AEA

A review of the efficiency and cost assumptions for road transport vehicles to 2050

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Executive Summary

Introduction

The Committee on Climate Change (CCC) has a number of priorities, including a key priority of providing advice, analysis and information to Government and the Devolved Administrations on the setting of carbon budgets. The CCC utilises a range of analytical tools for informing and developing its recommendations on the UK's carbon budgets, including sectoral or economy wide models with a strong emphasis on reducing GHG emissions as cost-effectively as possible.

The CCC has identified a need to carry out a thorough review and update of its current assumptions on the fuel efficiency and capital costs of road vehicle technologies to inform its understanding of the potential future development of their performance and costs in the period 2010-2050.

The CCC therefore commissioned this project, with the following main aims and objectives:

i. Carry out a review of the literature on the fuel efficiency and capital costs associated with road transport technologies to 2050;

ii. Using information from the literature review, develop assumptions for fuel efficiency and capital costs for each technology to 2050;

iii. Based on these findings advise the CCC on the validity of their default assumption that there would be no or minimal change to the fuel efficiency and capital costs of the dominant vehicle technologies in the absence of any government policy to reduce GHG emissions.

The aim of the study was to develop a detailed understanding of how the uptake of technological options to improve efficiency/reduce GHG emissions is likely to impact on overall costs and efficiencies of different vehicle classes in the period 2010-2050.

The primary deliverable for this work is the dataset provided to CCC alongside this report detailing the projected costs and vehicle efficiencies developed for the study. The purpose of this report is to provide a summary of the methodological approach and the key sources and assumptions used to define this dataset and a short summary of the results of the analysis.

Development of the Road Vehicle Cost and Efficiency Dataset

The initial phase of the work included establishing a categorisation framework within which to carry out a literature review of the performance and cost characteristics of road transport vehicles to 2050, before developing the future trajectory of these characteristics to 2050. The categorisation agreed with CCC included 9 mode categories (cars, vans, motorcycles, small rigid trucks, large rigid trucks, articulated trucks, construction trucks, buses and coaches) and an additional split by core powertrain technology (including 13 categories for cars/vans, 8 for heavy duty vehicles and 4 for motorcycles/mopeds).

As part of the project's analysis phase an Excel-based calculation framework was developed to facilitate consistent repeatable calculations across all modes and allow selected key parameter assumptions to be easily changed, such as the vehicle characteristics, technology performance, costs and deployment levels and potential learning rates for cost trajectories.

One of the principal objectives of the work was also to help CCC gain a better understanding of how the improvements in efficiency and resulting capital costs break down into different impact areas and components. The information collected and the subsequent disaggregation of cost and efficiency calculations were carried out under the following agreed categories:

- Core Powertrain
- Energy Storage
- Glider
- Powertrain Efficiency Technologies
- Aerodynamics
- Rolling Resistance
- Vehicle Weight
- Other Options

The methodological approach developed also included an estimation of the real-world fuel efficiency of the final vehicle, using a percentage uplift factor on the test-cycle based fuel efficiency figure. This was included in an attempt to factor in a range of considerations that affect the performance of vehicles in the real-world versus the specific conditions used in the calculation of fuel consumption using regulatory (or other) test-cycles.

Full details on the methodology developed and implemented in the calculation framework and on the key data sources and assumptions used in the calculations are provided in the main body of this report.

Summary of Key Results from the Analysis

Key results from the developed calculation framework analysis are summarised below:

⇒ *For passenger cars and vans:*

- Conventional powertrains have the greatest potential for % improvements in fuel efficiency in the long term (though being less efficient in absolute terms), versus increasingly electrified powertrain alternatives. The overall potential reduction in energy consumption 2010-2050 ranges from 27%-50% depending on powertrain.
- Capital cost differentials are expected to narrow substantially by 2030, with many alternatives becoming cost-competitive if fuel savings are included (depending on future tax rates for different fuels). Assumptions on electric driving range and battery cost reductions are critical factors. Under low cost assumptions BEV cars become comparable in price to ICEs by 2050, but under high cost assumptions H2FC variants become the more cost-effective ultra-low GHG option.
- The benefits of additional improvements to the ICE appear to be marginal for REEVs after 2020. Also the cost of efficiency improvements to BEVs beyond those to the basic powertrain are extremely high per gCO_2e/km abated. Therefore uptake of these may be more limited than for other powertrains, although the impacts on battery capacity/costs also need to be factored into the equation.

