Decarbonising surface transport in 2050

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Introduction

The Climate Change Act 2008 requires that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline. This is considered the appropriate UK contribution to a global emissions trajectory consistent that would stabilise atmospheric GHG concentrations at 475-550 parts per million, and limit the expected rise in global temperatures to close to 2° C by 2100.

In 1990, domestic UK greenhouse gas (GHG) emissions (i.e. excluding those from international aviation and shipping) were 769.4 $MtCO_2e$. Therefore, the 2050 emissions target is to limit domestic UK GHG emissions to around 154 $MtCO_2e$.

In 2010, domestic UK GHG emissions were 587.8 $MtCO_2e$, a 23.6% reduction on 1990 levels of 769.4 Mt. Of these, road transport GHG emissions were 112.0 $MtCO_2e$ in 2010, with other transport GHG emissions (including rail, domestic aviation and shipping) at 9.8 $MtCO_2e$.

Of the 112.0 $MtCO_2e$ road transport GHG emissions in 2010, 111.1 Mt (99%) were accounted for by CO_2 emissions, and the remaining 0.9 Mt accounted for by non-CO_2 GHGs. All GHG emissions from road transport are caused by the combustion of fossil fuels (petrol and diesel).

Meeting the 2050 emissions target can be accomplished by replacing high-emitting technologies with low- or zero-emitting technologies, and/or by reducing demand for the goods and services that are produced with high-emitting technologies. The availability and cost of low- and zero-emitting technologies, and of opportunities to reduce demand for goods and services, vary by sector. It is important to ensure that the economic burden of meeting the 2050 emissions target is as low as possible. This requires prioritisation of **cost-effective** technologies and policies, i.e. those that achieve emissions reductions at lower economic cost. It is unlikely that the appropriate approach to achieving the 2050 emissions target is an equal reduction in emissions in each sector; rather, the reduction in emissions should be greater in those sectors where the available technologies and policies are more cost-effective.

There are a number of opportunities to reduce CO_2 emissions from road transport. Use of hydrocarbon fuels can be reduced through technologies that improve fuel efficiency, or can be reduced or eliminated through use of lower- or zero-emitting powertrain technologies such as electric vehicles; the fossil CO_2 content of transport fuels can be reduced through use of biofuels; and the demand for travel by high-emitting modes and inefficient use of vehicles can be reduced through behaviour change.

This paper considers the first two opportunities: technologies that improve fuel efficiency and lower- or zero-emitting powertrain technologies. Biofuels are not assumed to be available as the Committee on Climate Change's analysis of the best use of bioenergy[1] has indicated that the

[1] Committee on Climate Change (2011): Bioenergy review. www.theccc.org.uk/reports/bioenergy-review

diversion of a scarce bioenergy resource from sectors that could generate negative CO_2 emissions (power generation with carbon capture and storage) or sectors with few options to eliminate CO_2 emissions (industry, aviation) to a sector with a range of options to eliminate CO_2 emissions (road transport) would significantly increase the cost meeting the 2050 emissions target. While behaviour change is not considered here, a reduction of demand for travel by high-emitting modes and inefficient use of vehicles reduces CO_2 emissions and delivers a range of additional benefits (reduction in congestion, improved air quality, reduced noise levels, improved health outcomes, etc.), and is a key component of the Committee on Climate Change's recommendations.

While some of the opportunities to reduce emissions from road transport are well-established, some (e.g. electric vehicles) have only recently become available, while others (e.g. hydrogen fuel-cell vehicles) are not yet mature, and there is considerable uncertainty around their future costs. A number of recent studies have attempted to estimate future costs. This paper draws on two studies commissioned by the Committee on Climate Change:

- AEA (2012): A review of the efficiency and cost assumptions for road transport vehicles to 2050. This study included development of a spreadsheet tool to calculates the fuel consumption and capital cost of vehicles with different powertrain technologies, for each major road transport mode

- Element Energy (2012): Cost and performance of EV batteries. This study investigated the future trajectory of cost and performance of electric vehicle batteries, and developed assumptions on battery costs for battery electric and plug-in hybrid electric cars and vans. These assumptions were used in the AEA (2012) spreadsheet model.

This paper seeks to identify how the road transport sector could make an appropriate contribution to achieving the 2050 emissions target. The analysis is set out in 6 sections.

Section 1 sets out forecasts of vehicle travel demand to 2050, and the emissions trajectory that would occur if lower-CO_2-emitting powertrain technologies are not deployed. Section 2 describes the vehicle powertrain technologies available today and those likely to become available by 2050, from each major road transport mode. Section 3 sets out forecasts of the fuel consumption and capital cost of those powertrain technologies, and the total lifetime costs of the powertrain technologies accounting for capital and fuel costs. Section 4 develops a ranking of the powertrain technologies by cost-effectiveness for the years 2020, 2030 and 2050 using DECC's carbon prices. Section 5 discusses the implications of the ranking for the appropriate rate of deployment of cost-effective powertrain technologies. Section 6 sets out a scenario of deployment of powertrain technologies for each major road transport mode and compares the emissions trajectory and economic cost with the baseline scenario in which lower-CO_2-emitting powertrain technologies are not deployed.

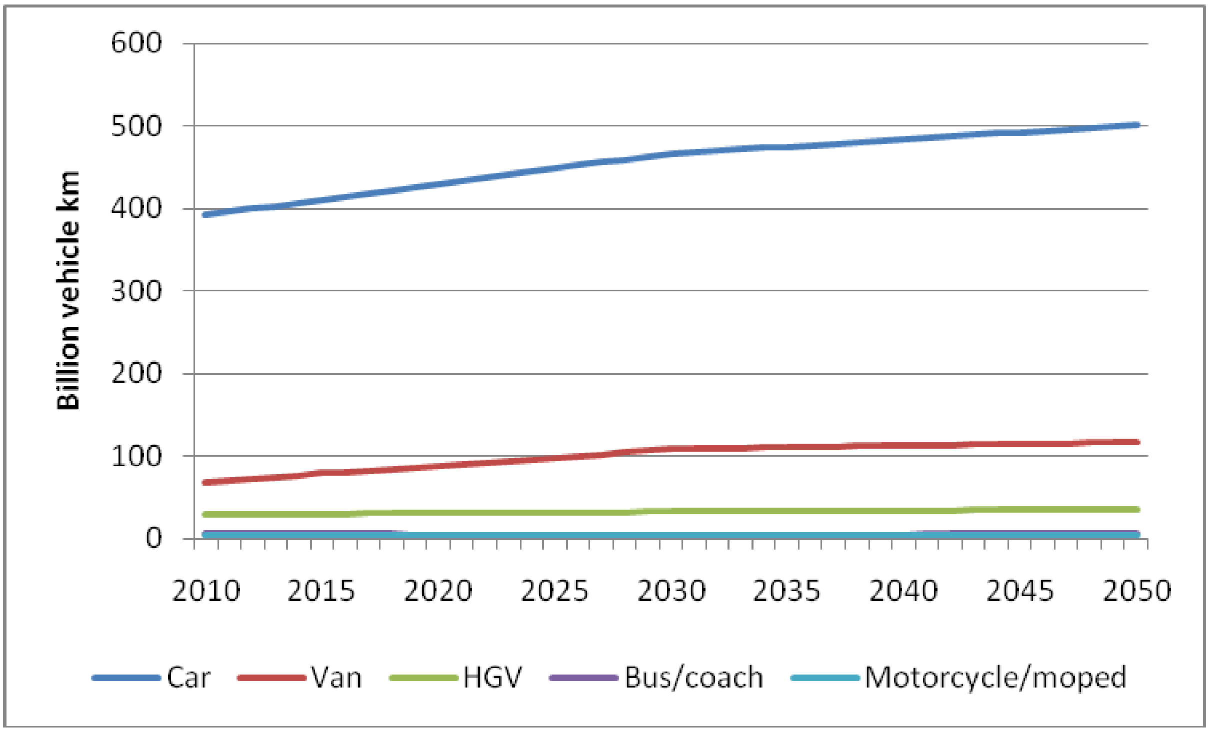
The major road transport modes consist of light-duty vehicles, heavy-duty vehicles and motorcycles. Light-duty vehicles comprise cars and vans, and the powertrains and fuel efficiency technologies available to light-duty vehicles are similar. Therefore, to maintain clarity, Sections 2-4 discuss results for passenger cars only. Results for all road transport modes are set out in Annex 3.

Section 1: forecast road transport travel demand and CO_2 emissions

This section sets out forecasts of vehicle travel demand to 2050, and the emissions trajectory that would occur in a reference, or "business as usual" scenario in which the choice of which technologies to deploy is not guided by the objective of reducing emissions.

Vehicle km for each vehicle category are derived from National Transport Model forecasts to 2030, and assumed to increase in proportion with the increase in UK population thereafter. Figure 1 sets out the trajectory of vehicle km for each mode (with HGV categories combined):

Figure 1: vehicle km by mode



Source: CCC analysis based on National Transport Model outputs and ONS population forecast

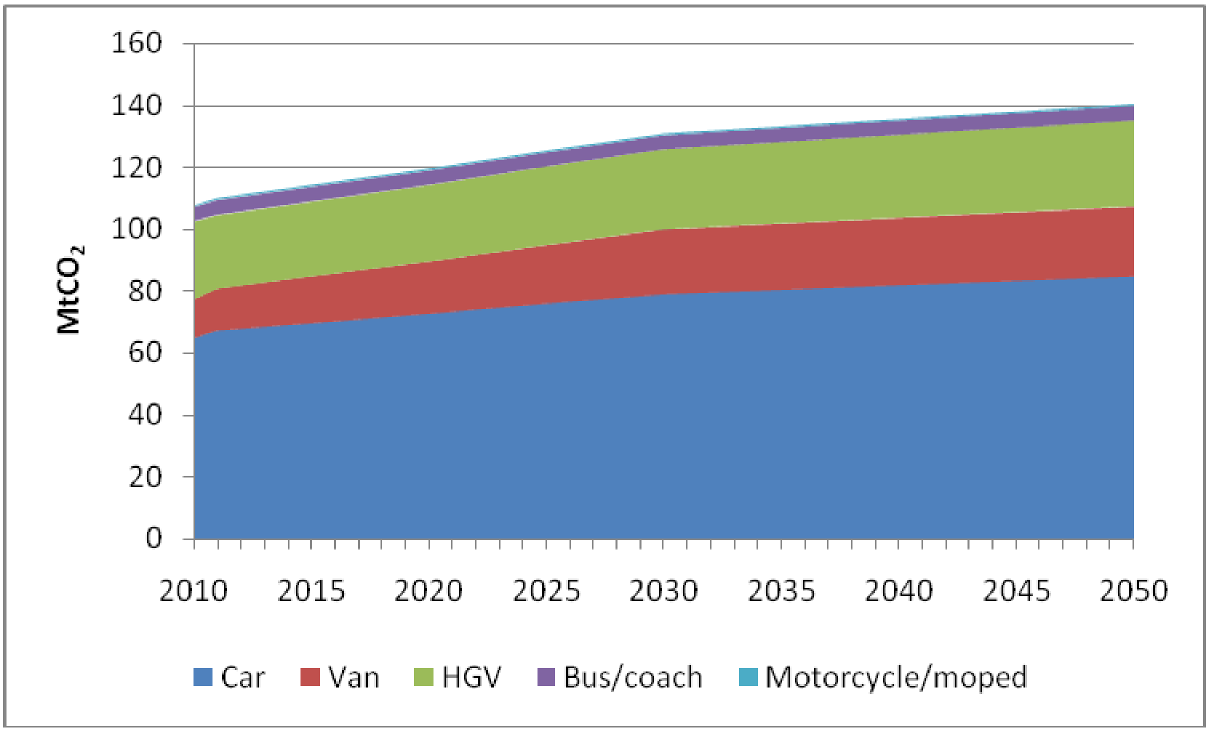
Between 2010 and 2030, van km are forecast to increase by 59%. This is followed by car km, forecast to increase by 18%. HGV km are forecast to increase by 10%, and motorcycles/mopeds by 9%, while Bus and coach km are forecast to decrease by 6% during this period. Between 2030 and 2050, all modes are assumed to increase a further 7.4%, in proportion with the increase in UK population. This may underestimate the increase in vehicle km, as it implies that the expected increase in GDP per capita during this period is not accompanied by an increase in vehicle km per capita.

In the reference scenario, it is assumed that:

- only those powertrain technologies that are widely deployed today, i.e. conventional internal combustion engine powertrains, will continue to be deployed to 2050
- the fuel consumption and capital cost of these conventional internal combustion engine vehicles remain at 2010 levels through to 2050, for each vehicle category.

Figure 2 sets out the trajectory of CO_2 emissions in the reference scenario for each vehicle category, based on the fuel consumption of the internal combustion engine powertrain and the trajectory of vehicle km for each vehicle category:

Figure 2: reference scenario CO_2 emissions by mode



In this scenario, total road transport CO_2 emissions increase 31%, from 107.5 $MtCO_2$ in 2010 to 140.6 $MtCO_2$ in 2050, in proportion with vehicle km for each vehicle category.

Section 2: vehicle technologies

This section sets out the vehicle powertrain technologies available today and those likely to become available by 2050, from each major road transport mode.

The major road transport modes comprise:

- Passenger cars (67.4 $MtCO_2$ in 2010, accounting for around 61% or road transport CO_2 emissions)
- Light duty vehicles (15.1 Mt, 14%)
- HGVs (22.9 Mt, 21%)
- Buses (4.7 Mt, 4%)
- Mopeds & motorcycles (0.6 Mt, 1%)

AEA (2012) considers a number of vehicle categories within the major transport modes, and identifies the powertrain technologies for each vehicle category that may be deployed over the period to 2050. The vehicle categories and powertrain technologies covered are set out in Table x:

Table 1: vehicle categories and powertrain technologies

<table>
<tr><th>Mode</th><th>Category</th><th>Powertrain Technology</th></tr>
<tr><td>Car</td><td>Average car (defined as an average of the C+D market segments for this study)</td><td rowspan="2">Petrol ICE
Diesel ICE
Petrol HEV
Diesel HEV
Petrol PHEV (30km electric range)
Diesel PHEV (30km electric range)
Petrol REEV (60km electric range)
Diesel REEV (60km electric range)
Battery Electric Vehicle (BEV)
Hydrogen Fuel Cell Vehicle (FCV)
Hydrogen Fuel Cell PHEV
Hydrogen Fuel Cell REEV
Natural Gas ICE</td></tr>
<tr><td>Van</td><td>Average van (defined according average split across Class I, II and III vans)</td></tr>
<tr><td rowspan="4">Heavy Truck</td><td>Small rigid truck (<15 t GVW)</td><td rowspan="6">Diesel ICE
Diesel HEV
Diesel Flywheel Hybrid Vehicle (FHV)
Diesel Hydraulic Hybrid Vehicle (HHV)
Battery Electric Vehicle (BEV) (small rigid and bus only)
Hydrogen Fuel Cell Vehicle (FCV)
Natural Gas ICE
Dual Fuel Diesel-Natural Gas ICE</td></tr>
<tr><td>Large rigid truck (>15 t GVW)</td></tr>
<tr><td>Articulated truck</td></tr>
<tr><td>Construction</td></tr>
<tr><td rowspan="2">Buses and Coaches</td><td>Bus</td></tr>
<tr><td>Coach</td></tr>
<tr><td>Motorbikes and mopeds</td><td>Average motorbike or moped</td><td>Petrol ICE
Petrol HEV
Battery Electric Vehicle (BEV)
Hydrogen Fuel Cell Vehicle (FCV)</td></tr>
</table>

Source: AEA (2012).

