vehicles



5.1.5 Predicted market share of battery electric vehicles

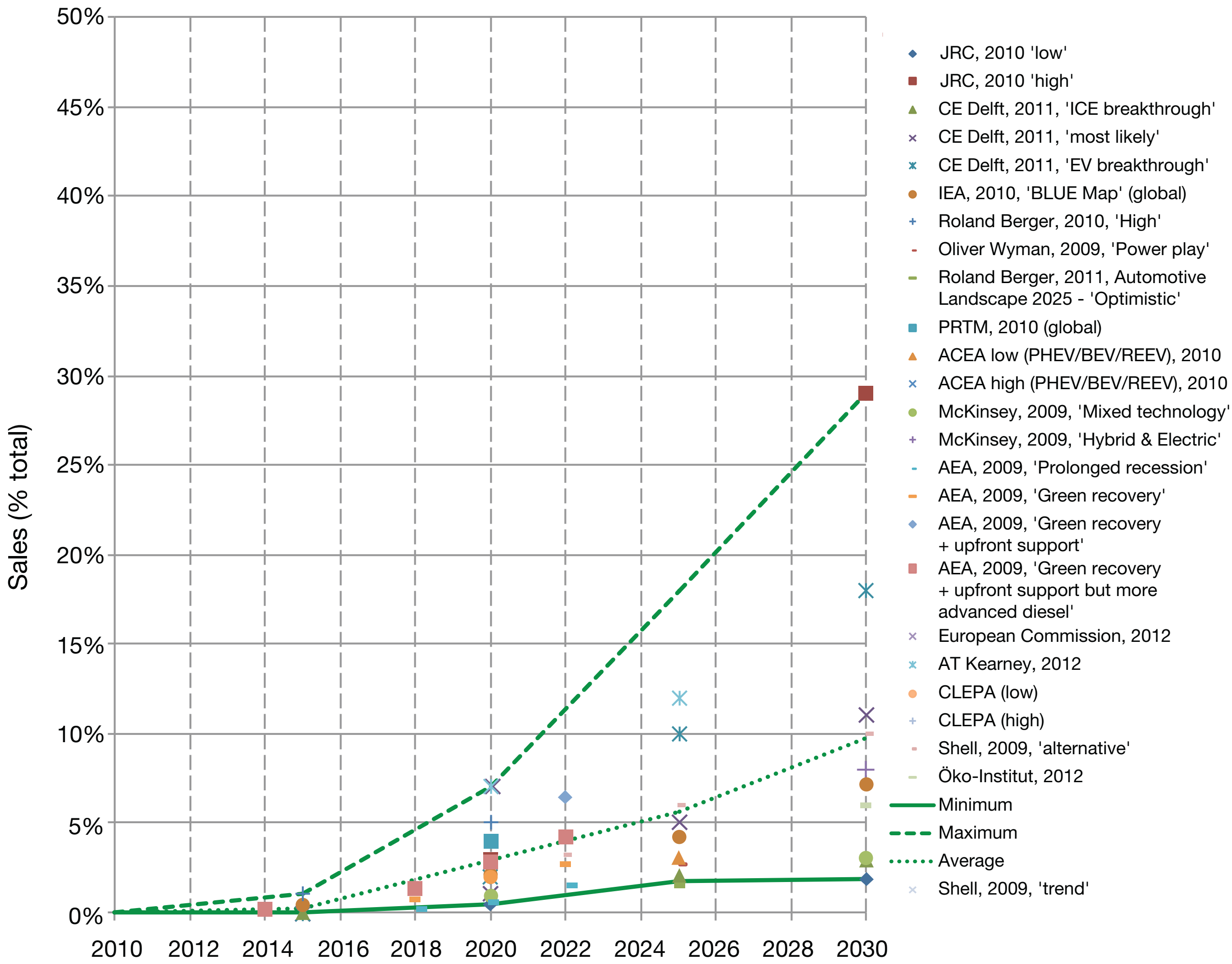
Mainstream estimates – battery electric vehicles	
2020	1% to 5%
2030	5% to 20%

The predicted share for pure EVs from the same range of studies was reviewed. There were more forecasts available for pure EVs than for any other technology option, which is a measure of the amount of attention that has been paid to this technology. For the year 2020, 15 of the 17 forecasts were of a market share of 5% or less (see Figure 5.5). AT Kearney's forecast is for 7% and is based on the assumptions given in the previous section; this figure matches a memo released by the European Commission in November 2012 (European Commission, 2012a) which states:

> “While electric vehicles sales in EU in 2011 reached only 11,000 units, electro-mobility is firmly on track and it is expected that by 2020, registrations of vehicles with traditional combustion engines will fall while the registrations of electric vehicles will increase its share to 7%.”

By 2030 the spread of forecasts has widened to a minimum of 1.9% and a maximum of 29%. Both these figures come from the JRC’s *Market penetration scenarios of electric drive vehicles* (JRC-IPTS, 2010) and represent a combination of two variables – recharging infrastructure and battery technology. In the low forecast, recharging infrastructure provision is assumed to match published national plans, with less than 20% of residences having recharging facilities by 2030. Battery costs are assumed to reduce to just over €300/kWh (£240/kWh) by 2030, with the useable state-of-charge window (a measure of the energy available to drive the vehicle compared to the battery’s overall rated capacity) and battery calendar life staying constant at 70% and 10 years respectively. In the high forecast, almost 70% of residences have recharging by 2030, and battery cost has come down to just over €200/kWh (£160/kWh) by 2030, with useable state of charge going up to 85% while calendar life rises to 15 years.