⇒ *For motorcycles* the reduction potential identified for different powertrain technologies is lower than cars and vans (10-36%), but may be due to insufficient information in the literature. BEV and HEV technologies may become cost-competitive with ICE by 2030.

⇒ *For heavy duty vehicles in predominantly urban cycles (small rigid trucks and buses):*

- Efficiency improvement benefits by 2050 are expected to reach 16-28%. These reductions are predominantly due to powertrain improvements, with lower levels of benefit from rolling resistance and lightweighting. The greatest benefits are therefore achieved through switching from conventional ICE to more efficient alternative powertrains.
- Purely in terms of capital costs, H2FC technology is the lowest cost ultra-low GHG option for the long-term, however the comparison with BEV changes if fuel costs are included. Factoring in likely future fuel costs brings most technologies to overall cost levels comparable with or lower than Diesel ICE by 2030 (depending on future fuel tax levels).

⇒ *For heavy duty vehicles with the greatest proportions of their km outside of urban areas (large rigid, articulated and construction trucks, coaches):*

- Efficiency improvement benefits by 2050 are expected to reach 23-43% (depending on type/powertrain). These reductions are mostly due to improvements in the powertrain and aerodynamics (except construction trucks), with lower levels of benefit from rolling resistance, lightweighting and other technologies.

- Capital costs of alternative powertrains drop to within 6-14% of Diesel ICE by 2050 (depending on vehicle type/powertrain). Factoring in likely future fuel costs brings most technologies to combined cost levels comparable with or lower than Diesel ICE by 2030 and essentially all by 2050 (depending on future fuel tax levels).
- DNG ICE powertrains appear to offer a cost effective alternative (under current tax levels) versus alternatives with substantial lifecycle GHG savings in the short-medium term, which could be further improved through the use of biomethane. In the long term H2FC offer greater GHG savings at similar capital costs.

Assessment of CCC's Default Trajectory

The purpose of Task 4 was to: *"advise on the validity of the CCC's default assumption that in the absence of any government policy to reduce GHG emissions (including existing new vehicle CO_2 regulations), there would be no or minimal change to the fuel efficiency and capital costs of the dominant vehicle technologies within each vehicle category."*

The following provides a summary of the main findings of this assessment:

⇒ For passenger cars there is not sufficiently strong evidence to suggest that the assumption of a flat counterfactual is incorrect and that the CCC should therefore continue to use this assumption in its modelling work.

⇒ For van/light commercial vehicle efficiency there is some evidence to suggest that the assumption of a flat counterfactual is not valid for vans and it may be more appropriate for CCC to revise this assumption in its modelling work to reflect a gradual rate of annual improvement in van efficiency.

⇒ For heavy duty truck efficiency there is good evidence to suggest that the assumption of a flat counterfactual is incorrect for specific sizes of heavy trucks. However, the general trend of increasing vehicle sizing (presumably in a drive to increase operational efficiency on a tonne-km basis) means that the fleet as a whole has a trend to increasing MPG. CCC may therefore wish revise these elements into its modelling work to reflect annual increases in heavy truck efficiency, but factoring in changes in relative vehicle sizing affecting actual energy consumption per km.

⇒ For buses and coaches there some evidence to suggest that the assumption of a flat counterfactual for bus and coach efficiency is incorrect and that the CCC should therefore consider revising this assumption in its modelling work.

⇒ For the capital costs of vans, trucks, busses and coaches, there is not sufficiently strong evidence to suggest that the assumption of a flat counterfactual is incorrect and that the CCC should therefore continue to use this assumption in its modelling work for the capital costs of other vehicles.