A description of the powertrain technologies is provided in Annex 1.

Section 3: vehicle fuel consumption and cost

This section sets out forecasts of the fuel consumption and capital cost of those powertrain technologies, and the total lifetime costs of the powertrain technologies accounting for capital and fuel costs.

Fuel consumption of powertrain technologies

The starting point for our analysis is the AEA (2012) spreadsheet tool, using Element Energy's (2012) assumptions on battery costs for battery electric and plug-in hybrid electric cars and vans.

The AEA spreadsheet tool contains assumptions on

- the expected trajectory of fuel consumption and capital cost of the different powertrain technologies (i.e. before the introduction of fuel efficiency technologies);
- the effect on fuel consumption and capital cost of a range of fuel efficiency technologies;

- the level of deployment of the fuel efficiency technologies in new vehicles over the period to 2050;
- the degree to which the capital costs of the fuel efficiency technologies are expected to decrease as a function of total cumulative deployment;
- the expected cost trajectory of electric vehicle batteries and hydrogen fuel cells
- the expected range of electric and plug-in hybrid vehicles.

These assumptions are set out in AEA (2012). Element Energy's (2012) battery cost forecasts are set out in Annex 2.

The output of the spreadsheet tool is a dataset of the fuel consumption and capital cost of each powertrain technology, reflecting these assumptions.

Figures 2, 3 and 4 set out the trajectory of fuel consumption, CO_2 emissions and capital cost of powertrain technologies for cars:

Figure 3: car fuel consumption in 2010 and 2050

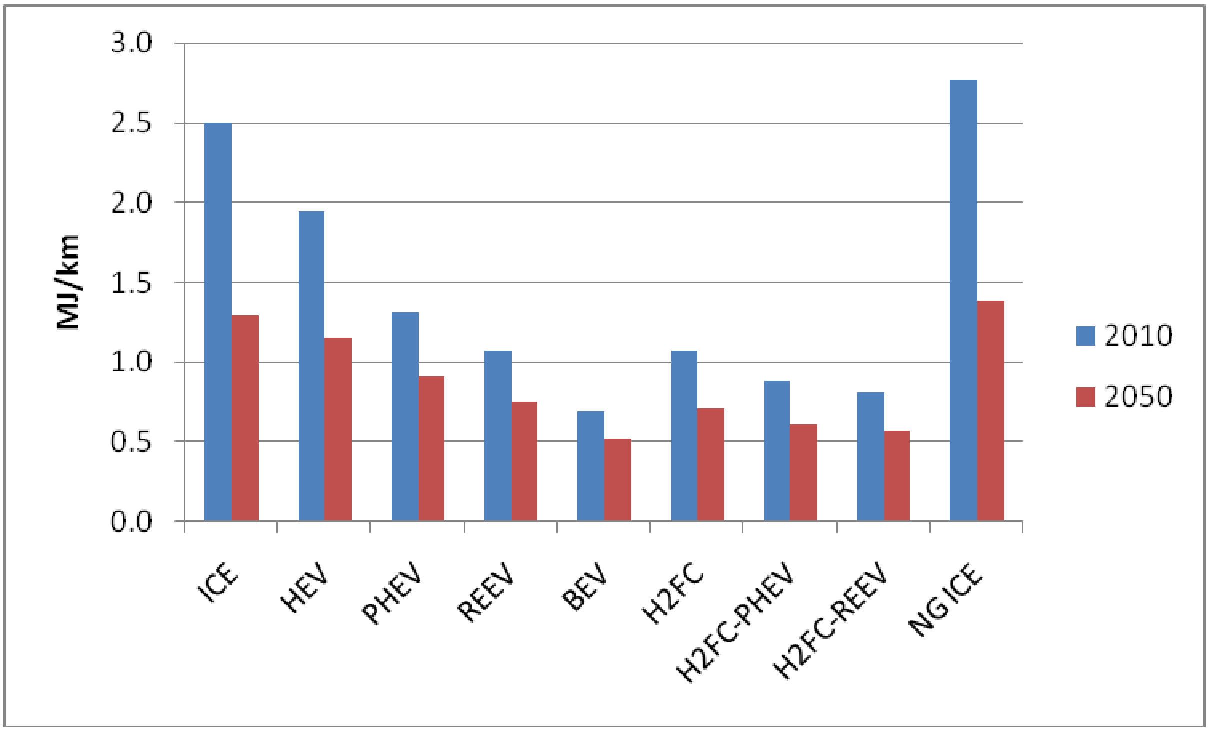
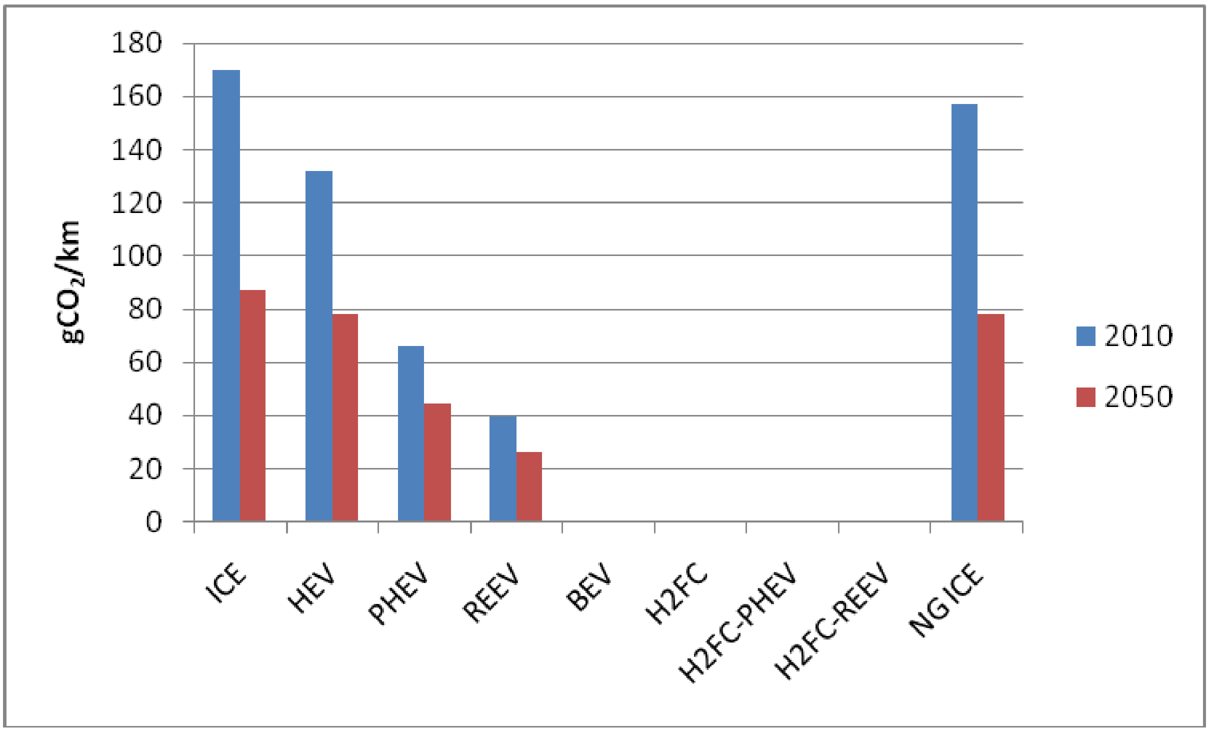


Figure 4: car CO_2 emissions in 2010 and 2050



Powertrain fuel consumption and CO_2 emissions in 2010 is estimated as follows (in decreasing order):

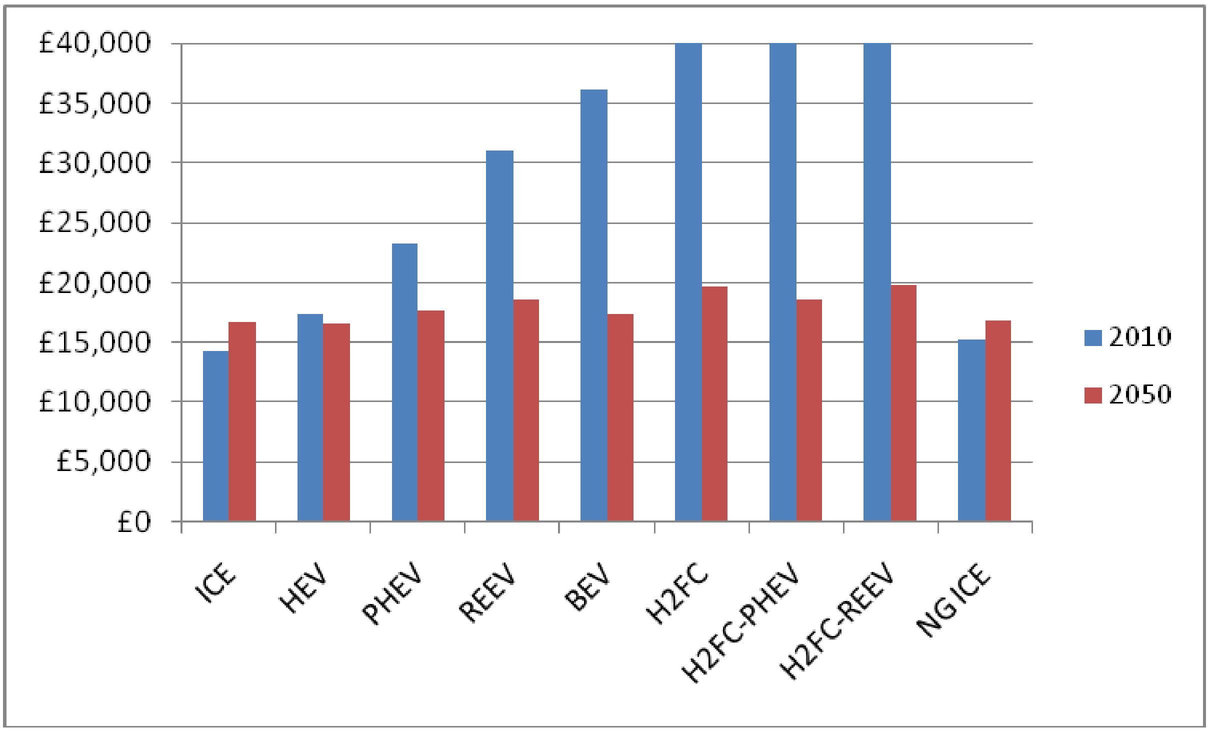
- The fuel consumption of a natural gas internal combustion engine (ICE) car is estimated at 2.8 MJ/km, emitting around 184 gCO_2/km in 2010;
- A conventional ICE car requires 2.5 MJ/km, emitting 170 gCO_2/km
- `A hybrid car requires 1.9 MJ/km, emitting 132 gCO_2/km
- A "plug-in hybrid" electric car (here assumed to have parallel hybrid architecture and a range of 30 km, or around 19 miles) requires 1.6 MJ/km, emitting around 91 gCO_2/km, while a "range extended" electric car (assumed to have series hybrid architecture and a range of 60 km, or around 38 miles) requires 1.2 MJ/km, emitting around 50 gCO_2/km.
- A hydrogen fuel cell car requires 1.1 MJ/km, while hydrogen fuel cell plug-in hybrid eclectic cars and range extended electric cars require 1.0 and 0.8 MJ/km respectively. A battery electric car requires 0.7 MJ/km. These vehicles emit zero tailpipe emissions.

Over the period to 2050, the fuel consumption of each powertrain technology decreases by 25-50%, while the CO_2 emissions from each powertrain (apart from those with zero tailpipe emissions) decreases by 33-48%.

Capital costs of powertrain technologies

Figure 5 sets out the trajectory of capital cost of powertrain technologies for cars:

Figure 5: car capital costs in 2010 and 2050



Generally speaking, the lower the fuel consumption and CO_2 emissions of a powertrain technology, the higher the cost. Thus in 2010 the ICE car is the lowest cost at £14,334; the cost of a hybrid car is £17,399, the costs of plug-in hybrid and range-extended cars are £23,315 and £31,139 respectively, while the costs of zero-emission cars are the highest (ranging from £79,866 for a hydrogen fuel cell plug-in hybrid electric car to £115,918 for a hydrogen fuel cell range-extended electric car).

Over the period to 2050, the capital costs of ICE and NG ICE technologies increase slightly as more fuel efficiency technologies are applied, while the capital costs of other powertrain technologies decreases as battery and hydrogen fuel costs decrease. The most significant cost decrease is seen in hydrogen fuel cell vehicles, as production scales up from prototype models to commercial-scale production. The costs of powertrains with lower fuel consumption remain higher than those with higher fuel consumption. However, this difference decreases over time as capital costs converge, such that by 2050 the capital costs of powertrain technologies fall within the range £14,334-£21,087.

Total lifetime costs of powertrain technologies

The total lifetime costs of a vehicle are a function of its fuel consumption, capital cost, and a number of other variables:

- Distance travelled
- Vehicle lifetime
- The cost of fuel
- The discount rate.

The average annual distance travelled and vehicle lifetime for each vehicle category is set out in Table 2:

Table 2: average annual distance and vehicle lifetime

Mode	Annual vehicle km	Vehicle lifetime (years)
Car	13000	14
Van	21000	13
Rigid HGV (small)	50000	12
Rigid HGV (large)	54000	12
Artic HGV	119000	8
Bus/coach	30000	15

Source: CCC analysis based on National Transport Model outputs, DfT Vehicle Licensing Statistics, DfT Road Freight Statistics

Table 3 sets out the fuel costs used in this analysis. Petrol and diesel costs are taken from DECC's central energy cost forecasts.