Figure 5.5: Predicted market shares for battery electric vehicles

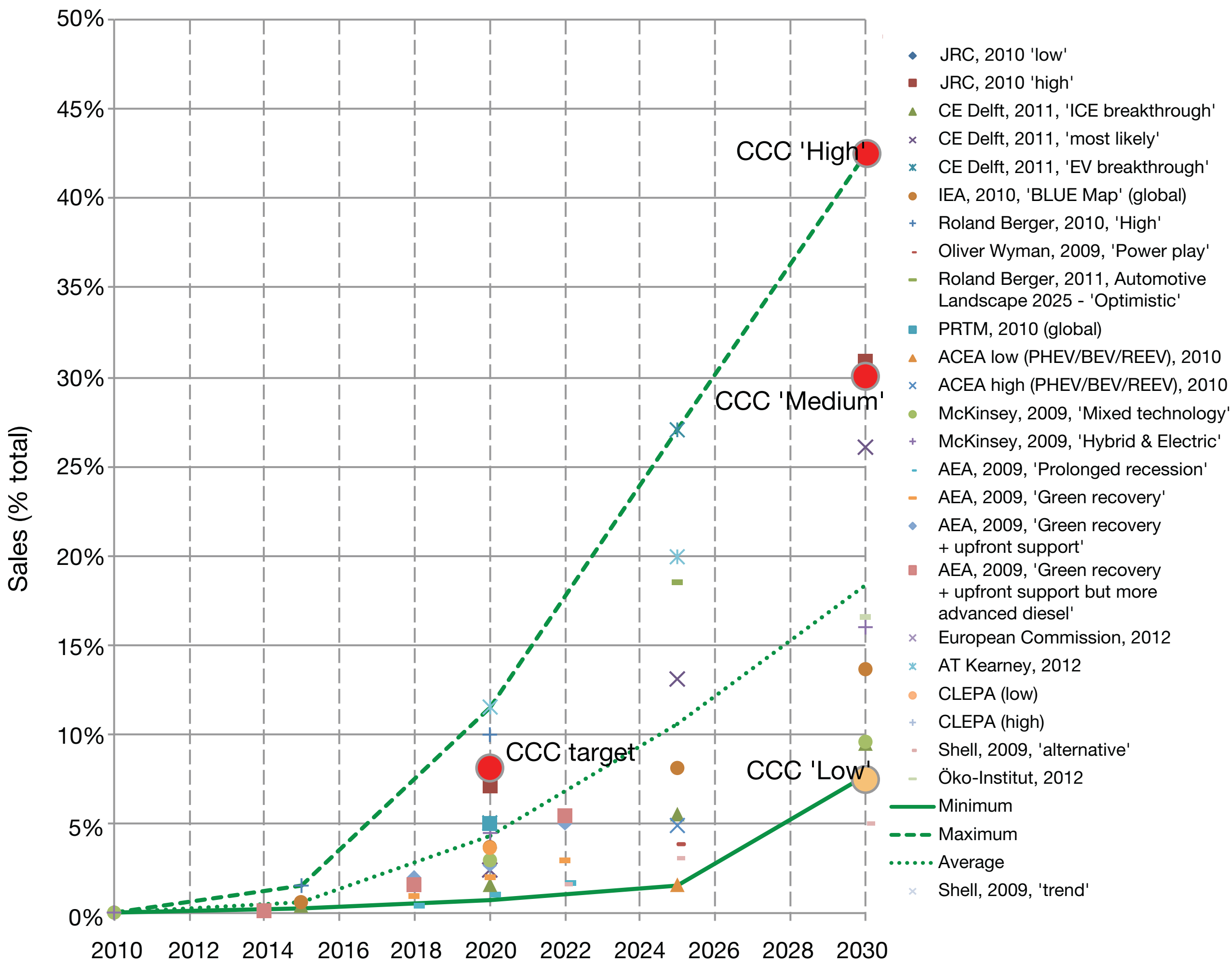


5.1.6 Combined predicted market share of 'advanced electric vehicles' (plug-in hybrid and battery electric vehicles)

Mainstream estimates – advanced electric vehicles	
2020	2% to 10%
2030	20% to 50%

All the studies reported examined a range of technologies. Market share predictions for one will naturally have been influenced by another. In most studies, the greatest emphasis is placed on the need to move to plug-in EVs. In Figure 5.6, forecasts for PHEVs and BEVs from the studies are combined to illustrate their predicted total market share.

Figure 5.6: Predicted market shares for advanced electric vehicles



To achieve the UK's targets the CCC recommends the government should aim for EVs and PHEVs together to achieve a market share of 16% by 2020 (CCC, 2010). This is higher than all the forecasts other than Roland Berger's 'The Future Drives Electric' scenario and AT Kearney's study. The Committee's 'low' and ‘high’ scenarios for 2030 almost exactly correspond to the lowest and highest figures for market share from the studies examined for this report.

Optimistic expectations for electric vehicles from the automotive industry

Perhaps in the hope of inspiring consumer confidence, the automotive industry has made bold claims for the speed with which EVs will gain market share. Carlos Ghosn, the CEO of the Renault–Nissan Alliance, which has invested €4 billion (£3.2 billion) into developing and bringing to market BEVs, has repeatedly forecast that BEVs alone will account for 10% of global new car sales by 2020. This is more than double the average of the predictions reviewed for this report, and above even the maximum forecast. The Ford Motor Company has also publicly stated that it expects 10–25% of vehicle sales to be ‘heavily electrified’ by 2020, although only a small proportion of those are expected to be pure BEVs (ChargePoint Technology, 2011). The low end of this prediction is above the average shown in Figure 5.6, while the upper end is higher than the maximum forecast from the range of studies reviewed here.

A number of manufacturers have made predictions for large volumes of sales of plug-in vehicles (see Table 5.2). However, actual sales so far appear to be below these expectations. In September 2012, Renault–Nissan was reported to have sold a combined total of 77,000 (Tschampa, 2012), compared to a target of 250,000 annual sales in 2013 and a cumulative target total of 1.5 million by the end of 2016. Nissan aimed to sell 20,000 units of its LEAF electric car in America in 2012, but was reported in October 2012 to have sold only just over a quarter of that target (Edelstein, 2012). Sales of the Peugeot iOn (a rebadged version of the battery electric Mitsubishi i-MiEV) were only 50% of their target in 2011 (François-Feuerstein, 2012).

Table 5.2: European OEM targets for production/sales of battery electric vehicles and plug-in hybrid electric vehicles

Manufacturer	Number of units
Renault–Nissan	250,000 in 2013 and 500,000 in 2015 (BBC, 2011). Cumulative total of 1.5 million EVs by end of 2016 (Nissan, 2011).
Volkswagen Group	3% of sales by 2018 (Gupta, 2010). On the basis of 2010 production, this would equate to 220,000 cars. By 2018, it is likely to be higher.
PSA (Peugeot Citroën)	30,000 in 2015 (Frost, 2010)
Daimler (incl. Mercedes Benz)	10,000 electric smart cars (about 10% of production) (Tschampa, 2012)
BMW	3–6% of sales in 2020 (Massey, 2011). On the basis of 2010 production, this would equate 45,000–90,000 cars.
Volvo	4,000–6,000 in 2014 (V60 plug-in hybrid diesel) (ETI, 2012). Expects 10% of V60 sales to be plug-in variant and will offer plug-in hybrid technology on all future models (excluding V40) (TechVehi, 2012).

Source: IEA (2011)

ACEA forecasts are rather more cautious – predicting 3–10% market share by 2025 for the combined sales of all plug-in vehicles (ACEA, 2010).

5.1.7 Predicted market share of fuel cell vehicles

While many OEMs have active R&D programmes developing fuel cell technology, there are still a number of barriers to bringing the technology to the marketplace, perhaps the biggest two being the continuing high costs and the need for refuelling infrastructure.

As a result, the focus over the last five years has been on battery technology and plug-in vehicles. However, at least one market analyst is predicting re-emerging interest in FCVs, given the disappointing sales performance of some battery electric models, and highlights that OEMs are still stating that initial rollout will be between 2013 and 2015 (Pike Research, 2012b). Indeed in February 2013, Hyundai started production of its ix35 fuel cell model stating that it plans to produce 1,000 of these vehicles for lease to public and private fleets by 2015 (Hyundai, 2013).

The Automotive Council UK's technology roadmap shows FCVs moving from the demonstrator phase to production in the early 2020s. Only one study was found which includes any predictions for market shares for FCVs (Carbon Trust, 2012). This predicts that FCVs could achieve more than 30% market share in the medium-sized car market by 2030. This is based on predictions for polymer fuel cell technology to achieve a step-change in cost reduction with expected mass production costs coming down to around US$36/kW (current fuel cell system costs are around US$1,200/kW). The technology to achieve this is being developed by UK companies, as part of the Carbon Trust's Polymer Fuel Cells Challenge (PFCC), which aims to accelerate the commercialisation of breakthrough polymer fuel cell technologies.