⇒ For motorcycles and mopeds, no evidence has been identified to suggest a change in the current assumption.

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Glossary of terms and abbreviations[1]

BAU	Business as usual, i.e. the projected baseline of a trend assuming that there are no interventions to influence the trend.
BEV	Battery electric vehicle, also referred to as a pure electric vehicle, or simply a pure **EV**.
CNG	Compressed Natural Gas. **Natural gas** can be compressed for use as a transport fuel (typically at 200bar pressure).
CO_2	Carbon dioxide, the principal **GHG** emitted by transport.
CO_2e	Carbon dioxide equivalent. There are a range of **GHGs** whose relative strength is compared in terms of their equivalent impact to one tonne of **CO_2**. When the total of a range of **GHGs** is presented, this is done in terms of CO_2 equivalent or CO_2e.
Diesel	The most common fossil fuel, which is used in various forms in a range of transport vehicles, e.g. heavy duty road vehicles, inland waterway and maritime vessels, as well as some trains.
DOH	Degree of hybridisation. This is usually defined as the percentage of the total vehicle peak power provided by the electric motor.
EV	Electric vehicle. A vehicle powered solely by electricity stored in on-board batteries, which are charged from the electricity grid.
FCEV	Fuel cell electric vehicle. A vehicle powered by a fuel cell, which uses hydrogen as an energy carrier.
GHGs	Greenhouse gases. Pollutant emissions from transport and other sources, which contribute to the greenhouse gas effect and climate change. GHG emissions from transport are largely **CO_2**.
HDV	Heavy duty vehicles – includes heavy trucks, buses and coaches
HEV	Hybrid electric vehicle. A vehicle powered by both a conventional engine and an electric battery, which is charged when the engine is used.
ICE	Internal combustion engine, as used in conventional vehicles powered by petrol, diesel, **LPG** and **CNG**.
IEA	International Energy Agency
LDV	Light duty vehicles – includes cars and vans
LED	Light-emitting diode
Lifecycle emissions	In relation to fuels, these are the total emissions generated in all of the various stages of the lifecycle of the fuel, including extraction, production, distribution and combustion. Also known as **WTW emissions** when limited specifically to the energy carrier/fuel.
LNG	Liquefied Natural Gas. **Natural gas** can be liquefied for use as a transport fuel.
LPG	Liquefied Petroleum Gas. A gaseous fuel, which is used in liquefied form as a transport fuel.
MAC	Mobile air conditioning
MACC	Marginal Abatement Cost Curve
MPG	Miles per gallon
$MtCO_2e$	Million tonnes of **CO_2e**.

[1] Terms highlighted in bold have a separate entry.

NAEI	National Atmospheric Emissions Inventory. This is the UK inventory of air quality pollutants (AQP) and greenhouse gasses (**GHGI**).
Natural gas	A gaseous fossil fuel, largely consisting of methane, which is used at low levels as a transport fuel in the EU.
NEDC	New European Driving Cycle
NGOs	Non-government organisations
NGV	Natural Gas Vehicle. Vehicles using natural gas as a fuel, including in its compressed (**CNG**) and liquefied (**LNG**) forms.
OECD	Organisation for Economic Co-operation and Development
Petrol	Also known as gasoline and motor spirit. The principal fossil fuel used in light duty transport vehicles, such as cars and vans.
PHEV	Plug-in hybrid electric vehicle. Vehicles that are powered by both a conventional engine and electric motor plus battery, which can be charged from the electricity grid. The battery is larger than that in an **HEV**, but smaller than that in an **EV**. Typically the form of this vehicle where the electric motor and **ICE** work in series is also known as range extended electric vehicle (**REEV**)
PTWs	Powered two-wheelers
REEV	Range extended electric vehicle. This is a specific type of **PHEV** that operates with the electric motor and **ICE** work in series, with the **ICE** essentially operating like a generator to top-up the battery.
SOC	State of charge for a battery – i.e. how full it is versus total capacity.
SUV	Sport utility vehicle
TTW emissions	Tank to wheel emissions, also referred to as direct or tailpipe emissions. The emissions generated from the use of the fuel in the vehicle, i.e. in its combustion stage.
VVA	Variable valve actuation, also known as variable valve timing (VVT)
VVTL	Variable valve timing and lift
WTT emissions	Well to tank emissions, also referred to as fuel cycle emissions. The total emissions generated in the various stages of the lifecycle of the fuel prior to combustion, i.e. from extraction, production and distribution.
WTW emissions	Well to wheel emissions. Also known as **lifecycle emissions** when limited specifically to the energy carrier/fuel.