Electricity costs are based on Committee on Climate Change analysis of costs of low carbon power generation. Electric vehicles are assumed to charge where possible at night, in the off-peak period, when electricity costs are lower. The level of demand that can be met with off-peak electricity depends on the generation capacity and the time profile of electricity demand from non-transport sectors. This analysis is based on a power sector scenario consistent with meeting the 2050 emissions target, in which the grid is progressively decarbonised and its capacity increased to meet additional demand for electricity in the transport and heat sectors. With such a power sector scenario, relatively low levels (up to 30 TWh) of transport electricity demand can be met with existing capacity (i.e. capacity required to meet demand from non-transport sectors), whereas with higher levels require new capacity. Electricity costs to 2030 are assumed to be the short run marginal cost of low carbon generation. Electricity costs post-2030 are assumed to rise towards the long run marginal cost of low carbon generation, with costs in 2050 being a weighted average of 50% short run and 50% long-run marginal costs.

Hydrogen is (Box 4.4), at a cost of £61/MWh (based on £78m capital cost of a 0.5 TWh per year steam methane reformation plant with CCS).

Hydrogen costs are taken from Committee on Climate Change analysis of costs of hydrogen production and assume hydrogen is co-produced with electricity at large-scale directly from fossil fuels during pre-combustion CCS.

Table 3: fuel costs

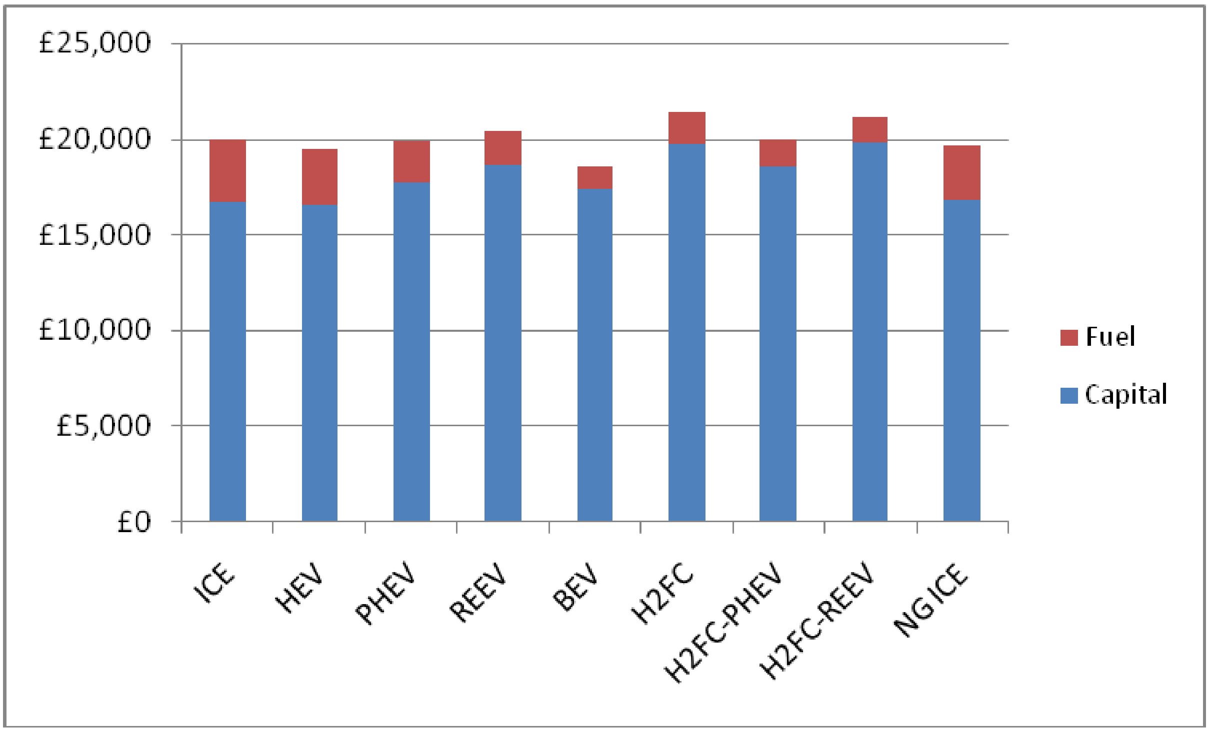
	2010	2020	2030	2040	2050
Petrol p/l	43.85	55.00	59.61	59.61	59.61
Diesel p/l	42.38	61.32	66.43	66.43	66.43
Electricity (p/kWh)	2.70	2.70	2.70	5.70	5.70
Hydrogen (£/MWh)	60.70	60.70	60.70	60.70	60.70

Source: DECC (2011): Valuation of energy use and greenhouse gas emissions for appraisal and evaluation, Tables 4-9: Energy prices - Central, 2011 prices

All costs and benefits are converted to present values at the social discount rate of 3.5%, as required by HM Treasury's Green Book guidance on appraisal and evaluation in central government[2]. Private discount rates for fuel efficient vehicles can be considerably higher. The divergence in social and private discount rates can result in a different balance of costs and benefits. This implies the need for additional economic incentives to align the private and social perspectives, or measures to address any market failures that affect the private discount rate. The private perspective is beyond the scope of this paper.

Figure 6 sets out the total lifetime cost of powertrain technologies for cars in 2050:

Figure 6: car lifetime costs in 2050



Over the period to 2050, the total lifetime cost of each powertrain technology decreases. As with capital costs, the total lifetime cost of power trains with lower fuel consumption remain higher than those with higher fuel consumption, with the difference decreasing over time. However, as the powertrain technologies with higher capital costs are those with lower fuel consumption, the total lifetime cost premium is lower than the total capital cost premium, and total lifetime costs converge to a greater degree than total capital costs. By 2050 the total lifetime costs of powertrain technologies fall within the range £16,815-£22,596.

Section 4: cost-effectiveness of powertrain technologies

This section develops a ranking of the powertrain technologies by cost-effectiveness for the years 2020, 2030 and 2050 using DECC's carbon prices.

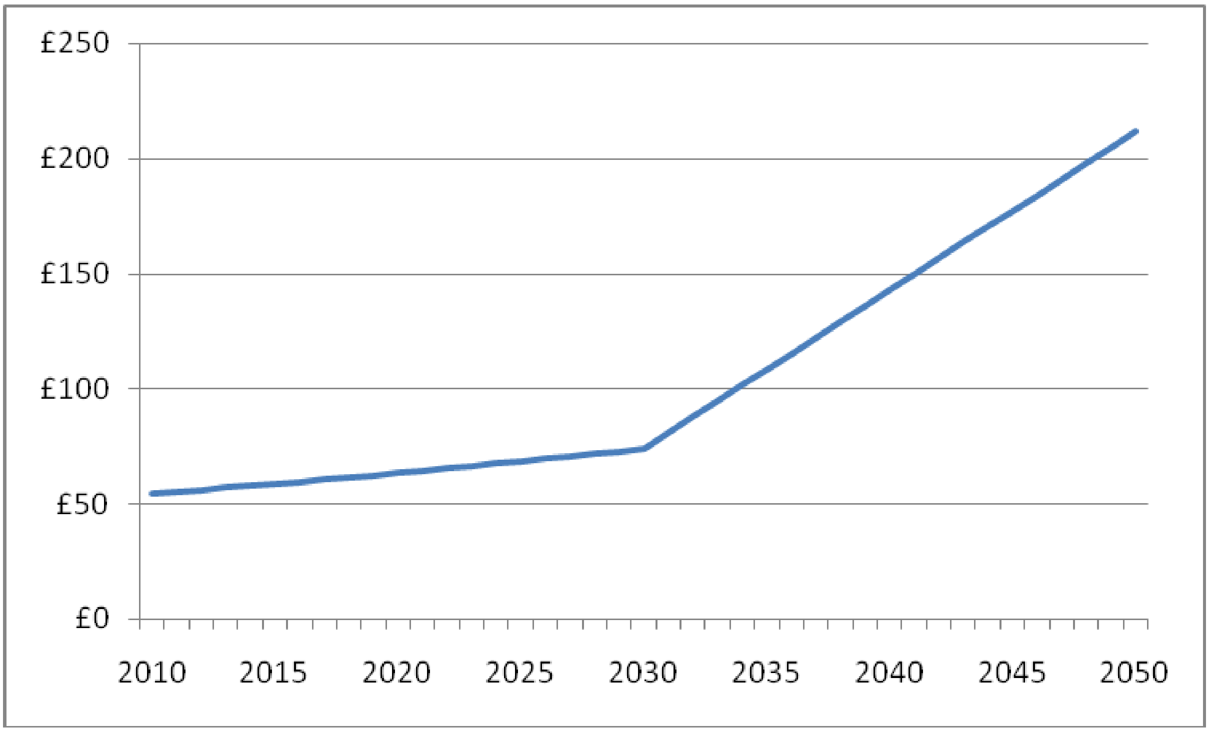
[2] HM Treasury (2003): The Green Book: Appraisal and Evaluation in Central Government. http://www.hm-treasury.gov.uk/data_greenbook_index.htm

Total social cost

A range of powertrain technologies, with different levels of CO_2 emissions and lifetime costs, could be deployed over the period to 2050. **Cost-effective** powertrain technologies can be identified based on their total social cost, i.e. the sum of their lifetime and carbon costs.

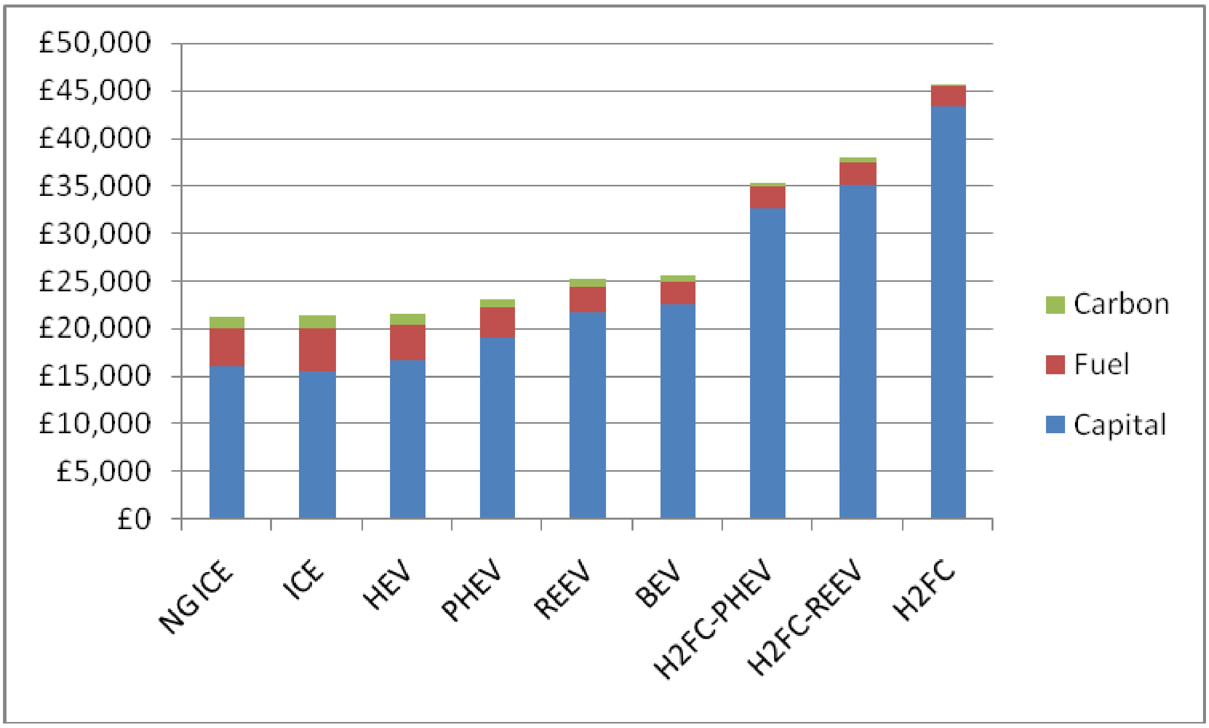
DECC's carbon prices for the non-traded sector are estimates of the marginal cost of reducing emissions, at a global level, for a global emissions trajectory consistent that would stabilise atmospheric GHG concentrations at 475-550 parts per million, and limit the expected rise in global temperatures to close to 2° C by 2100. DECC's carbon prices rise from £55 in 2010 to £74 in 2030, and £212 in 2050 (Figure 7).

Figure 7: DECC’s carbon prices



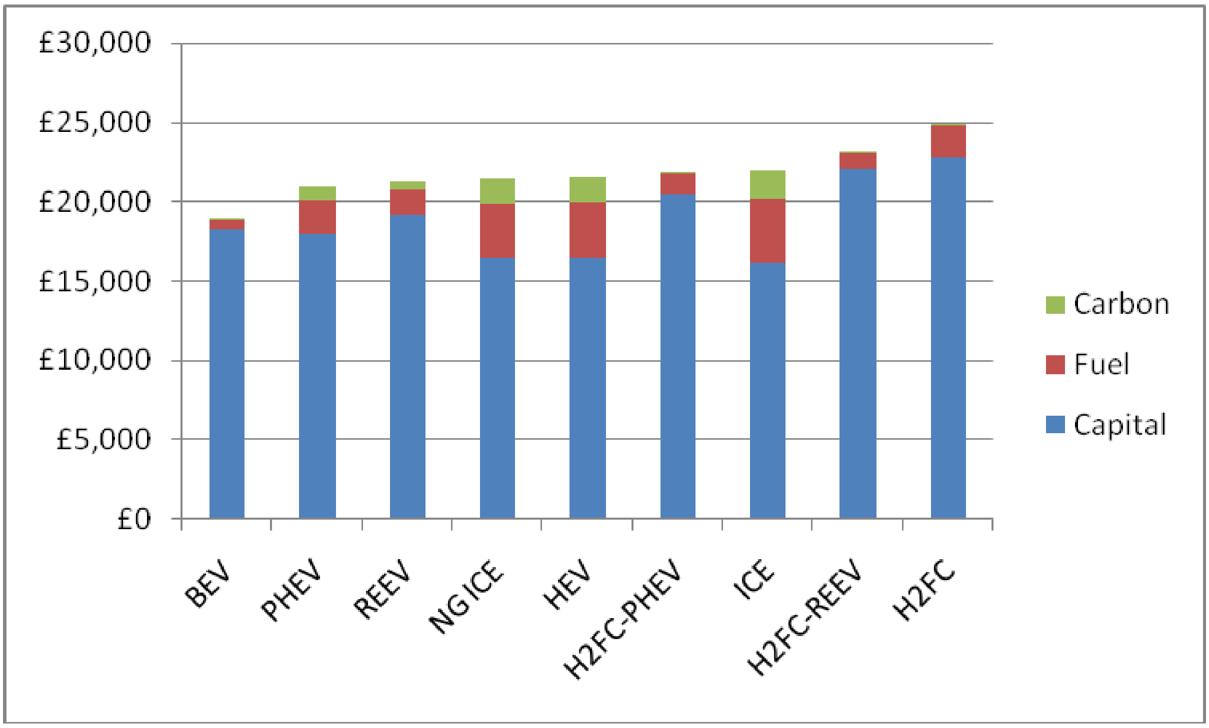
DECC’s carbon prices can be used to compare the cost-effectiveness of different technologies and policies. In order to achieve the required emissions trajectory, any CO_2 emitted requires a compensating reduction in CO_2 either elsewhere in the UK economy, or overseas through the purchase of carbon credits on the international market. The carbon price represents the cost of the compensating reduction in CO_2. For two substitute technologies, the technology with the lowest total social cost (i.e. the total cost including the cost of carbon) is the most cost-effective, taking account of any requirement for a compensating reduction in CO_2 or purchase of emissions credits. Figures 8-10 set out the total social costs of powertrain technologies for cars in 2020, 2030 and 2050.