A scenario study has been conducted by a group of companies, government organisations and an NGO – the majority of which have a specific interest in the potential (or the commercialisation) of FCVs and hydrogen (European Commission, 2012a). The study involved backcasting from three different scenarios for 2050, with varying assumed ratios of FCVs, BEVs, PHEVs, and ICEs. These set FCV market penetration levels at 5%, 25% and 50%. A key finding was that FCV technology is best suited to larger, premium cars which, the study states, make up 50% of the vehicle market and 75% of CO_2 emissions. The study found that from 2030, total cost of ownership for FCV technology is expected to be lower than for BEVs or PHEVs in the largest car segments. However, given the interests of the companies involved in the study, these calculations may be optimistic.

The study (European Commission, 2012a: 9) concludes that:

> "The emerging [fuel cell vehicle] market (2010–20) requires close value chain synchronisation and external stimulus in order to overcome the first-mover risk of building hydrogen retail infrastructure. While the initial investment is relatively low, the risk is high and therefore greatly reduced if many companies invest, coordinated by governments and supported by dedicated legislation and funding. With the market established, subsequent investment (2020–30) will present a significantly reduced risk and by 2030 any potentially remaining economic gap is expected to be directly passed on to the consumer."

In August 2012, a review of the current status for fuel cell deployment in LDVs found that FCVs should be seen as complementary to BEVs and PHEVs (Fuel Cell Today, 2012). It states that BEVs are best realised as smaller cars in applications that require a continuous range of less than 125 miles, and that given the limited range of BEVS, FCVs offer the only zero-emissions option for larger cars travelling longer distances.

5.2 Predicted future mix of fuels

The mix of fuels which will power our cars in the future will of course be determined by the mix of powertrain technologies in use, with the one exception being the use of biofuels, which can be a direct replacement for liquid fossil fuels in ICEs. The use of food crop-based biofuels is now being limited as a result of concerns about the limited GHG reductions achieved, and wider environmental and social issues (as described in Box 2.1). However, next-generation advanced biofuels are being developed which address these issues and can provide high-quality direct replacements for fossil fuels.

As section 5.1 has shown, there are wide variations in the predictions for the speed with which electrification of powertrains will take place. In this section, four different scenarios are examined from two different sources:

1. IEA's baseline and BLUE Map global scenarios for 2050;
2. Ricardo-AEA's proprietary modelling of 'business as usual' and 'low biofuel' scenarios for Europe to 2050.

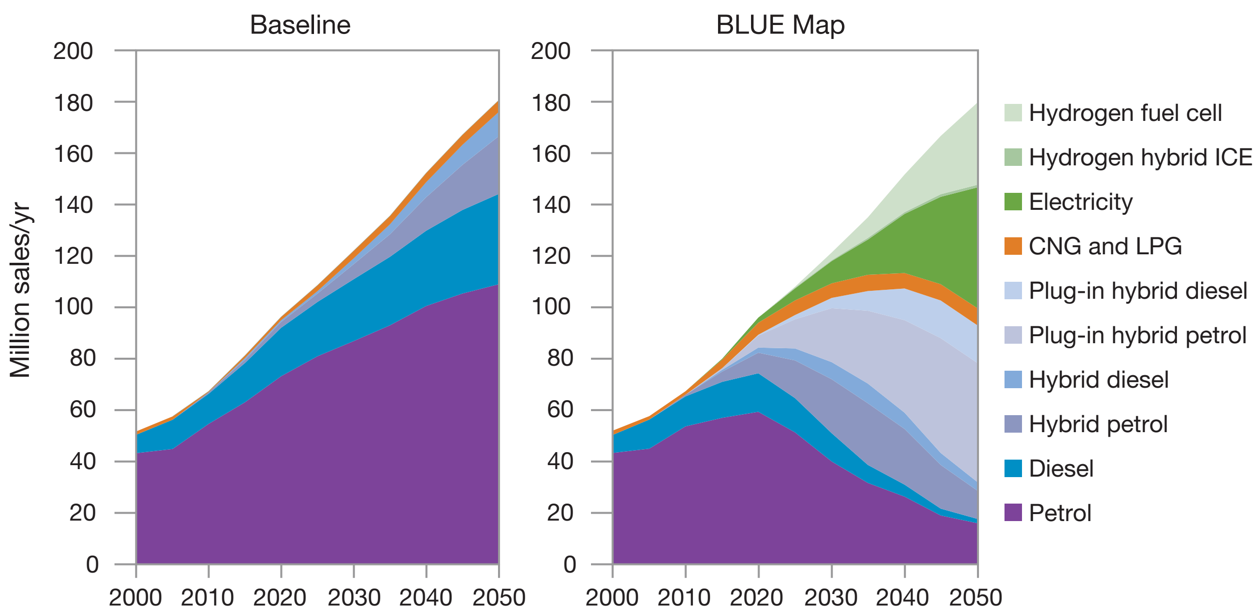
5.2.1 Future mix of fuels for IEA baseline and BLUE Map scenarios

IEA's BLUE Map scenario backcasts from the IPCC targets for a 50% reduction of energy-related CO_2 emissions by 2050 on 2005 levels. Transport is expected to contribute to this overall reduction by cutting CO_2 emissions levels in 2050 to 30% below 2005 levels.

The BLUE Map scenario reflects the uptake of technologies and alternative fuels across transport modes that are economic at a carbon price of up to US$175 per tonne of CO_2e saved by 2050. New powertrain technologies such as hybrids, EVs and FCVs start to penetrate the LDV and truck markets. Strong energy efficiency gains are realised for all modes. Very low-GHG alternative fuels – such as hydrogen, electricity and advanced sustainable biofuels – achieve large market shares.

A comparison of the baseline and BLUE Map scenarios for LDV sales is shown in Figure 5.7. The percentage market shares for PHEVs and BEVs are close to the average of the various predictions examined in this chapter.

Figure 5.7: IEA Baseline and 'BLUE Map' scenarios for global light-duty vehicle sales



Source: IEA (2010)

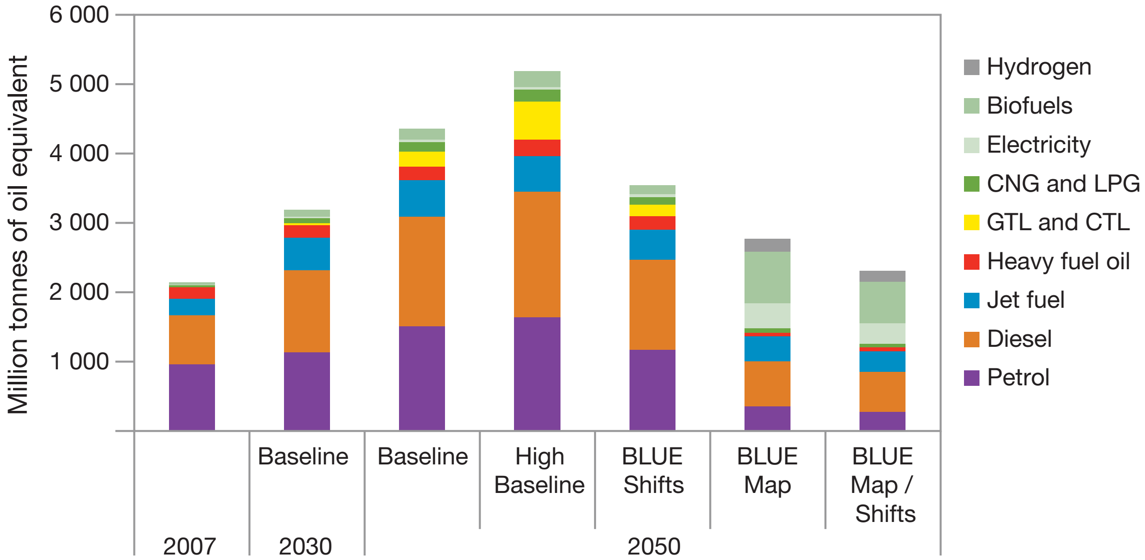
The IEA's calculations of resulting fuel mix show the results for all forms of transport, including aviation; however, as can be seen in Figure 5.8, energy consumption is dominated by petrol and diesel use. In the baseline scenario, energy use increases strongly from 2007, through 2030 to 2050, with petrol and diesel retaining about a two-thirds share of the total.