1 Introduction

1.1 Background

The Committee on Climate Change (CCC) has a number of priorities, including a key priority of providing advice, analysis and information to Government and the Devolved Administrations on the setting of carbon budgets.

The CCC utilises a range of analytical tools for informing and developing its recommendations on the UK's carbon budgets, including sectoral or economy wide models with a strong emphasis on reducing GHG emissions as cost-effectively as possible. As part of its advice for the Fourth Carbon Budget Report (2023-2027), the CCC's central scenarios were designed to be consistent with the objective of delivering car, van and HGV fleets that are almost entirely decarbonised by 2050. According to other CCC analysis it is envisaged that this level of reduction will be necessary in order to achieve overall transport GHG reduction objectives since there are fewer options/lower potential for reductions in aviation and shipping.

As part of its forthcoming 2012 work plan, CCC need to carry out further detailed analysis that will assess the emissions trajectory and economic costs of transport technology deployment in the longer term for the period from 2030-2050. In order to do this the CCC needs to extend its assumptions on the fuel efficiency and capital costs of all relevant vehicle technologies through to 2050. In addition, there is also a need to review CCC's current assumptions for the period 2010-2030 as part of the 2014 review of the Fourth Carbon Budget. There have been a number of significant new studies in the period since these assumptions were last developed and updated and a range of estimates available now in the literature for different vehicle technologies.

The CCC has therefore identified a need to carry out a thorough review and update of its current assumptions to inform its understanding of the potential future development of road vehicle technology performance and costs.

1.2 Aims and Objectives

In order to review and update its current assumptions for road transport vehicles, CCC commissioned this project, with the following main aims and objectives:

iv. Carry out a review of the literature on the fuel efficiency and capital costs associated with road transport technologies to 2050;

v. Using information from the literature review, develop assumptions for fuel efficiency and capital costs for each technology to 2050;

vi. Based on these findings advise the CCC on the validity of their default assumption that there would be no or minimal change to the fuel efficiency and capital costs of the dominant vehicle technologies in the absence of any government policy to reduce GHG emissions.

Supplied with the evidence from this project the CCC will be able to take a more informed, forward looking view of the technically possible, economically viable and realistic deployment of road transport technologies under different scenarios to 2050. Consequently, the CCC will be in a better position to advise government on:

- Strategy to support the decarbonisation of the road transport sector;
- The potential impacts of this on future carbon budgets.

1.3 Scope of the Work

The focus of the study was on road transport technologies, with the aim to develop a detailed understanding of how the uptake of technological options to improve efficiency/reduce GHG emissions is likely to impact on overall costs and efficiencies of different vehicle classes in the period 2010-2050.

The primary deliverable for this work is the dataset provided to CCC alongside this report detailing the projected costs and vehicle efficiencies developed for the study. The purpose of this report is to provide a summary of the methodological approach and the key sources and assumptions used to define this dataset and a short summary of the results of the analysis.