Figure 8: car social costs in 2020



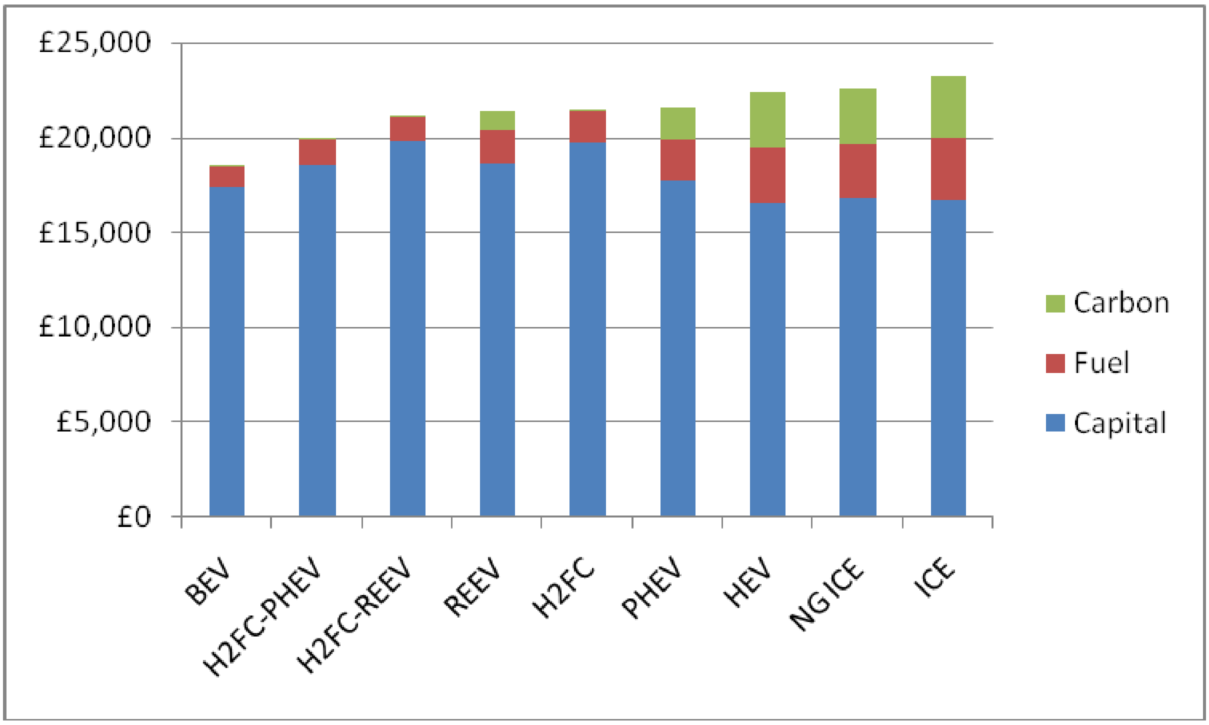
By 2020, with a carbon price of around £64/tonne, the most cost-effective powertrain technology is the natural gas ICE car (97 gCO_2/km on a test-cycle basis), followed by the conventional ICE car (108g) and the hybrid car (88g). The cost of the CO_2 emitted by these cars is not sufficient to justify the higher costs of lower-emitting electric and hydrogen powertrain technologies.

Figure 9: car social costs in 2030



By 2030, following significant reductions in electric vehicle battery costs and with a carbon price of around £74/tonne, the battery electric vehicle becomes the most cost-effective powertrain technology, followed by the plug-in hybrid (30 km range) and range-extended (60 km range) cars. The cost of the CO_2 emitted by the natural gas, hybrid and conventional ICE cars is now sufficient to justify the higher lifetime costs of lower-emitting electric technologies, though in the case of natural gas and hybrid cars is not yet sufficient to justify the higher costs hydrogen powertrain technologies.

Figure 10: car social costs in 2050



By 2050, following significant reductions in hydrogen fuel cell costs and with a carbon price of around £212/tonne, the battery electric vehicle remains the most cost-effective powertrain technology, followed by the hydrogen fuel cell plug-in hybrid (30 km range) and range-extended (60 km range) cars. The cost of the CO_2 emitted by the natural gas, hybrid and conventional ICE cars is now sufficient to justify the higher lifetime costs of all lower-emitting electric and hydrogen powertrain technologies.

Electric vehicle range

The above analysis has assumed that the range of battery electric vehicles remains constant at 160 km (100 miles). While such a range is capable of meeting the majority of travel requirements for the average driver, it is not capable of meeting travel requirements on the minority of days when a driver exceeds this distance, without a potentially costly and CO_2-intensive fast-charging network of sufficient coverage and density. It is likely that for a certain proportion of drivers, the behaviour change required to adapt to a limited-range electric vehicle would be unacceptable, and it is therefore unlikely that such vehicles could dominate the UK car fleet. However, given the significant cost differential between the BEV and the most cost-effective CO_2-emitting powertrain technology (the PHEV in 2030, or the REEV (H2FC-PHEV) in 2050), there is scope for increasing the battery electric vehicle's range and potential market share.

Figures 11 and 12 set out the total social costs of powertrain technologies for cars in 2030 and 2050, with the range of battery electric vehicles increasing to 240km by 2030, and an additional variant with a range of 320km in 2050:

Figure 11: car social costs in 2030 with longer-range BEV

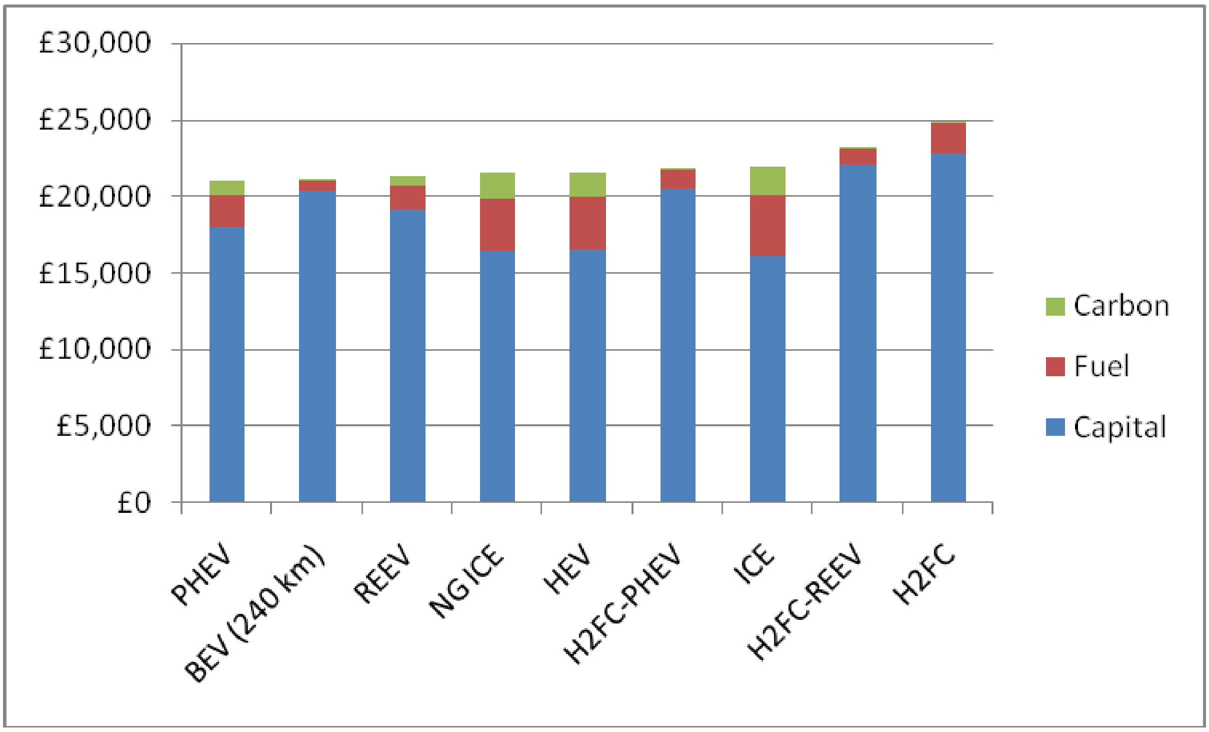
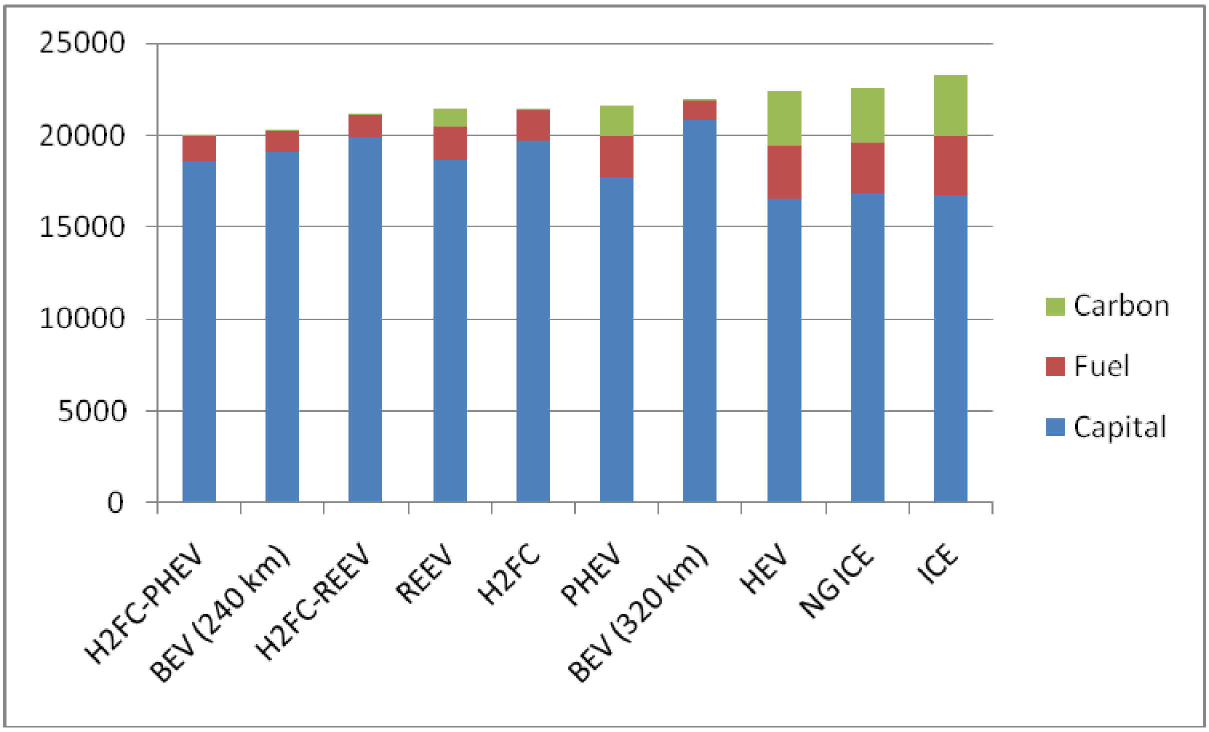


Figure 12: car social costs in 2050 with longer-range BEV



With a BEV range of 240km in 2030, the total social costs of the BEV (£21,110) are comparable to those of the PHEV (£21,000). This indicates that a range significantly higher than the 160km previously assumed would be cost-effective. In 2050, the total social costs of the 240km BEV (£20,273) are comparable to those of the hydrogen fuel cell PHEV (£20,024), and significantly lower than those of the most cost-effective CO_2-emitting powertrain technology (the range-extended electric vehicle, £21,429), while the total social costs of the 320 km BEV (£21,988) are comparable to those of the range-extended electric vehicle. This confirms that a range significantly higher than the 160km previously assumed would be cost-effective in 2050, and in the event of technical challenges or insufficient cost increases in hydrogen fuel cells, indicates that a range significantly higher than 240 km would be cost-effective by this date.

Section 5: deployment trajectory

This section discusses the implications of the ranking of the powertrain technologies by cost-effectiveness for their appropriate rate of deployment.

Table 4 sets out the three most cost-effective powertrain technologies in 2020, 2030 and 2050 for each vehicle category, in order of cost-effectiveness, as set out in Section 4 (for cars) and Annex 3 (for all road transport modes):

Table 4: ranking of powertrain technologies by cost-effectiveness

Vehicle category	2020	2030	2050
Cars	NG ICE (ICE, HEV)	BEV (PHEV, REEV)	BEV (H2FC-PHEV, H2FC-REEV)
Vans	PHEV (REEV, NG ICE)	BEV (H2FC-REEV, REEV)	H2FC-REEV (BEV, H2FC)
Small rigid HGVs	BEV (H2FC, HEV)	BEV (H2FC, HEV)	H2FC (BEV, HEV)
Large rigid HGVs	DNG ICE (H2FC, HEV)	H2FC (DNG ICE, HEV)	H2FC (DNG ICE, HEV)
Articulated HGVs	DNG ICE (NG ICE, H2FC)	H2FC (DNG ICE, NG ICE)	H2FC (DNG ICE, NG ICE)
Buses/coaches	HEV (H2FC, FHV)	H2FC (HEV, FHV)	H2FC (HEV, FHV)
Motorcycles	ICE (HEV, BEV)	BEV (HEV, ICE)	BEV (HEV, ICE)

By 2020, the most cost-effective powertrain technologies for cars and large rigid and articulated HGVs is the natural gas ICE (or for HGVs, the Dual Fuel Diesel-Natural Gas ICE). However, by 2030, across all modes and vehicle categories, zero-emission powertrains replace the natural gas ICE as the most cost-effective powertrain technologies. Natural gas vehicles therefore have the potential to be a cost-effective technology for less than 20 years, and it would take considerable time for natural gas vehicles to achieve a significant share of the new vehicle market, and subsequently the fleet through vehicle stock turnover. It is very unlikely that the economic cost required to develop a natural gas distribution, compression and fuelling infrastructure could be justified for such a short time period.