By comparison, in the BLUE Map scenario, by 2050, petrol and diesel's combined share of total transport energy consumption has dropped to just over one third, with biofuels making up a much larger proportion of the total. Growth in use of hydrogen and electricity is substantial, but they still account for a relatively small proportion of the total, with approximately 7% and 13% shares respectively.

It should be noted that owing to the very high efficiency of electric powertrains, the relative share of total UK energy consumption of electricity by these vehicles remains less than might be expected purely from looking at the numbers of EVs (and also PHEVs).

The King Review highlighted that even if the entire UK passenger car and taxi fleet was converted to battery electric technology, their electricity consumption would equate to only 16% of total demand (King, 2007: 35). Given that much of the recharging necessary could take place overnight when demand is low, then the additional impact in terms of required generating capacity might be relatively low.

Figure 5.8: IEA Baseline and BLUE Map energy use by fuel type globally



Source: IEA (2010)

Note: CNG = compressed natural gas, LPG = liquefied petroleum gas, GTL = gas to liquid, CTL = coal to liquid.

5.2.2 Future mix of fuels for Ricardo-AEA baseline and low-biofuel scenarios

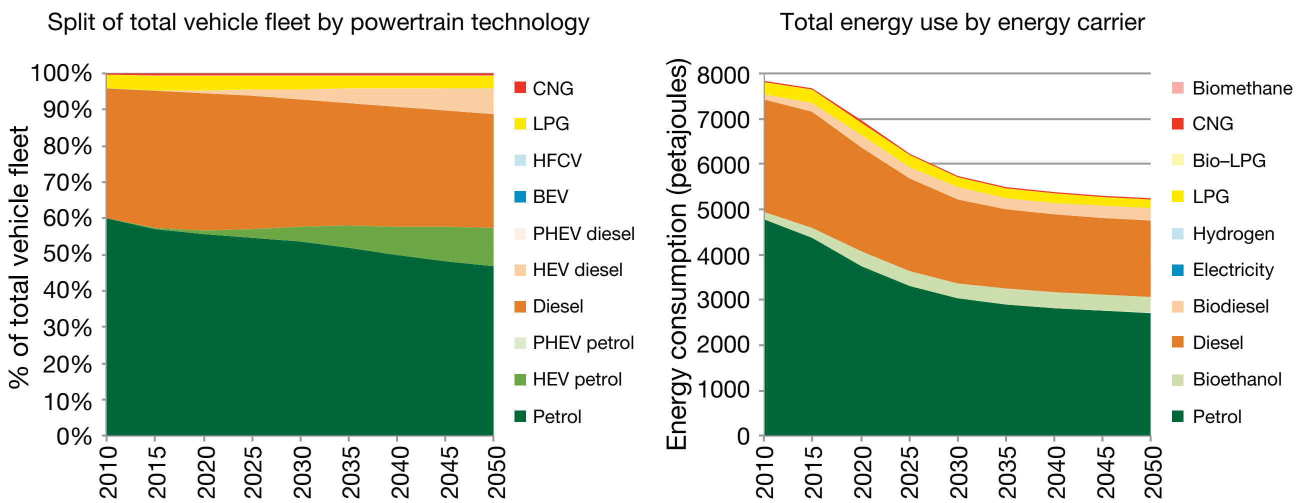
The Ricardo-AEA team has developed a model of the European vehicle fleet (the SULTAN – SUstainabLe TrANsport – illustrative scenario tool) in order to explore transport decarbonisation scenarios for the European Commission through to 2050 (AEA, 2009). The model uses data on potential future technology costs and efficiency, and has been used to explore the impacts of scenarios concerned with the likely future mix of vehicle technologies and fuels. The baseline (business as usual) scenario developed under the most recent project (AEA/TNO/CE Delft, 2012) can be compared to what is now considered the most likely alternative scenario to meet the 2050 reduction target for the EU transport sector's GHG emissions. **Note: in both cases the**

vehicle technology splits shown are for the total fleet, not the market share of new car sales.

In the baseline (business as usual) scenario, 84% of fuel energy in 2050 would be from fossil petrol and diesel, and carbon reduction targets would not be met

The baseline scenario already includes the 2020 regulatory CO_2 targets for new cars (95 gCO_2/km) and vans (147 gCO_2/km). Despite this, plug-in technologies are not predicted to achieve any significant market share. Only hybrid vehicle sales increase, growing to account for 18% of the total vehicle fleet by 2050. As a result of these fuel efficiency improvements and technology shifts, consumption of fossil petrol and diesel has gone down by 39%, but between them they retain an 84% share of energy use in 2050 (Figure 5.9).

Figure 5.9: Baseline scenario – vehicle fleet and energy carrier splits



Source: AEA (2012)

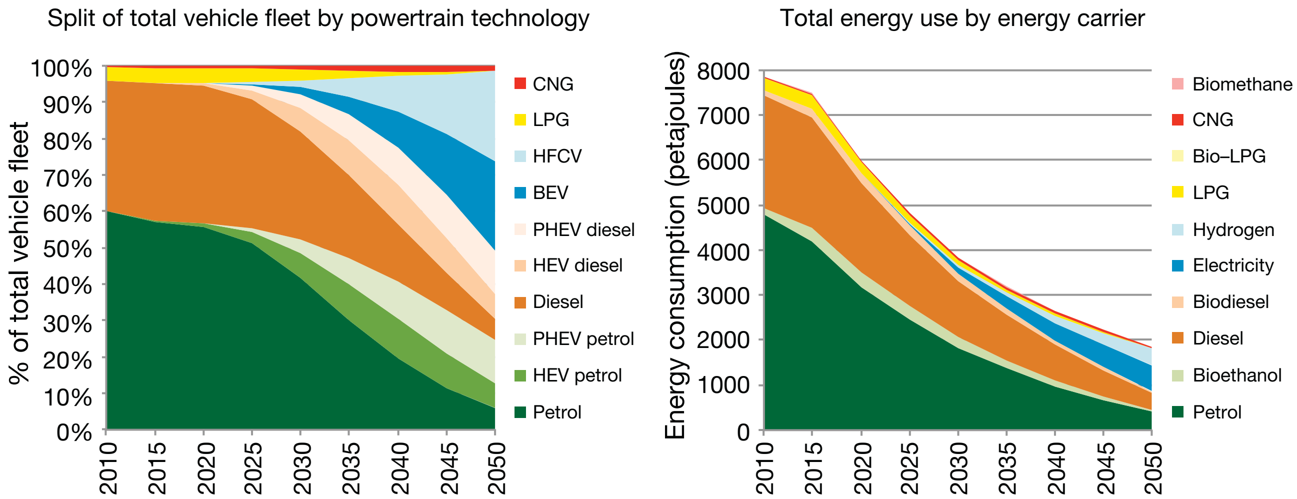
In the most likely scenario to meet 2050 carbon reduction targets, fossil petrol and diesel's share of energy consumption falls to 42% in 2050.