1.4 Structure of the Report

This report is structured so that the main methodology and input assumptions are described in the main body of the report, with the full details of assumptions and references provided in the appendices. The main body of the report contains the following sections:

2 *Methodology, Vehicle and Technology Definitions*	This chapter provides a summary of the general methodological approach, the vehicle classes and powertrains combinations assessed and a summary of the sub-technologies included in the calculations.
3 *Efficiency Assumptions*	This chapter provides a detailed review of the calculation methodology, key data sources and assumptions used for the assessment of vehicle efficiency improvements.
4 *Capital Cost Assumptions*	This chapter provides a detailed review of the calculation methodologies, key data sources and assumptions used for the assessment of the costs associated vehicle efficiency improvements.
5 *Technology Compatibility and Deployment Assumptions*	This chapter provides a summary of the assumptions used in the calculations with regards to possibilities for combination / stacking of different technological options, and the assumptions on the rates of deployment of the different technologies used in the calculations.
6 *Results: Cost and Efficiency Trajectories from 2010 to 2050*	This chapter provides a summary review of the key results of the cost and efficiency calculations – the resulting trajectories in efficiency and costs for different vehicle classes and powertrains from 2010 to 2050.
7 *Evaluation of CCC's Default Trajectory Assumptions*	This chapter provides an assessment of the validity of CCC's default assumption that there would be no or minimal change to the fuel efficiency and capital costs of the dominant vehicle technologies in the absence of any government policy to reduce GHG emissions.
8 *References*	This chapter provides a full list of the references included in this report, as well as all other principal literature sources reviewed as part of the study.

2 Methodology, Vehicle and Technology Definitions

2.1 Vehicle Categorisation

The purpose of first part of the study was to establish the categorisation framework within which to carry out a literature review of the performance and cost characteristics of road transport vehicles to 2050, before developing the future trajectory of these characteristics to 2050. Specifically, the objective was to establish a set of vehicle categories for each major road transport mode, and the powertrain technologies to be considered within each vehicle category. These needed to be sufficiently disaggregated to enable an accurate estimate of the emissions trajectory and economic costs associated with deployment of vehicle technologies, whilst also avoiding unnecessary detail to reduce analytical complexity.

The following categorisation in Table 2.1 was agreed with CCC at the start of the study, with a short summary of the different powertrain technologies also provided in Table 2.2. It was not deemed necessary to include separate variants for flex-fuel (i.e. E85) variants of petrol vehicles, since these would be expected to be essentially identical in performance and incur minimal additional capital cost (in the order of £100-200) according to industry sources. Advanced biodiesel fuels (e.g. from biomass-to-liquid or hydrotreated oil processes) are also not anticipated to have compatibility issues with conventional diesel technology, negating the necessity of including specific vehicle variants for these fuels.

Table 2.1: Road vehicle categorisation utilised in the study assessment

<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) *
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>

Notes:

* BEVs are only assessed/deemed appropriate for small rigid trucks (often used for urban delivery) and buses.

** DfT statistics on heavy duty vehicle are not fully consistent on the size categorisation used for different statistical datasets. For example, fuel consumption statistics included ranges 'Over 7.5t to 14t' and 'Over 14t to 17t', however licensing statistics include ranges 'Over 7.5 tonnes up to 15 tonnes' and 'Over 15 tonnes up to 18 tonnes', and annual vehicle km per vehicle statistics include ranges 'Over 7.5 to 17t' and 'Over 17 to 25t'. For the purposes of this study an approximate cut-off at around 15 t GVW has been utilised wherever possible.
*** For most vehicle classes it is assumed the form of natural gas used by the vehicle is CNG (compressed natural gas), however it is most likely that LNG (liquefied natural gas) would be utilised in long-haul operations, where articulated trucks are typically used.

Table 2.2: Summary descriptions of road transport vehicle powertrain technologies

Powertrain technology	Summary description
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.

The categorisation in Table 2.1 was developed in an attempt to strike the best balance between complexity, analytical needs and possible differences between different categories of vehicle within a particular transport mode and the available time and study resources.