Excluding natural gas vehicles, by 2020, the most cost-effective powertrain technologies for cars, buses/coaches and motorcycles are conventional ICE and hybrid vehicles, while for other modes the most cost-effective powertrain technologies are low- or zero-emitting due to the greater distance travelled (and therefore fuel cost savings) of these modes. The most cost-effective powertrain technologies for vans are ultra-low-emitting plug-in hybrid and range-extended electric vehicles, while the most cost-effective powertrain technologies for HGVs are zero-emitting battery electric and hydrogen fuel cell vehicles.

From 2030, the most cost-effective powertrain technologies for these vehicles are zero-emission powertrains: BEVs for cars, vans, small rigid HGVs and motorcycles, and hydrogen fuel cell vehicles for large rigid and articulated HGVs, and buses/coaches. By 2050, hydrogen fuel cell vehicles appear to become more cost-effective relative to battery electric vehicles for vans and small rigid HGVs. However, given uncertainty over the relative pace of reduction in cost of electric vehicle batteries and hydrogen fuel cells over the longer term, it may be more appropriate to take the view that either battery electric or hydrogen fuel cell vehicles could potentially emerge as the more cost-effective, or that these technologies could be equally cost-effective over the longer term.

A focus on cost-effectiveness as the only determinant of the rate of deployment fails to consider two other important issues:

- Infrastructure requirements
- Market penetration rates

Infrastructure requirements

In addition to cost-effectiveness, the appropriate rate of deployment of powertrain technologies also depends on their infrastructure requirements. Infrastructure requirements for the two main zero-emitting powertrain technologies are:

- Electric (BEV, PHEV and REEV) vehicles. Very large numbers of electric vehicles could be charged and driven with minimal additional infrastructure, as charging can be undertaken at home and around 70% of UK households have off-street parking. Some public charging infrastructure would be required to provide consumer confidence and reduce range anxiety, and some fast-charging infrastructure may be required to enable limited-range vehicles to undertake long-distance journeys. On-street charging infrastructure would be required for consumers who do not have off-street parking.

- Hydrogen fuel cell vehicles. These have very significant infrastructure requirements in terms of development of hydrogen production facilities, a hydrogen distribution network, and hydrogen fuelling stations. At the smaller end of the scale, fleets that operate on a depot fuelling basis (e.g. bus fleets) could install hydrogen production and fuelling facilities on a distributed basis without the need for publically available infrastructure with nationwide coverage. Deployment in the HGV sector would require more significant production, distribution and fuelling infrastructure, with fuelling stations covering the UK motorway network. Deployment in the car and van sector would require much more extensive production, distribution and fuelling infrastructure, with fuelling stations covering the entire UK road network.

As the infrastructure requirements for electric vehicles are relatively low, it is possible to deploy these with no lead times (and indeed, they are currently being deployed, with several models on the market in 2012 and development of public charging infrastructure currently underway). By 2030, electric vehicles are the most cost-effective powertrain technologies for cars, vans, small rigid HGVs and motorcycles. A cost-effective abatement strategy would aim to deploy electric vehicles in these vehicle categories at very high levels by this date.

In contrast, the infrastructure requirements for hydrogen fuel cell vehicles are relatively high, and significant coordination would be required to ensure adequate development of production, distribution and fuelling infrastructure. Long lead times would therefore be required to deploy these vehicles. By 2030, hydrogen fuel cell vehicles are the most cost-effective powertrain technologies for Large rigid and Articulated HGVs, and Buses/coaches. However, due to the infrastructure requirements and lead times it would be difficult to deploy hydrogen fuel cell vehicles in these vehicle categories at very high levels by this date.

Market penetration rates

New technologies take time to dominate the market, for three reasons:

- Supply-side barriers: it takes time to develop the production capacity (new industries, firms and production facilities) required to produce a new technology in sufficient volumes.
- Demand-side barriers: it takes time to develop consumer confidence in a new technology, and to shift preferences from the old to the new technology.
- Technology costs and learning: production of a new technology in increasing volumes over time generally results in cost reductions as learning takes place; it takes time for the cost reductions to be sufficient to support mass-market commercialisation.

It is unlikely that a new powertrain technology could dominate the vehicle market within a very short time; rather, take up is likely to be gradual as the barriers to market dominance are addressed. It is therefore necessary to deploy a technology early to ensure that the barriers to market dominance are addressed by the time a technology should be widely deployed. The challenge is to deploy the technology sufficiently early and in sufficient volumes to allow production capacity to develop, incentivise consumer uptake and deliver potential cost reductions, while limiting total expenditure on the technology while it is still expensive.

Taking account of the cost-effectiveness of the powertrain technologies, their infrastructure requirements and potential market penetration rates, the appropriate rate of deployment of powertrain technologies could follow the following path.

- Due to very limited infrastructure requirements, **electric cars and vans** should be deployed at an early stage to facilitate their wide-scale take up by 2030. A trajectory of gradual deployment to 2030 would address barriers to commercialisation while limiting total expenditure during the period when these technologies are still expensive.
- Due to significant infrastructure requirements, **hydrogen fuel cell HGVs** could only be deployed following development of sufficient production, distribution and fuelling infrastructure. Due to the economic cost, time frame and level of coordination required to

develop this infrastructure, it may not be possible to achieve wide-scale take up by 2030. It is more likely that **hydrogen fuel cell buses** could achieve wide-scale take up by 2030, as these could use with on-site hydrogen production and fuelling. This would help address the supply-side and demand-side barriers to wider take up of the hydrogen fuel cell powertrain and help realise early cost reductions, facilitating later deployment of hydrogen fuel cell HGVs.

Section 6: emissions trajectory and economic cost of technology deployment scenario

This section sets out a scenario of deployment of powertrain technologies for each major road transport mode and compares the emissions trajectory and economic cost with a baseline scenario in which lower-CO_2-emitting powertrain technologies are not deployed.

In order to limit analytical complexity, this is a relatively simple scenario in which two powertrain technologies are deployed in each vehicle category. Initially, only conventional internal combustion engine powertrains are deployed. Subsequently, zero-emitting powertrain technologies are introduced and deployed at increasing levels, eventually reaching 100% of new vehicle sales. The deployment of zero-emitting powertrain technologies for each vehicle category in the abatement scenario is as follows:

- For cars and vans, the modelled zero-emitting powertrain technology is the BEV. Deployment of BEVs begins in 2010, reaching 16% of new car sales (5% of the fleet) in 2020, 60% (31% of the fleet) in 2030 and 100% (73% of the fleet) in 2040. By 2050 deployment of BEVs reaches 97% of the fleet, i.e. conventional ICE cars comprise only 3% of the fleet.

- For HGVs (small and large rigid and articulated HGVs), the modelled zero-emitting powertrain technology is the hydrogen fuel cell vehicle. Deployment of FCVs begins in 2030, and reaches 100% of new HGV sales (49% of the fleet) in 2040. By 2050 deployment of FCVs reaches 91% of the fleet.

- For buses and coaches, the modelled zero-emitting powertrain technology is the hydrogen fuel cell vehicle. Deployment of FCVs in buses begins in 2010, reaching 50% in 2030 and 100% in 2040. Deployment of FCVs in coaches begins in 2030, reaching 100% in 2040.

- For motorcycles, the modelled zero-emitting powertrain technology is the BEV. Deployment of BEVs begins in 2020, reaching 100% (33% of the fleet) in 2040. By 2050 deployment of BEVs reaches 75% of the fleet.

The deployment of zero-emitting powertrain technologies for each vehicle category in the abatement scenario is set out in

Figure 13:

Figure 13: zero-emitting powertrain deployment

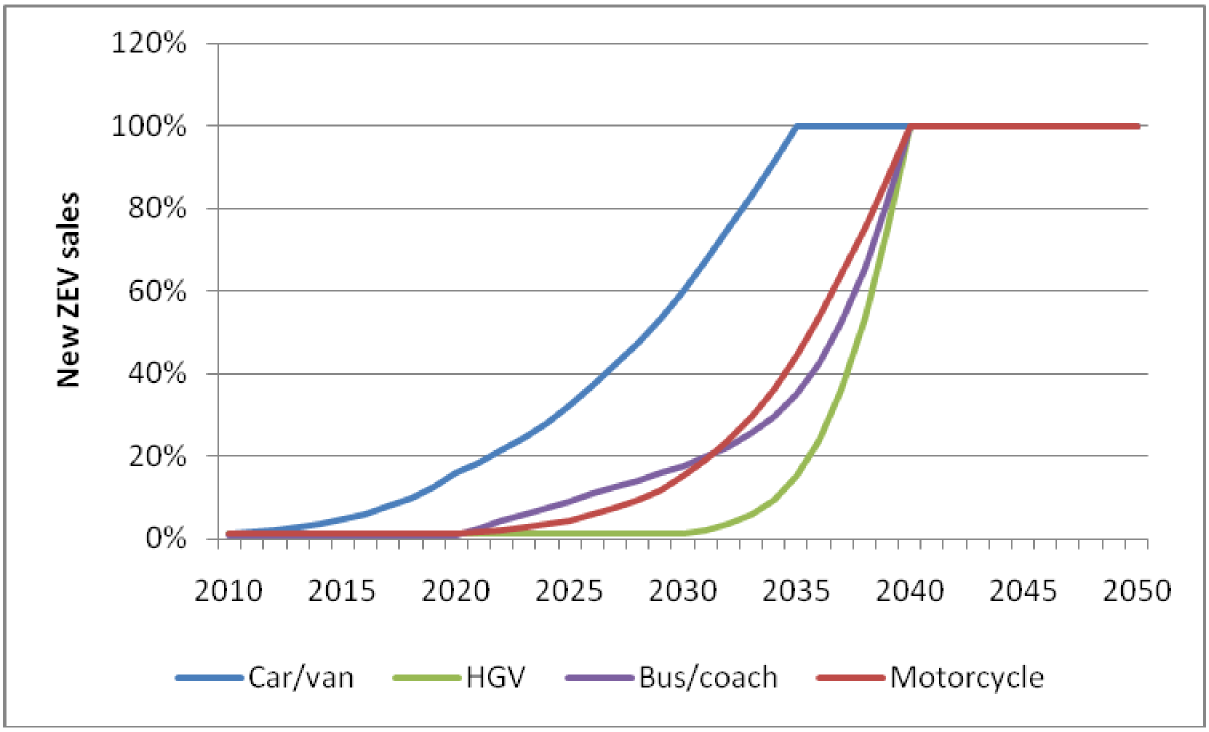
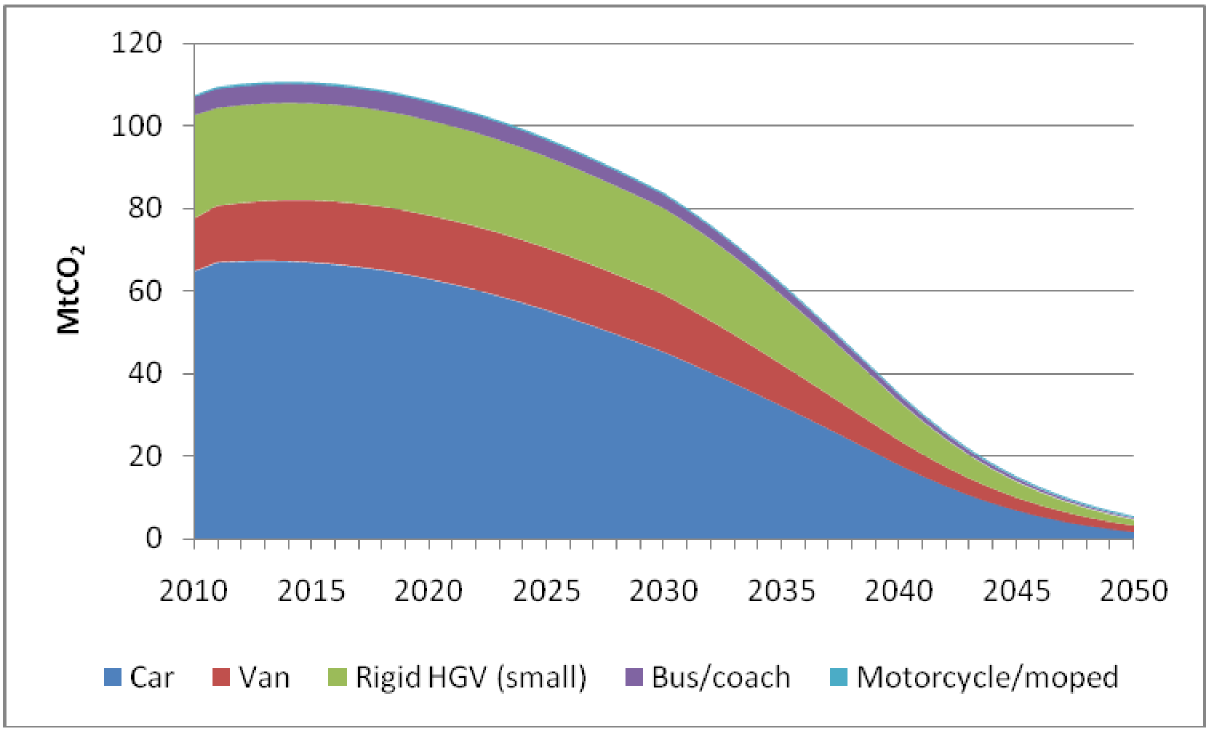


Figure 14 sets out the trajectory of CO_2 emissions in the abatement scenario for each vehicle category, based on the fuel consumption of the internal combustion engine powertrain and the trajectory of vehicle km for each vehicle category:

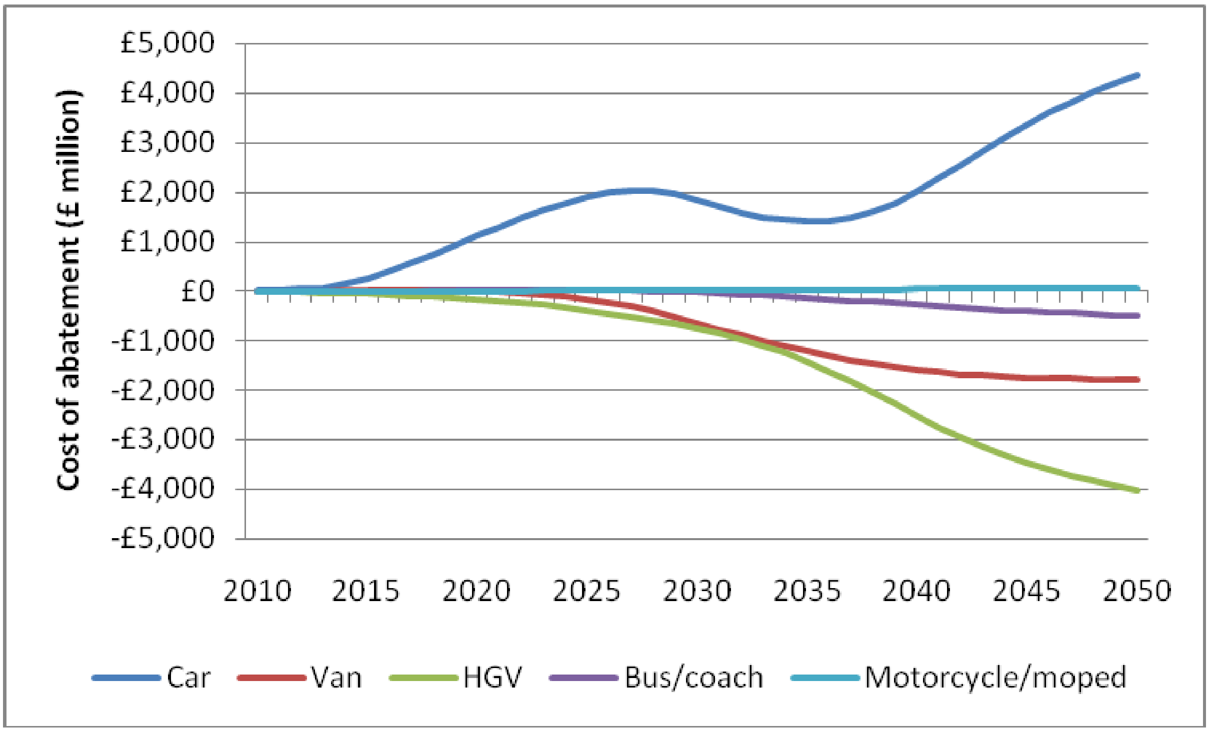
Figure 14: CO_2 emissions by mode



In this scenario, total road transport CO_2 emissions decrease 95%, from 107.5 $MtCO_2$ in 2010 to 5.4 $MtCO_2$ in 2050.

Figure 15 sets out the trajectory of costs relative to the reference scenario for each vehicle category. The costs are composed of capital costs and fuel costs, based on the fuel consumption of the internal combustion engine powertrain and the trajectory of vehicle km for each vehicle category:

Figure 15: abatement cost by mode

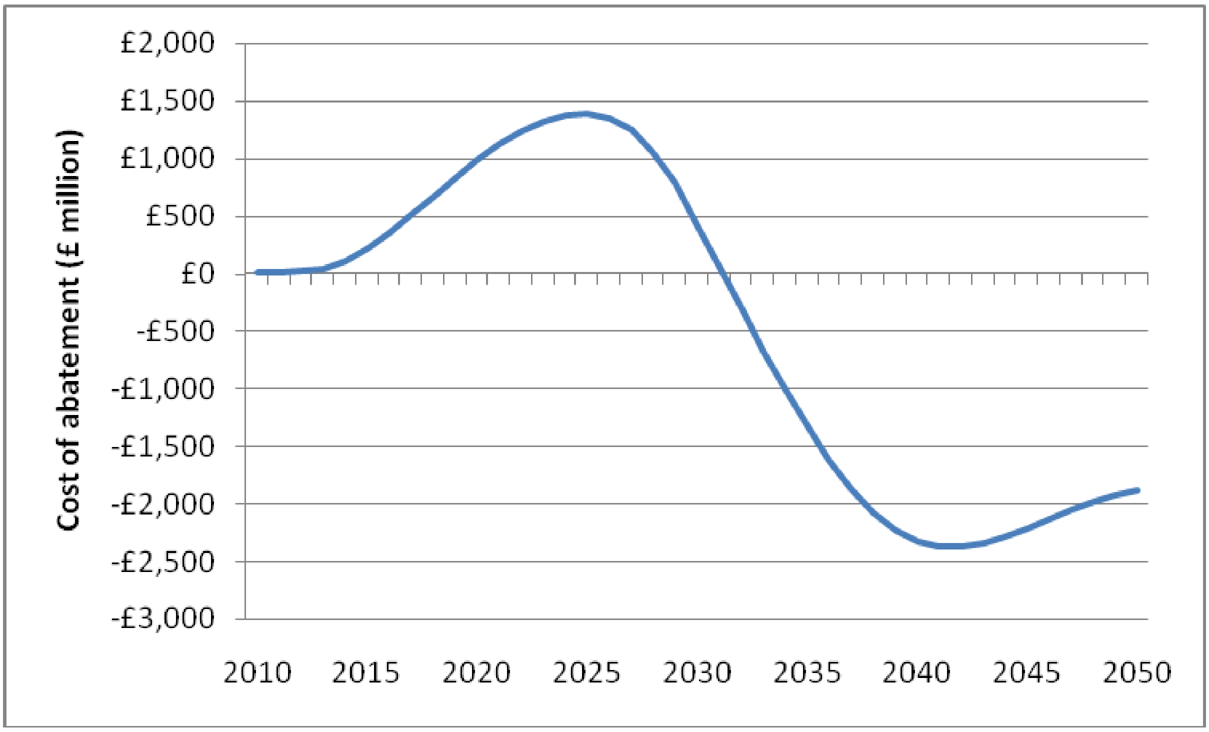


Reducing emissions from cars incurs the highest costs. The total annual abatement cost for cars reaches £1,815 million in 2030, rising further to £4.4 billion in 2050. Reducing emissions from motorcycles/mopeds incurs a small cost of £25 million in 2030, rising to £54 million in 2050.

Due to their high mileage, reducing emissions from vans, HGVs and buses/coaches delivers a cost saving. Reducing emissions from HGVs delivers the greatest cost saving. The total annual cost saving for HGVs reaches £739 million in 2030, rising further to £4 billion in 2050. The total annual cost saving for vans reaches £667 million in 2030, rising further to £1.8 billion in 2050, while the total annual cost saving for buses/coaches reaches £17 million in 2030, rising further to £496 million in 2050.

Figure 16 sets out the trajectory of total costs across all modes relative to the reference scenario:

Figure 16: total abatement cost



Total annual abatement costs reach their maximum of £1.4 billion in 2025. Costs decrease to zero in 2031-2, following which reducing emissions further delivers cost savings. Total cost savings reach their maximum of £2.4 billion in 2042, decreasing to £1.9 billion in 2050.

Figures 17-19 set out the trajectory of liquid fuel (petrol and diesel), electricity and hydrogen demand to 2050:

Figure 17: liquid fuel demand

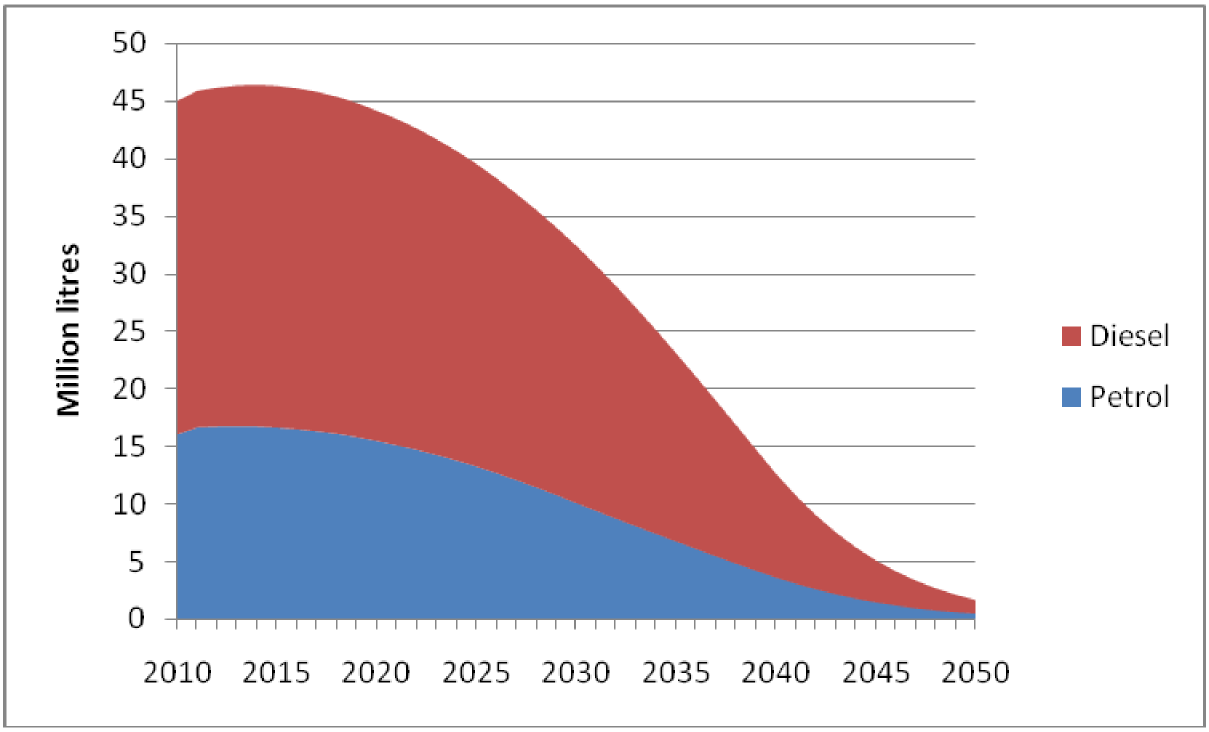


Figure 18: electricity demand

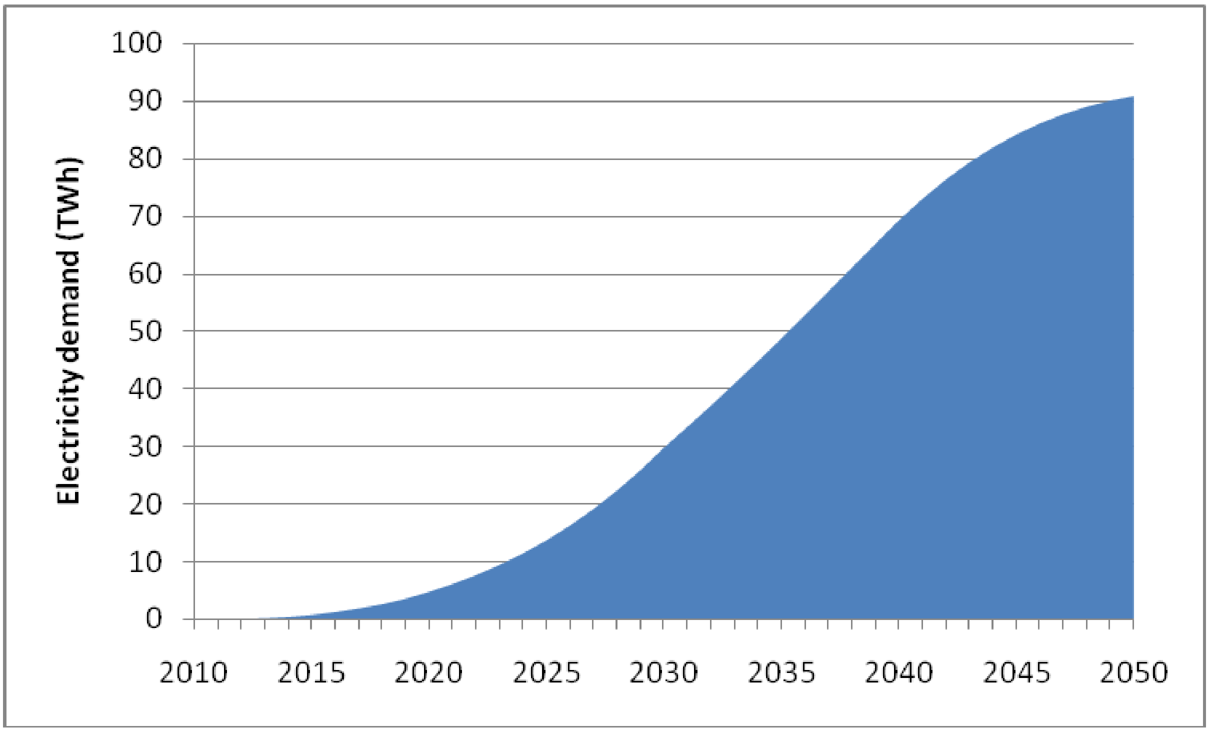
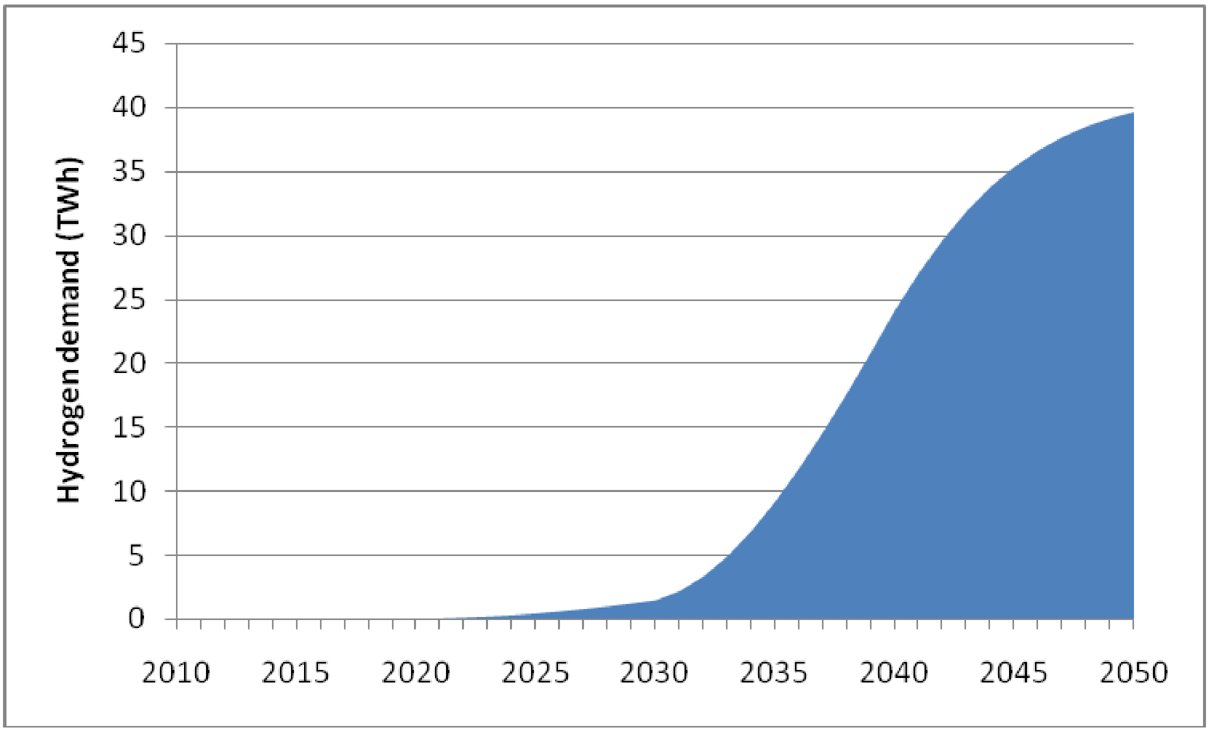


Figure 19: hydrogen demand



As all GHG emissions from road transport are caused by the combustion of petrol and diesel, the trajectory of liquid fuel demand is the same shape as the trajectory of GHG emissions (Figure 14). Total liquid fuel demand in 2010 is 45.0 million litres (16.1 million litres of petrol and 28.9 million litres of diesel). By 2050, total liquid fuel demand is only 1.7 million litres (0.5 million litres of petrol and 1.2 million litres of diesel).