In the European Commission's original plans for transport carbon reduction, a significant share was anticipated to be achieved through the use of biofuels. Subsequently, the low-biofuel 2050 scenario (see Figure 5.10) was developed to illustrate what increased deployment of other technologies would be necessary in the event that GHG savings from biofuels were lower than originally expected (either through significantly reduced levels of deployment, or realised GHG savings per unit of fuel). As explained in section 2.2.3, in October 2012 the European Commission announced a 5% limit on the use of biofuels from food crops allowed in transport by 2020 and the ending of all public subsidies for crop-based biofuels after the current legislation expires in 2020. In addition, recent analysis presented in the DfT/DECC/Defra Biofuel Strategy has suggested sustainable bioenergy may be able to provide only up to 10–12% of the UK's future energy needs (DECC, 2012e).

As discussed earlier in section 3.3, there is also increasing consensus that – in addition to competition for biomass in other sectors reducing overall availability – for transport applications, sustainable biofuels may be most effectively prioritised for aviation and shipping in the medium to long term. So the low-biofuel scenario is now considered the most representative scenario for meeting 2050 carbon reduction targets. In this scenario, the biofuel substitution rates for conventional fuels are relatively low for road transport (up to 10–12%), as in this scenario the available sustainable biofuel supply is focused more on aviation and shipping (with up to 40%, 25% substitution respectively by 2050). The trajectories for technology splits in this scenario indicate that by 2030 hybrids might account for 13% of the total vehicle fleet, PHEVs 8%, and BEVs and FCVs 2% each. To achieve this, would require that the new car sales share for conventional petrol and diesel vehicles reduces by over 50% between 2020 and 2030.

The result of this would be that overall energy consumption in 2050 is dramatically lower. As a result, although fossil petrol and diesel's share of the total energy consumption in 2050 is still 42%, there has been an 89% reduction in their use. Ricardo-AEA has also modelled a 'maximum technology uptake' scenario, which illustrates what might be considered to be the maximum feasible rate of uptake for new low-carbon technologies if action is taken early. This results in petrol and diesel's combined share in 2050 being 35%.

Figure 5.10: Low-biofuel scenario – vehicle fleet and energy carrier splits



Source: AEA (2012)

5.3 Assessment of the key sensitivities

In analysing the studies used to provide market share predictions, it was found that a range of factors had been taken into account in the development of different scenarios. These included:

- government incentives / upfront support / policy / legislation (particularly future vehicle CO_2 legislation);
- ability to achieve CO_2 reductions using conventional ICE technologies;
- battery cost (and lifetime / useable state of charge);
- recharging infrastructure;
- recharging time;
- energy prices – particularly the price of oil, but also costs of alternatives;
- total cost of ownership;
- availability of new vehicle models/range;
- consumer interest and demand;
- new business models; and
- wider economic issues – recession / green growth.

Because of the variations in assumptions between different studies, it is not possible to objectively assess which of these factors have the greatest influence over the likely future mix of vehicle technologies and fuels can be difficult. However, there are two main themes which will determine the future: government policy and legislation, and breakthroughs in technologies and fuels. These are now examined in more detail.

5.3.1 Government policy and legislation

This is the area which can have the biggest influence on the future mix of low-carbon vehicles and fuels. Government legislation and policy sets the framework within which both manufacturers and consumers operate. Government has the ability to influence the prices and availability of different vehicle and fuel options through a variety of means. While policymakers are constrained by political and fiscal considerations, they nevertheless control the levers which must be used to ensure that carbon reduction targets are met. These include:

a. **Setting out a long-term vision and strategy for transport carbon reduction** – providing a strategy and a clear roadmap for how transport carbon reduction targets will be met.
b. **Ensuring the provision of necessary refuelling infrastructure –** coordinating and planning the provision of the necessary refuelling or recharging infrastructure required to achieve that vision.
c. **Enabling informed consumer choice** – ensuring that consumers have access to the information needed to make informed decisions.
d. **Influencing upfront vehicle costs –** introducing policies, such as first-year VED rates and plug-in vehicle grants, which may influence consumer choice.

e. **Influencing vehicle running costs** – structuring policies such as fuel duty rates, taxes on electricity use, VED rates, congestion charging or other road charging schemes to strongly encourage that new lower-carbon vehicle technologies and fuels are taken up in the marketplace; for example, policies which create zones where only vehicles capable of operating in a 'zero-emissions' mode are allowed access might create stronger demand for such vehicles.

5.3.2 Breakthroughs in technologies and fuels

The second area is under the control of vehicle manufacturers and fuel suppliers. Government can set out the vision, and the framework of policy and legislation, but it is industry which must deliver the products. Industry must continuously invest in the necessary R&D to bring low-carbon cars and fuels to the marketplace, together with the technologies necessary to refuel them. The research challenges which will have the greatest influence on future low-carbon cars and fuels are:

a. **Reducing costs and improving performance of energy storage (and fuel cell) technologies** – reducing the costs and increasing the performance and longevity of batteries and fuel cells in particular, but also developing alternative energy storage systems such as ultra-capacitors and flywheels. There are wide variations in predictions of the speed with which battery costs will reduce, and this is a key sensitivity.
b. **Reducing vehicle energy consumption** – focusing on minimising the energy needs of new vehicle designs, particularly through reducing vehicle weight, but also through improving aerodynamics and reducing rolling resistance. While this improves the efficiency of all vehicles, it is particularly beneficial for EVs, as these factors account for the majority of their overall energy losses.
c. **Developing technologies and standards for refuelling/recharging** – a large-scale switch away from fossil petrol and diesel will require development of new technologies to make the use of alternatives as easy and convenient as possible. EV owners must have confidence that they can locate facilities and recharge their vehicles wherever they go, and billing systems must be in place to allow this. Fast-charging and contactless charging both make EV ownership easier and more convenient. Growth in sales of HFCVs will be critically dependent on the provision of sufficient hydrogen refuelling infrastructure.

Uptake of low-carbon cars will be determined primarily by 'value for money', which in turn is influenced substantially by government policy

Ultimately when businesses or private individuals make new car purchase decisions, there are a range of factors involved. Decisions can be influenced by image and emotions, particularly for private buyers, but to a large extent the decision is one of value for money. When UK respondents were asked what the principal reason for being more likely to buy an electric, plug-in/range-extended hybrid or hydrogen car would be, 49% said if “they were less expensive to buy than they are now”, and 30% if “I knew that they were cheaper to run than an ordinary car” (RAC, 2011). Only about 9% of European car buyers would purchase an environmentally friendly car if they had to pay more over the life of the vehicle (BCG, 2011).

The automotive industry is the largest private investor in R&D in Europe, investing a total of over €26 billion (*c*.£20 billion) every year (ACEA, 2011b). Much of this will be aimed at reducing the costs and improving the performance of low-carbon car technology.

However, government policies have the largest potential influence over both the vehicle choices available and the ‘value for money’ equation for new car buyers, as set out in Chapter 2. Government policies can influence upfront purchase costs and running costs to a much greater extent than the industry itself.