For passenger cars, vans, and motorbikes and mopeds only a single vehicle category for each of these vehicle types was utilised. This is consistent with the approach taken for long-term energy modelling often used in overall economy-wide analysis. Also, if it were desirable in the future to split these categories further into for example different size categories for cars and vans (e.g. to facilitate modelling of downsizing in cars, or a shift to larger vans) this could be achieved relatively simply by CCC outside of the project by scaling the output to key size parameters. This is because the technologies utilised for different sized light-duty vehicles are essentially the same and differences in the relative performance and costs of different technology components for different vehicle sizes are relatively minor.

However, the same cannot be said for heavy duty vehicles (heavy trucks, buses and coaches), which are much more diverse in their relative sizes, technical specifications and typical usage patterns. As a result, the technologies likely to be employed, their effectiveness and their costs will vary significantly between different categories. For example, in smaller trucks used typically in urban delivery cycles, vehicle light-weighting and hybrid powertrains will have a greater impact due to significant stop-start activity and speed fluctuations, compared to heavier trucks used for regional delivery or long haul operations. Conversely the application of aerodynamic improvements has little effect on vehicles predominantly used at lower urban speeds, but can achieve significant benefits for vehicles travelling at high speeds on major roads and motorways for a significant proportion of their activity. For heavy trucks the vehicle purpose and body type also can have a significant effect on the application of measures.

For example trucks used in freight operations with relatively uniform shaped configurations (i.e. box, curtain sided and refrigerated body types) can to utilise aerodynamic measures on their bodies or trailers that could significantly reduce their fuel consumption. However, trucks with more irregular or unpredictable body shapes due to their purpose (e.g. concrete mixers, tankers, vehicle carriers) or load (e.g. tipper trucks, flat bed trailers) have fewer options/lower potential here. These significant differences in operational profiles and technical characteristics mean that it would not be appropriate to characterise trucks using a single vehicle category. In contrast to cars and vans, it would not be possible to apply simple scaling factors to the data for a single truck category at a later date (i.e. after the study work was completed) should it be necessary characterise the costs and performance of different types of trucks. For these reasons, it was deemed more robust to include up-front a variety of truck types in the list of vehicle categories that were covered. Hence, heavy duty trucks were split into four different categories, as set out in Table 2.1. For the same reasons, we propose to characterise buses and coaches as two separate vehicles categories rather than as a combined, single bus/coach category.

Some vocational vehicles have significantly different restrictions on the technologies that can be applied and/or their effectiveness (and also different activity profiles for modelling). Construction vehicle body types (tipper, concrete mixer and skip-loader) are the most significant category account for over 20% of rigid vehicles according to DfT statistics (and tipper truck semi-trailers for articulated vehicles account for around 8% of all semi-trailers according to trailer statistics from CLEAR, 2010). Hence, it was decided to include a specific category for construction vehicles.

In terms of the weight categorisation used to define different sizes of rigid trucks – this was informed by DfT statistical definitions. DfT statistics on heavy duty vehicle are not fully consistent on the size categorisation used for different statistical datasets. Some datasets include ranges up to 14t or 15t GVW and then ranges above this (e.g. vehicle numbers from licensing statistics and fuel consumption statistics), and others include ranges up to 17t or 18t GVW and then ranges above this (e.g. fuel consumption and activity/annual km per vehicle statistics). For the purposes of this study an approximate cut-off at 15 t GVW has been used and data scaled accordingly.

Heavy duty truck PHEVs were excluded from the powertrain category as the battery power is used primarily to power auxiliary equipment or keep the vehicle's cab at a comfortable temperature at a job site, rather than for providing motive power. This option was instead assessed as a separate add-on technology (see Section 2.4).

2.2 Methodological Overview

The central aim of the project was to review the literature on the fuel efficiency and capital costs associated with road transport technologies to 2050, and to develop assumptions for fuel efficiency and capital costs for each technology to 2050. One of the principal objectives of the work was also to help CCC gain a better understanding of how the improvements in efficiency and resulting capital costs break down into different impact areas (e.g. engine efficiency improvements, improved aerodynamics, reduced weight, etc) and components (body and chassis, powertrain components). CCC also would like to better understand to what degree the overall efficiency of PHEVs (and related REEVs) were affected due to the application of technologies to improve the fuel efficiency of the vehicles would result merely from the addition of the electric powertrain, and what degree of improvement would result from additional factors affecting the ICE drive only.