As petrol and diesel demand decreases, electricity and hydrogen demand increase. Electricity demand increases from zero in 2010 to 29.7 TWh in 2030 and 90.8 TWh in 2050. Hydrogen demand increases from zero in 2010 to 1.4 TWh in 2030 and 39.6 in 2050.

Annex 1

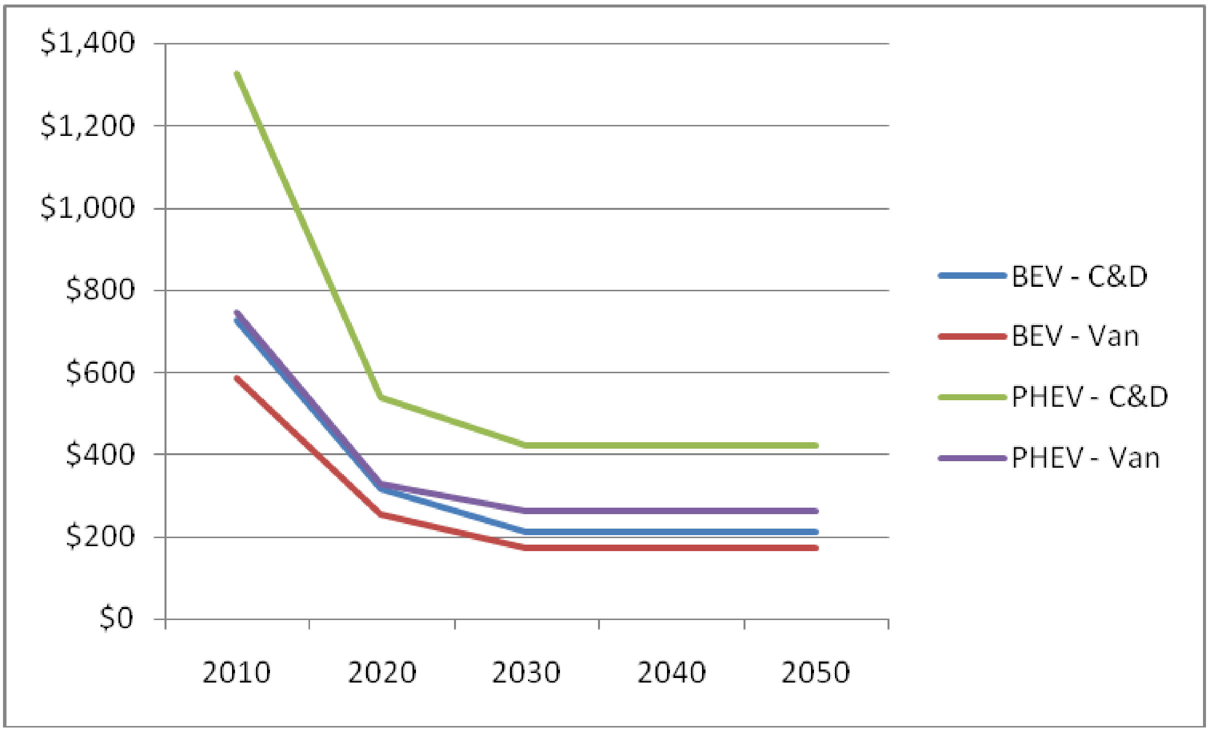
A description of the powertrain technologies considered in this study is set out below:

- **ICE**: Internal combustion engines are used in conventional vehicles powered by petrol, diesel, LPG and CNG.
- **Dual Fuel**: Dual Fuel diesel-natural engines derived from diesel gas internal combustion engines have been recently introduced for heavy-duty vehicle applications. In these engines a small amount of diesel is injected to ensure ignition of the fuel mix, but the majority of the fuel is natural gas mixed with the incoming air. The advantage of this technology is that (a) it uses compression ignition engine technology that is higher in efficiency than spark-ignition engines used in dedicated natural gas vehicles, and (b) if the vehicle runs out of natural gas it can operate entirely on diesel. The diesel substitution rate depends on the integration of the fuel system and the type of vehicle operation, with typical rates varying from 40 to 80% (TSB 2011).
- **FHV**: Flywheel hybrid vehicles. A vehicle powered by a conventional engine where surplus or otherwise wasted (i.e. through braking) mechanical energy can be stored for short periods in a flywheel system for use later to improve overall vehicle efficiency.
- **HHV**: Hydraulic hybrid vehicles. A vehicle powered by a conventional engine where surplus or otherwise wasted energy (i.e. through braking) can be stored in a hydraulic system for use later to improve overall vehicle efficiency.
- **HEV**: Hybrid electric vehicle. A vehicle powered by both a conventional engine and an electric battery, which is charged when the engine is used. Surplus or otherwise wasted energy (i.e. through braking) can be stored for use later to improve overall vehicle efficiency. HEVs can have a very limited electric-only range (as full-hybrids), but run only on electricity produced from the main petrol or diesel fuel.
- **PHEV**: Plug-in hybrid electric vehicles. These vehicles are a combination of HEVs and BEVs. They vehicles operate in a similar way to HEVs, but have a larger battery (smaller than BEVs) and can be plugged in and recharged directly from the electricity grid to allow for electric-only drive for longer distances. These vehicles can be designed with the ICE and electric motor in parallel configurations, or in series (where they are often referred to as REEVs).
- **REEV**: Range extended electric vehicles are a form of PHEV that has the ICE and electric motor operating in series. The ICE essentially acts as a generator and does not provide direct traction to the wheels of the vehicle.
- **BEV**: Battery electric vehicles. A vehicle powered entirely by electrical energy stored (generally) in a battery, recharged from the electricity grid (or other external source).
- **H2 FCV**: Hydrogen fuel cell electric vehicles. A vehicle powered by electrical energy obtained from stored hydrogen which is converted into electricity using a fuel cell.

Annex 2

The cost premium of an electric vehicle relative to a conventional ICE vehicle is due to the high cost of the battery pack. Significant reductions in battery costs are therefore required before electric vehicles can become cost-effective. Figure A2 sets out Element Energy's (2012) assumptions on battery costs for battery electric and plug-in hybrid electric cars and vans:

Figure A2: battery cost forecasts



Element Energy (2012) forecast that battery pack costs for battery electric cars could decrease from over $700/kWh today to just over $300/kWh by 2020, and further to just over $200/kWh by 2030, given sufficient R&D to develop greater energy density chemistries (reducing materials costs) and economies of scale in production of battery packs.

Element's analysis found that battery pack costs for plug-in hybrid electric cars are likely to be more expensive per kWh. This is because the smaller PHEV batteries discharge at a higher rate than BEV batteries, and battery chemistries better suited to a higher discharge rate are likely to have lower energy density and higher cost, and more costly cooling systems (liquid cooling rather than air cooling) is required to deal with the greater heat generated by the higher discharge rate and to be accommodated by the smaller space available for the battery pack. Consequently, Element Energy forecast that battery pack costs for plug-in hybrid electric cars would still cost over $500/kWh by 2020, and further to over $400/kWh by 2030.

Element also investigated batteries for battery electric and plug-in hybrid vans, finding that due to their larger capacity, costs were lower than for cars, with a much lower cost premium for PHEVs, as PHEV batteries in vans are of sufficient capacity that their discharge rate does not require alternative battery chemistries and cooling systems.

Element do not forecast further cost decreases beyond 2030.

Annex 3

Results for all road transport modes are set out below:

Fuel consumption in 2010 and 2050 (MJ/km)

Cars	2010	2020	2030	2040	2050
ICE	2.5	1.9	1.6	1.4	1.3
HEV	1.9	1.6	1.4	1.3	1.2
PHEV	1.3	1.1	1.0	1.0	0.9
REEV	1.1	0.9	0.8	0.8	0.8
BEV	0.7	0.6	0.6	0.5	0.5
H2FC	1.1	0.9	0.8	0.8	0.7
H2FC-PHEV	0.9	0.8	0.7	0.7	0.6
H2FC-REEV	0.8	0.7	0.7	0.6	0.6
NG ICE	2.8	2.1	1.7	1.5	1.4

Vans	2010	2020	2030	2040	2050
ICE	2.9	2.5	2.2	2.0	1.8
HEV	2.4	2.2	2.0	1.8	1.6
PHEV	1.9	1.5	1.4	1.4	1.3
REEV	1.4	1.2	1.2	1.1	1.0
BEV	0.7	0.7	0.6	0.6	0.6
H2FC	1.4	1.3	1.1	1.1	1.0
H2FC-PHEV	1.2	1.0	0.9	0.9	0.8
H2FC-REEV	1.0	0.9	0.8	0.8	0.7
NG ICE	3.3	2.7	2.4	2.2	2.0

Small rigid HGVs	2010	2020	2030	2040	2050
ICE	9.4	8.9	8.2	7.7	7.4
FHV	8.0	8.1	7.4	7.0	6.7
HHV	8.5	8.5	7.8	7.3	7.0
HEV	7.6	7.6	7.0	6.6	6.3
BEV	2.9	2.8	2.6	2.5	2.3
H2FC	4.4	4.1	3.8	3.5	3.2
NG ICE	10.8	10.2	9.4	8.8	8.5
DNG ICE	9.4	8.9	8.2	7.7	7.4

Large rigid HGVs	2010	2020	2030	2040	2050
ICE	12.4	11.1	9.3	8.6	8.0
FHV	11.6	10.7	8.9	8.2	7.7
HHV	11.9	10.9	9.0	8.2	7.7
HEV	11.3	10.3	8.5	7.7	7.2
H2FC	5.9	5.1	4.4	3.9	3.5
NG ICE	14.3	12.7	10.7	9.8	9.2

DNG ICE	12.4	11.1	9.3	8.6	8.0

Articulated HGVs	2010	2020	2030	2040	2050
ICE	14.0	11.8	9.4	8.5	7.9
FHV	13.4	11.5	9.2	8.4	7.8
HHV	13.7	11.6	9.3	8.4	7.8
HEV	13.2	11.3	8.9	8.1	7.4
H2FC	6.6	5.6	4.7	4.2	3.8
NG ICE	16.1	13.6	10.8	9.8	9.1
DNG ICE	14.0	11.8	9.4	8.5	7.9

Buses and coaches	2010	2020	2030	2040	2050
ICE	14.0	13.2	11.7	11.2	10.8
FHV	11.3	11.1	9.9	9.4	9.1
HHV	12.0	11.7	10.5	10.0	9.6
HEV	9.9	9.7	8.8	8.5	8.1
H2FC	6.6	6.2	5.7	5.3	4.9
NG ICE	16.1	15.2	13.5	12.9	12.4
DNG ICE	14.0	13.2	11.7	11.2	10.8

Motorcycles	2010	2020	2030	2040	2050
ICE	1.7	1.5	1.3	1.2	1.1
HEV	1.2	1.1	1.0	0.9	0.8
BEV	0.3	0.3	0.3	0.3	0.3
H2FC	0.7	0.7	0.7	0.6	0.6

CO_2 emissions in 2010 and 2050 (gCO_2/km)

Cars	2010	2020	2030	2040	2050
ICE	169.5	129.8	106.9	95.3	87.5
HEV	131.9	108.0	93.5	85.6	78.1
PHEV	66.0	55.6	49.9	46.8	44.3
REEV	39.6	33.4	29.9	28.1	26.6
BEV	0.0	0.0	0.0	0.0	0.0
H2FC	0.0	0.0	0.0	0.0	0.0
H2FC-PHEV	0.0	0.0	0.0	0.0	0.0
H2FC-REEV	0.0	0.0	0.0	0.0	0.0
NG ICE	157.0	117.3	95.8	85.3	78.3

Vans	2010	2020	2030	2040	2050
ICE	192.7	165.1	145.7	130.3	119.5
HEV	161.0	143.5	130.6	119.4	108.8
PHEV	111.1	83.4	78.5	73.9	70.0
REEV	61.2	55.6	52.3	49.2	46.7
BEV	0.0	0.0	0.0	0.0	0.0
H2FC	0.0	0.0	0.0	0.0	0.0
H2FC-PHEV	0.0	0.0	0.0	0.0	0.0
H2FC-REEV	0.0	0.0	0.0	0.0	0.0
NG ICE	189.0	154.8	137.0	121.8	111.2

Small rigid HGVs	2010	2020	2030	2040	2050
ICE	622.7	588.3	542.1	508.5	488.9
FHV	533.5	535.7	493.5	462.8	444.8
HHV	564.9	567.2	518.7	482.1	463.5
HEV	502.1	505.1	465.4	440.7	420.4
BEV	0.0	0.0	0.0	0.0	0.0
H2FC	0.0	0.0	0.0	0.0	0.0
NG ICE	610.7	577.0	531.7	498.8	479.6
DNG ICE	531.1	501.7	462.3	433.7	417.0