5.4 Analysis of the wider factors affecting uptake

While government policies and technological breakthroughs are certainly two of the most important factors which will determine the likely future mix of low-carbon cars and fuels, there are many other considerations which will play a role. Some of the more important ones are reviewed here.

5.4.1 Economic and resource factors

Declining incomes make low-carbon technologies less affordable, and reduce fleet turnover rates.

The current economic recession will be reducing the disposable income available for the purchase of new vehicles, whether company cars or privately owned. This can have two concurrent effects:

- reducing the affordability of more expensive low-carbon technologies; and
- reducing the frequency with which private individuals and companies replace their cars.

Both of these factors may hinder the rate of reduction of the GHG intensity of emissions from the UK car fleet. In 2011, UK car sales fell to their lowest level since 1994. However, impacts on overall GHG emissions may be offset by a reduction in car use, as individuals and companies seek to reduce their outgoing costs. Of particular note in this respect is the fact that the distance travelled in company cars has fallen 45% between 1997 and 2009 (Potter & Atchulo, 2012).

Low-carbon car policy needs to consider fairness issues

Historically, the amount that people travel has increased with increasing GDP. Much of the increase in total UK car mileage has come as a result of car ownership becoming more affordable for more people. The highest growth in car ownership is now among households in the lowest income group (Bayliss, 2009). However, with rising fuel and insurance costs, the poorest fifth of households now have to spend between 17% and 25% of their income to run a car (Social Exclusion Unit, 2003). The lack of practical alternatives to car ownership due to inadequate and expensive public transport, and hostile walking and cycling environments, has been reported to be forcing millions of people to choose between debt and social exclusion (Sustrans, 2012).

This may be exacerbated by policies designed to discourage the use of less fuel-efficient vehicles, which are often the more affordable, older vehicles. At the same time, policies such as the Plug-in Car Grant may be effectively subsidising the wealthiest households to purchase an electric car as their second vehicle.

Policies to promote uptake of low-carbon cars may be unaffordable

In April 2009, the government committed £230 million to the Plug-in Car Grant, giving up to £5,000 discounts to purchasers of ultra-low-emission cars. However, this equates to only 50,000–125,000 vehicles, or 2–5% of a single year of UK new car sales. The question is whether this will be sufficient to allow plug-in vehicle sales to increase further without continuing support.

The CCC estimated that £800 million would be needed in price support before EVs and PHEVs would break even in comparison to conventional cars (CCC, 2009). They also estimated that the costs of the charging infrastructure necessary to support 1.7 million EVs and PHEVs/REEVs in 2020 could amount to around £1.4 billion. Given the current administration's focus on deficit reduction, it is unlikely that such funds would be made available.

Ultimately, for low-carbon cars and fuels to see widespread uptake they must be affordable in comparison to alternatives.

Rising oil prices might not speed take-up of plug-in vehicles

Rising oil prices might be expected to help speed the take-up of low-carbon cars. However, the principle effect is often political pressure to reduce fuel duty, since the total tax take (including VAT) on fuel sales accounts for about 60% of the cost of fuel to motorists. Reducing fuel duty directly reduces the revenue stream available to the government for funding policies, such as the Plug-in Car Grant and PIP programmes, to promote the uptake of low-carbon cars.

Since private individuals who are currently buying plug-in vehicles will tend to come from wealthier households, it is also questionable to what extent their decisions are influenced by concerns of rising fuel prices or the availability of government grants (House of Commons Transport Committee, 2012).

Nevertheless, consumer priorities do appear to have shifted in favour of smaller, more fuel-efficient vehicles. While there will be a variety of reasons for this, the fact that most people expect fuel prices to continue on a long-term rising trend will certainly be a factor.

Resource constraints will drive research into recycling and alternative materials

Current generation batteries and electric powertrains rely on the availability of certain key elements. There is already evidence that China, to take the most prominent example, has sought to protect certain mineral reserves for its own industry rather than export to other countries, with rare earth metals being a high-profile example. One study highlights that dysprosium, a key element needed for high-efficiency electric motors, has experienced explosive price increases in recent years (PwC, 2011). In a survey, 73% of automotive companies perceived minerals and metals scarcity as a "pressing problem", with 64% experiencing "unstable supply". The British Geological Survey 'risk list' in 2011 identified 52 critical minerals or metals, and China was the leading supplier for 27 of these (BGS, 2011).

Resource constraints will therefore drive part of the research agenda for future low-carbon cars, bringing pressure to bear to both improve recycling technologies and enable a search for alternatives (Allwood & Cullen, 2011). Such constraints might also inform the construction of new business models in which there is a greater emphasis on retaining ownership or control of the product over its entire life cycle. Resource constraints are also likely to be part of the reason why, at a technological level, there may be greater diversity in cars in the future.

5.4.2 Consumer and market factors

Higher upfront purchase costs are a major barrier to uptake for low-carbon cars

Cars featuring low-carbon technologies are often more expensive than less-efficient alternatives. Even if this additional upfront cost is more than compensated for by lower running costs over the vehicle's lifetime, this may not be enough to persuade consumers to pay the extra. While there is no doubt that consumers do care about fuel costs and do value fuel economy, particularly when fuel prices are rising, the question is how much over the odds they are willing to pay initially to make long-term savings in this area. A review of 28 studies on this subject was inconclusive, but recent in-depth survey evidence suggests that consumer behaviour does not follow a rational economic model (US EPA, 2010).

New business models such as battery leasing or car sharing may need to be adopted

The automotive industry may need to find alternative business models to overcome the problem of higher upfront cost. For example, Renault's approach of leasing the battery for their EV range of vehicles results in the vehicle purchase price being very similar to that of an equivalent ICE vehicle. It also reduces risk for the consumer, as Renault will guarantee the condition and maintenance of the batteries. However, it remains to be seen whether consumers will willingly adopt this concept, which means that they no longer own a large part of the value of the vehicle.

Another approach is moving away from vehicle ownership altogether. Vehicle manufacturers are exploring car-sharing schemes. Daimler runs the Car2go scheme using smart cars. Initially trialled in Ulm, Germany, and Austin, Texas in the USA, it has now expanded to cover ten locations.[13] The most recent addition uses the electric version of the smart fortwo vehicle in Amsterdam (Daimler, 2011).

13 car2go website available at: www.car2go.com.

Peugeot's Mu concept allows consumers to become members and have access to the full range of Peugeot mobility options, from scooters, to the new battery electric Peugeot iOn, through to a seven-seater MPV (multipurpose vehicle). However, it should be noted that this new approach is only available at selected dealerships directly owned by PSA Peugeot Citroën group rather than franchised outlets – evidence that manufacturers are keen to maintain control while experimenting with these options (Wells & Nieuwenhuis, 2011).

However, car club schemes could pose a threat to vehicle sales. Levels of car ownership in the UK already appear to be saturating at around 470 cars per 1,000 population. Meanwhile, alternatives to car ownership such as leasing and membership of car clubs have seen strong growth. There were almost half a million car-sharing members across Europe in 2009, and this figure is expected to grow to somewhere between 1.5 million and 5.5 million by 2015 (Frost & Sullivan, 2010). In surveys of car club members, it has been found that each car club car replaces up to 20 privately owned cars (if vehicles which would have been purchased if a car club car was not available are included) (Carplus, 2011).

Range anxiety and charging requirements are second only to cost in barriers to uptake of low-carbon cars

Aside from high initial purchase costs, the other big barrier to uptake for pure EVs is range anxiety. In the RAC Motorists Survey, greater availability of charging points, and vehicles with a longer range, were ranked as the second and third most important factors (after cost) respectively for increasing the likelihood of purchasing an alternative fuel car (RAC, 2011). An international study found that while 85% of the UK drivers questioned said their average weekday mileage would be 50 miles, 70% would require a minimum range of at least 100 miles before they would consider buying or leasing an EV. On average, range expectations (what the consumer wants from a vehicle) exceeded reality (what the same consumer actually needs in daily use) by a factor of between two and three (Deloitte, 2011).

However, familiarity with plug-in vehicle technology may reduce range anxiety. In the UK ULCVDP, prior to the trial 100% of private drivers said they would be more concerned about reaching their destination with an EV than they would with their normal car. After three months, this dropped to 65%. Both before and after the trial, a high proportion (85% and 86% respectively) of private drivers expected to reach destinations reliably in the EV (TSB, 2011).

Increasing urbanisation may lead people to turn to alternatives to cars

A further factor which could influence uptake of low-carbon cars is competition from alternatives. As the UK population continues to increase, more and more people will be living in urban areas, rather than suburban or rural parts. In towns and cities, space is at a premium, and there is increasing pressure to achieve higher living densities to accommodate growing populations and reduce environmental impacts. There has long been a proposed direct relationship between increasing population density and reduced car or fuel usage (Newman & Kenworthy, 1989).

Some argue that EVs will be essential to improve air quality and reduce noise pollution in these cities. However, EVs are no more space-efficient than conventional ones. They also require the availability of dedicated recharging facilities, usually for several hours at a time – often a particular problem for those living in apartments. Public transport, walking and cycling are all substantially more space-efficient, and can also deliver air quality improvements, GHG emissions reductions, and reduced noise pollution.

New technology may make public transport more attractive

ICT technologies are increasingly being deployed to make public transport more attractive. Journey planning tools, real-time service information and personalised updates (with advanced warnings of any disruption) all help address some of the traditional barriers. These services are ever more widely available via smartphones, giving individuals control of their travel options. Integrated smart ticketing, which operates across different public transport systems, and contactless payment schemes increase convenience and reduce revenue loss from unpaid fares. The increasingly widespread availability of Wi-Fi on public transport allows journey time to be productive time. Technology is also improving public transport's environmental impact and reducing running costs, with hybrid and full electric buses becoming available, together with advanced driverless metro and tram systems. Personal Rapid Transit systems – self-guided, automated pods with four to six seats serving multiple destinations – can even start to rival the flexibility of private car use while having substantially lower energy consumption.

New personal mobility options offer alternatives to cars

While many vehicle manufacturers have been looking at developing ultra-lightweight city cars (see section 4.4.1), some have gone further still. For the most part these developments centre on the use of lightweight electric mobility devices of limited performance and range, being used as additions to or substitutes for cars. Such non-cars include urban mobility assistance scooters, electric bicycles and scooters, and fold-away ‘last mile’ commuter vehicles. These options may be offered in combination with a more traditional vehicle which has stowage space that has been specifically designed to transport them. Several examples of this ‘dual mode’ option have already been seen in prototypes (Hanlon, 2012).

5.5 Evolution or revolution?

Mainstream thinking from those within and those most close to the automotive industry is that there will be a gradual evolution of technology. However, there are some people, including those with a background in the automotive sector, who see the possibility of a much more radical revolution.

The **evolutionary** view is that the future car market will be dominated by offerings from traditional OEMs who will use their knowledge and experience, and their understanding of customer desires, together with economies of scale, to develop cost-effective new models with gradually increasing use of electrification in the powertrain. The traditional OEMs’ control of powerful brands and marketing strategies will give them a strong advantage over any new market entrants, who will struggle to compete. Electric and plug-in hybrid options will initially be adapted from conventional vehicles, or at least based on the same platforms. This will allow them to be produced in existing production facilities and primarily using known technologies. This approach will allow flexibility for OEMs to match production volumes of plug-in vehicles to demand, with plug-in options being manufactured on the same production line as conventional alternatives (the approach already being used by GM with the Chevrolet Volt/Vauxhall Ampera, and Renault with the Fluence). As battery and other costs reduce, demand and volumes will increase and there is likely to be a gradual transition towards newer technologies and vehicle designs, which can take advantage of the design flexibilities offered by electric and plug-in vehicle architectures.

The alternative **revolutionary** view is that the opportunities offered by pure EVs will lead to radical changes in the passenger car market and potentially rapid sales growth of novel new pure-EV concepts – primarily in the small or city car segment. New market entrants will emerge who bring radical fresh thinking and approaches to both vehicle design and manufacturing. They will be able to fully exploit the new design freedoms offered by electric powertrains. Ultra-light, compact and manoeuvrable pure-EV designs will be ideally suited to the increasing numbers of people living in cities, particularly because of their low air pollution and noise characteristics. As a result of their small size, innovative body structures, and use of new materials, the ultra-light weight of these new designs will reduce their energy consumption, and vehicles designed specifically for city use will not require a long range. As a result, battery size – and hence vehicle cost – will be able to be substantially reduced. The vehicles will be highly integrated and connected to mobile smart devices – particularly appealing to younger consumers. Much of the technical expertise needed to design and develop these vehicles will lie outside the traditional skill sets of existing OEMs, and the high barriers to entry associated with designing and developing ICEs which meet emissions regulations are eliminated in a pure electric design, potentially allowing new entrants to establish significant market shares.

Existing major OEMs have very large capital investments in conventional vehicle designs and technologies, particularly expertise and investment in the design and manufacture of ICE technology, so the evolutionary path would be expected to be their preference.

The reality is that the future is likely to contain elements of both these scenarios.

6. Conclusions and Future Potential

Much has changed since the first part of the King Review was published in 2007. Concerns about the impacts of climate change and the need to reduce carbon emissions have grown stronger. The UK has introduced the Climate Change Act 2008, legally obliging the UK government to meet its carbon reduction targets. The Committee on Climate Change has been established to monitor progress towards these targets and advise on suitable approaches, and government has put in place policies designed to bring UK emissions in line with the necessary target reduction trajectories.

Continuing to develop the necessary policy framework is crucial

Transport is a key sector for carbon reduction, and historically has been the only sector where carbon emissions were rising, driven primarily by car and van use. Many of the policies to achieve transport carbon reduction are determined at a European level. The introduction of tailpipe CO_2 reduction targets has been a crucial element in focusing the automotive industry on achieving carbon reduction, in particular the agreement on a 95 gCO_2/km target for 2020. European biofuel policies stimulated the market for biofuel supply, but have encountered controversy; the savings originally expected from first-generation biofuels now look unlikely to be achieved. However, next-generation biofuels are under development and may still hold substantial promise.

At a UK level, key policy interventions have included:

- the reform of company car tax, which has led to substantial reductions in both the CO_2 emissions levels of company cars and in the number of miles travelled by company car;
- the increased differentials in Vehicle Excise Duty, and particularly the introduction of a first-year rate;
- the widespread adoption of car fuel economy labelling, with easily understood colour coding; and the introduction of used-car labelling, helping to ensure that consumers make informed choices; and
- the formation of the Office for Low Emission Vehicles and the introduction of the Plug-in Car Grant and Plugged-in Places programmes.