Large rigid HGVs	2010	2020	2030	2040	2050
Diesel ICE	823.5	735.5	615.4	567.7	533.5
Diesel FHV	769.5	708.2	592.5	546.4	513.4
Diesel HHV	790.3	722.0	599.6	543.1	510.4
Diesel HEV	748.7	680.5	563.4	510.4	476.1
H2FC	0.0	0.0	0.0	0.0	0.0
NG ICE	807.6	721.4	603.6	556.8	523.3
DNG ICE	702.3	627.3	524.9	484.2	455.0

Articulated HGVs	2010	2020	2030	2040	2050
Diesel ICE	928.4	784.9	624.3	565.0	525.0
Diesel FHV	891.9	763.3	613.2	559.0	520.7
Diesel HHV	907.6	771.0	614.8	555.5	517.5
Diesel HEV	873.1	748.2	593.0	534.6	491.2
H2FC	0.0	0.0	0.0	0.0	0.0
NG ICE	910.6	769.8	612.3	554.1	515.0
DNG ICE	791.8	669.4	532.5	481.8	447.8

Buses and coaches	2010	2020	2030	2040	2050
Diesel ICE	929.0	875.7	779.0	744.8	716.4
Diesel FHV	750.8	733.7	655.2	626.3	602.2
Diesel HHV	797.8	779.6	696.1	665.4	639.8
Diesel HEV	657.0	646.3	587.4	563.3	537.5
H2FC	0.0	0.0	0.0	0.0	0.0
NG ICE	911.1	858.9	764.0	730.5	702.6
DNG ICE	792.3	746.8	664.4	635.2	611.0

Motorcycles	2010	2020	2030	2040	2050
Petrol ICE	110.0	98.8	87.1	77.7	70.8
Petrol HEV	82.5	73.8	65.9	59.7	53.9
BEV	0.0	0.0	0.0	0.0	0.0
H2FC	0.0	0.0	0.0	0.0	0.0

Capital costs

Cars	2010	2020	2030	2040	2050
ICE	£14,334	£15,630	£16,138	£16,493	£16,697
HEV	£17,399	£16,751	£16,474	£16,530	£16,548
PHEV	£23,315	£19,103	£17,931	£17,822	£17,689
REEV	£31,139	£21,661	£19,174	£18,897	£18,611
BEV	£36,239	£22,595	£18,228	£17,768	£17,359
H2FC	£109,423	£43,260	£22,744	£20,311	£19,695
H2FC-PHEV	£72,935	£32,592	£20,444	£19,029	£18,543
H2FC-REEV	£79,866	£35,149	£22,048	£20,464	£19,824
NG ICE	£15,291	£16,100	£16,425	£16,676	£16,815

Vans	2010	2020	2030	2040	2050
ICE	£12,068	£13,323	£13,797	£14,372	£14,654
HEV	£14,581	£14,391	£14,198	£14,457	£14,555
PHEV	£17,949	£15,887	£15,097	£15,192	£15,171
REEV	£22,530	£17,435	£15,814	£15,798	£15,675
BEV	£30,267	£20,700	£17,391	£17,736	£17,913
H2FC	£89,397	£35,742	£19,134	£17,308	£16,837
H2FC-PHEV	£93,147	£37,447	£20,303	£18,382	£17,825
H2FC-REEV	£63,892	£28,829	£18,301	£17,171	£16,717
NG ICE	£13,192	£13,866	£14,158	£14,576	£14,760

Small rigid HGVs	2010	2020	2030	2040	2050
ICE	£29,320	£35,280	£37,513	£39,512	£40,825
FHV	£35,669	£39,885	£40,571	£41,802	£42,615
HHV	£36,210	£38,227	£39,611	£41,360	£42,263
HEV	£37,168	£38,999	£39,224	£39,800	£40,410
BEV	£98,259	£64,496	£52,635	£53,479	£53,742
H2FC	£186,706	£79,995	£46,056	£41,852	£40,362
NG ICE	£44,276	£43,586	£43,889	£44,854	£45,527
DNG ICE	£46,317	£45,452	£45,806	£46,761	£47,425

Large rigid HGVs	2010	2020	2030	2040	2050
ICE	£48,009	£57,940	£61,688	£64,093	£66,165
FHV	£55,112	£63,356	£65,067	£66,476	£67,899
HHV	£53,843	£60,436	£63,221	£65,809	£67,413
HEV	£60,549	£64,512	£65,144	£66,174	£67,091
H2FC	£292,694	£126,916	£74,284	£67,392	£64,871
NG ICE	£65,490	£66,913	£67,684	£68,764	£69,967
DNG ICE	£68,809	£70,107	£71,032	£72,100	£73,297

Articulated HGVs	2010	2020	2030	2040	2050
ICE	£61,438	£76,189	£80,128	£83,202	£85,112
FHV	£71,519	£82,868	£84,239	£86,067	£87,170
HHV	£72,430	£80,648	£82,993	£85,564	£86,820
HEV	£78,559	£83,540	£84,064	£85,285	£86,269
H2FC	£411,104	£172,513	£97,714	£87,876	£84,520
NG ICE	£85,180	£88,359	£87,849	£89,168	£89,945
DNG ICE	£90,126	£92,868	£92,649	£93,966	£94,743

Buses	2010	2020	2030	2040	2050
ICE	£104,586	£113,077	£117,300	£120,015	£123,114
FHV	£112,782	£119,844	£122,020	£123,718	£126,156
HHV	£113,443	£117,650	£120,310	£122,264	£124,868
HEV	£116,351	£119,377	£120,266	£121,243	£123,308
H2FC	£277,341	£162,518	£127,210	£123,205	£122,720
NG ICE	£116,406	£119,895	£122,414	£124,456	£127,082
DNG ICE	£118,746	£121,981	£124,552	£126,554	£129,161

Motorcycles	2010	2020	2030	2040	2050
ICE	£6,211	£6,499	£6,681	£6,887	£6,983
HEV	£7,682	£7,020	£6,794	£6,820	£6,869
BEV	£10,012	£7,991	£7,109	£7,326	£7,541
H2FC	£63,977	£23,696	£11,067	£9,586	£9,288

Lifetime costs

Cars	2010	2020	2030	2040	2050
ICE	£18,702	£20,090	£20,118	£20,042	£19,956
HEV	£20,792	£20,460	£19,953	£19,717	£19,455
PHEV	£25,391	£21,357	£20,103	£20,197	£19,935
REEV	£32,688	£23,289	£20,730	£20,828	£20,437
BEV	£36,998	£23,282	£18,858	£19,034	£18,556
H2FC	£112,069	£45,577	£24,801	£22,209	£21,439
H2FC-PHEV	£74,637	£34,094	£21,788	£20,611	£20,013
H2FC-REEV	£81,191	£36,326	£23,107	£21,919	£21,185
NG ICE	£18,599	£20,052	£19,861	£19,734	£19,624

Vans	2010	2020	2030	2040	2050
ICE	£20,240	£22,103	£22,197	£21,883	£21,542
HEV	£21,409	£22,022	£21,729	£21,340	£20,829
PHEV	£23,028	£20,797	£20,065	£20,344	£20,051
REEV	£25,862	£21,074	£19,470	£19,924	£19,584
BEV	£31,455	£21,798	£18,424	£19,812	£19,880
H2FC	£94,660	£40,441	£23,418	£21,265	£20,479
H2FC-PHEV	£97,147	£40,597	£23,188	£21,530	£20,746
H2FC-REEV	£66,629	£31,295	£20,569	£19,962	£19,320
NG ICE	£19,268	£21,822	£21,653	£21,238	£20,846

Small rigid HGVs	2010	2020	2030	2040	2050
ICE	£90,611	£107,902	£110,050	£107,558	£106,249
FHV	£88,181	£106,019	£106,606	£103,729	£102,138
HHV	£91,811	£108,252	£109,017	£105,874	£104,278
HEV	£86,591	£101,354	£101,495	£98,764	£96,664
BEV	£109,361	£75,255	£62,798	£73,727	£72,912
H2FC	£225,241	£116,102	£79,093	£72,103	£68,193
NG ICE	£89,841	£112,434	£111,406	£108,191	£106,424
DNG ICE	£85,939	£105,319	£104,517	£101,837	£100,379

Large rigid HGVs	2010	2020	2030	2040	2050
ICE	£130,866	£150,755	£145,874	£141,747	£139,142
FHV	£132,545	£152,729	£146,119	£141,225	£138,134
HHV	£133,369	£151,548	£145,240	£140,107	£137,234
HEV	£135,888	£150,384	£142,215	£135,991	£132,222
H2FC	£345,062	£172,681	£113,338	£101,743	£96,143
NG ICE	£127,087	£154,903	£146,043	£141,044	£137,894
DNG ICE	£122,372	£146,620	£139,171	£134,951	£132,364

Articulated HGVs	2010	2020	2030	2040	2050
ICE	£216,922	£241,042	£222,266	£211,824	£204,645
FHV	£220,887	£243,197	£223,839	£213,330	£205,720
HHV	£224,419	£242,586	£222,954	£212,025	£204,633
HEV	£224,782	£240,699	£219,062	£206,999	£198,095
H2FC	£509,576	£255,886	£167,412	£149,893	£140,405
NG ICE	£179,507	£168,101	£151,278	£146,567	£143,287
DNG ICE	£172,149	£162,209	£147,806	£143,878	£141,128

Buses	2010	2020	2030	2040	2050
ICE	£166,783	£186,608	£188,202	£187,806	£188,317
FHV	£163,053	£181,455	£181,656	£180,721	£180,968
HHV	£166,856	£183,112	£183,673	£182,829	£183,105
HEV	£160,339	£173,651	£173,732	£172,511	£172,231
H2FC	£316,653	£199,244	£160,954	£154,459	£151,599
NG ICE	£162,644	£189,604	£188,410	£187,555	£187,772
DNG ICE	£158,952	£182,598	£181,939	£181,423	£181,936

Motorcycles	2010	2020	2030	2040	2050
ICE	£6,750	£7,107	£7,262	£7,405	£7,455
HEV	£8,087	£7,474	£7,233	£7,218	£7,228
BEV	£10,076	£8,055	£7,170	£7,452	£7,663
H2FC	£64,295	£23,997	£11,350	£9,853	£9,541

Social costs

Cars	2010	2010	2010	2010	2010
ICE	£20,443	£21,462	£21,927	£22,623	£23,219
HEV	£22,146	£21,601	£21,535	£22,036	£22,367
PHEV	£26,561	£22,243	£21,000	£21,504	£21,586
REEV	£33,784	£24,059	£21,311	£21,645	£21,429
BEV	£37,984	£23,878	£18,964	£19,115	£18,559
H2FC	£112,165	£45,643	£24,868	£22,265	£21,457
H2FC-PHEV	£75,178	£34,425	£21,874	£20,680	£20,024
H2FC-REEV	£81,910	£36,763	£23,201	£21,993	£21,193
NG ICE	£20,211	£21,292	£21,483	£22,043	£22,544

Vans	2010	2010	2010	2010	2010
ICE	£23,212	£24,724	£25,902	£27,183	£28,233
HEV	£23,892	£24,301	£25,051	£26,197	£26,923
PHEV	£25,212	£22,524	£22,132	£23,405	£23,973
REEV	£27,747	£22,537	£20,906	£22,009	£22,199
BEV	£32,975	£22,734	£18,594	£19,944	£19,884
H2FC	£94,848	£40,574	£23,554	£21,380	£20,515
H2FC-PHEV	£97,748	£41,075	£23,339	£21,652	£20,769
H2FC-REEV	£67,642	£31,926	£20,726	£20,087	£19,337
NG ICE	£22,183	£24,279	£25,136	£26,191	£27,076

Small rigid HGVs	2010	2010	2010	2010	2010
ICE	£112,759	£129,446	£141,833	£155,258	£169,394
FHV	£107,156	£125,639	£135,540	£147,140	£159,588
HHV	£111,901	£129,025	£139,427	£151,098	£164,131
HEV	£104,450	£119,853	£128,779	£140,098	£150,958
BEV	£123,457	£84,369	£64,464	£75,001	£72,954
H2FC	£226,609	£117,117	£80,135	£72,976	£68,471
NG ICE	£111,563	£133,564	£142,579	£154,976	£168,357
DNG ICE	£104,828	£123,693	£131,623	£142,519	£154,233

Large rigid HGVs	2010	2010	2010	2010	2010
ICE	£160,414	£177,929	£182,278	£195,469	£208,654
FHV	£160,158	£178,897	£181,167	£192,937	£205,034
HHV	£161,728	£178,224	£180,707	£191,507	£203,739
HEV	£162,755	£175,526	£175,543	£184,293	£194,261
H2FC	£346,897	£173,951	£114,554	£102,721	£96,450
NG ICE	£156,067	£181,556	£181,749	£193,735	£206,072
DNG ICE	£147,572	£169,796	£170,219	£180,770	£191,649

Articulated HGVs	2010	2010	2010	2010	2010
ICE	£269,464	£286,779	£280,510	£296,145	£312,537
FHV	£271,363	£287,679	£281,042	£296,760	£312,725
HHV	£275,780	£287,515	£280,305	£294,929	£310,972
HEV	£274,195	£284,301	£274,379	£286,791	£299,030
H2FC	£512,846	£258,080	£169,468	£151,566	£140,926
NG ICE	£231,040	£212,960	£208,404	£229,269	£249,108
DNG ICE	£216,961	£201,217	£197,480	£215,793	£233,146

Buses	2010	2010	2010	2010	2010
ICE	£190,043	£209,185	£220,355	£236,989	£253,448
FHV	£181,853	£200,372	£208,700	£222,078	£235,720
HHV	£186,831	£203,212	£212,407	£226,770	£241,279
HEV	£176,789	£190,315	£197,978	£209,706	£221,102
H2FC	£318,097	£200,313	£162,055	£155,392	£151,897
NG ICE	£185,458	£211,748	£219,946	£235,794	£251,653
DNG ICE	£178,790	£201,853	£209,362	£223,370	£237,484

Motorcycles	2010	2010	2010	2010	2010
ICE	£6,928	£7,272	£7,495	£7,738	£7,872
HEV	£8,221	£7,598	£7,409	£7,473	£7,546
BEV	£10,151	£8,103	£7,179	£7,459	£7,664
H2FC	£64,306	£24,005	£11,358	£9,860	£9,543