However, it is crucial that policy continues to be developed to ensure that progress continues. There are a number of issues which future European policy is already being developed to address:

- the role of biofuels – ensuring that the expected carbon reduction benefits are achieved without adverse social or environmental consequences;

- the widening gap between the fuel consumption and CO_2 emissions figures from type-approval testing and those achieved by motorists in the real world; and
- the need to move to a full life cycle emissions assessment for vehicles and fuels, allowing consumers to compare the overall environmental impacts of different fuel and technology options.

For the UK government there is also the significant concern of falling revenues from fuel duty, and how the shortfall should be replaced. Whatever course of action is taken, it will be important to ensure that it incentivises continuing reduction of carbon emissions from personal car use.

Government must recognise that in controlling the combination of legislation and policies acting on the automotive industry, and on motorists in general, it has the single biggest influence on the future of low-carbon cars and fuels.

Technological developments are also essential

While progress towards lower-carbon cars has certainly been made over the last five years, if it is to continue to achieve the necessary carbon reductions, it will need to accelerate. At the same time, the challenge is becoming greater, as the reductions made so far are likely to have been achieved through easier, lower-cost actions, meaning that continuing this rate of progress will become progressively more difficult.

The automotive and fuel industries must continue to meet the challenge to develop new technologies and fuels which will enable the carbon reductions that policymakers are striving to achieve.

Initially this is expected to continue to be dominated by further improving the efficiency of conventional petrol and diesel vehicles. The focus is likely to be engine downsizing and boosting, further improvements to fuel injection systems, widespread use of fully variable valve systems, and potentially variable compression ratios. One technology which is expected to see widespread deployment is that of stop–start systems, the more sophisticated of which will allow recapture of braking energy.

At the same time, alternatives to conventional petrol and diesel vehicles are expected to grow their market shares. There is general agreement on the technology roadmap, from hybrids, to plug-in hybrids, to range-extended electric vehicles, to pure electric vehicles (whether they be battery or, eventually, fuel cell). However, there are wide variations in predictions of how quickly these technologies will gain market share. A review of the literature indicates mainstream estimates as shown in Table 6.1.

Table 6.1: Mainstream estimates for market shares of new vehicle sales by technology

Technology	2020	2030
Hybrid electric vehicles	5–20%	20–50%
Plug-in hybrid electric vehicles	1–5%	15–30%
Range-extended electric vehicles	1–2%	5–20%
Battery electric vehicles	1–5%	5–20%
'Advanced electric vehicles' (plug-in/ range-extended hybrid and battery electric vehicles combined)	2–10%	20–50%

Notes: The ranges presented in the table above are for individual powertrain options and often from different sources. There will necessarily be interactions between the deployment of different options, and also with conventional ICE powertrains. The respective upper/lower limits for the different technologies cannot therefore be simply combined.

The variation in estimates is due to uncertainty over a range of factors, leading different studies to make different sets of assumptions.

The factors considered to have the greatest influence over the speed of uptake of these technologies are as follows:

Governmental factors

- Setting out a long-term vision and strategy for transport carbon reduction
- Ensuring the provision of necessary refuelling infrastructure
- Enabling informed consumer choice
- Influencing upfront vehicle costs
- Influencing vehicle running costs

Technology factors

- Reducing costs and improving performance of energy storage (and fuel cell) technologies
- Reducing vehicle energy consumption
- Developing technologies and standards for refuelling/recharging

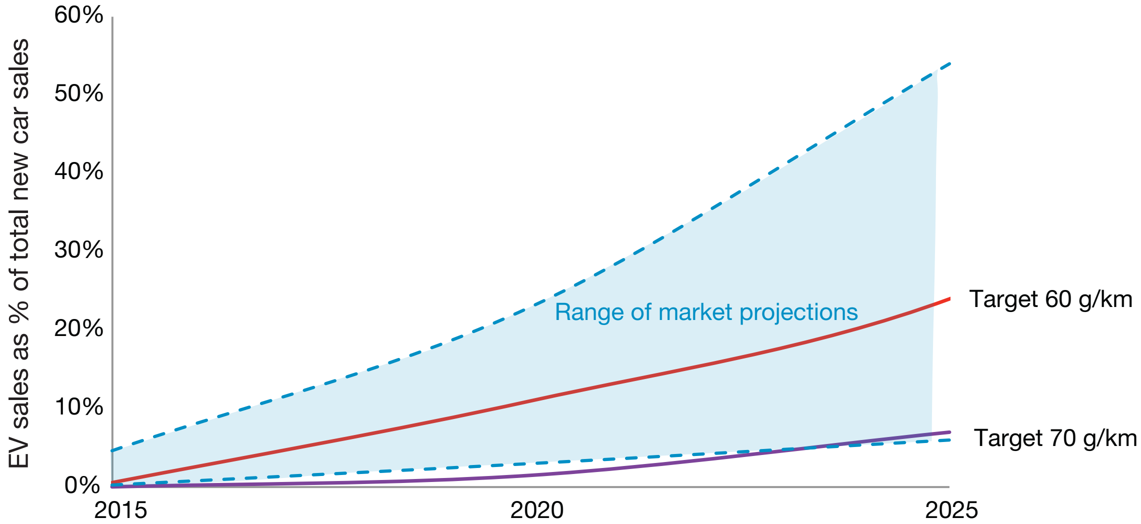
One of the key questions for future policy is at what level to set the target tailpipe CO_2 emissions for 2025. Ricardo-AEA has conducted modelling analysis using its in-house-developed *Road Vehicle Cost and Efficiency Calculation Framework*[14] to assess what the potential CO_2 reductions from improving conventional technology and increased market share for hybrids

14 The current version has been further developed and modified from that developed for the CCC by AEA Technology in 2012.

could be out to 2025. For a given target number, it is then possible to determine what the estimated necessary market share of plug-in hybrid and battery electric vehicles (‘advanced electric vehicles) would be.

In Figure 6.1 the sales equating to a 70 gCO_2/km and a 60 gCO_2/km target for passenger car emissions are shown and compared to the range of market projections of advanced electric vehicle market penetration.

Figure 6.1: Market share of advanced electric vehicles required for 60 gCO_2/km and 70 gCO_2/km target for passenger car emissions by 2025



Note: As neither the 2025 target nor modalities for reaching it have been determined at this stage, factors such as eco-innovations and super credits are not included in these calculations.

The 70 gCO_2/km target line appears to match the most pessimistic market uptake projections, whereas the 60 gCO_2/km line would require plug-in/range-extended hybrid electric vehicles and battery electric vehicles to gain market shares which are towards the midpoint of the range of projections.

There is no doubt that a 60 gCO_2/km target for new passenger car emissions would be a challenge. However, some experts believe this could be achieved if government and the automotive industry work to create the right policy framework and ensure the necessary advances in technology are realised.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The UK Petroleum Industry Association (UKPIA) represents the interests of nine member companies engaged in the UK oil refining and downstream industry on a range of common issues relating to refining, distribution and marketing of oil products, in non-competitive areas.

UKPIA's role is to inform its members of proposed legislation and related developments, and to help form and advocate the industry's position.

UKPIA is also an authoritative source of information or reference on the UK downstream industry.

The Royal Automobile Club Foundation for Motoring is a transport policy and research organisation which explores the economic, mobility, safety and environmental issues relating to roads and their users. The Foundation publishes independent and authoritative research with which it promotes informed debate and advocates policy in the interest of the responsible motorist.

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