The overall methodological approach developed was to categorise different efficiency and cost component technologies into a series of 'Basic Component' and 'Efficiency Improvement' categories, as summarised in Table 2.3, under which individual component technologies would be included. An example is given for the basic components in a fuel cell vehicle in Table 2.4.

Table 2.3: Summary and definition of the categorisation of vehicle components and efficiency improvements in the applied methodology

Area	Component	Definition
Basic components	Powertrain	Includes combustion engines and transmission, electric motors, fuel cells, electric drivetrain components, dual-fuel systems, flywheels or hydraulic hybrid components, etc.
	Energy storage	Includes conventional liquid fuel tanks, gaseous or liquid storage systems for natural gas or hydrogen, electric storage medium (i.e. batteries or capacitors)
	Glider	Vehicle chassis and non-powertrain specific components, excluding energy storage.
Efficiency improvements	Powertrain efficiency	Includes the application of *additional** or *alternative* technical measures aimed at generating improvements to the powertrain systems (e.g. to conventional engine or transmission efficiency)
	Aerodynamics	Technical options that are applied to reduce aerodynamic drag and thereby reduce motive power requirements and improve overall vehicle efficiency.
	Rolling resistance	Technical options that are applied to reduce rolling resistance from tyres/wheels and thereby reduce motive power requirements and improve overall vehicle efficiency.
	Vehicle weight	Technological options that are applied to reduce the overall weight of the vehicle and thereby reduce motive power requirements and improve overall vehicle efficiency.
	Other options	Other technical options not readily applying into the other categories (e.g. improvement in the efficiency of auxiliaries, thermo-electric heat recovery, etc)
Complete vehicle	Real-World Efficiency	% Uplift from test-cycle based efficiency figures to reflect the actual typical in-use efficiency of the vehicle.

Notes: * Does not include general improvements to the core powertrain technology (e.g. general improvements in fuel cell efficiency), which are accounted for in the 'Basic components area'.

Table 2.4: Example – basic components for a hydrogen fuel cell electric vehicle

Area	Component category	Component
Basic components	Powertrain	1. Fuel cell, 2. Electric motor, 3. Other electric powertrain components
	Energy storage	1. Hydrogen storage, 2. Small battery
	Glider	Everything else

The total capital cost and efficiency improvements achieved under each of the categories in Table 2.3 is calculated based on the appropriate combination of the different sub-component options included within them. For capital costs, the category total are calculated on an additive basis, i.e.:

Total Capital Cost = Cost Technology A + Cost Technology B + Cost Technology C + …

However, overall efficiency improvements are not additive and are calculated in a multiplicative way from individual efficiency components, e.g. for 3 technical options (A, B and C) achieving 3%, 4% and 5% energy savings individually:

Overall efficiency improvement = 1 – ((1 – 3%) x (1 – 4%) x (1 – 5%))

= 1 – (97% x 96% x 95%) = 11.54% < (3% + 4% + 5%)

There were a significant number of technical options for improving efficiency identified (see Section 2.4), which are not all mutually compatible/stackable and also may have upper limits in their levels of deployment (which are discussed in more detail in Chapter 5). Furthermore, the purpose of this study is to establish what the average/typical change in vehicle efficiencies and costs might be going forwards. Therefore in order to calculate this it was necessary to generate the estimated average % deployment of each technology across the new vehicle fleet. This therefore becomes a factor in the cost and efficiency calculations, i.e. for technology 'A':

Net cost (A) = Basic cost (A) x % Deployment (A)

Net efficiency (A) = Basic efficiency saving (A) x % Deployment (A)

Further details on the assumed deployment levels for individual technology options is provided in Chapter 5, bearing in mind incompatibilities and natural limits.

The final part of the methodological approach involves an estimation of the real-world fuel efficiency of the final vehicle, using a percentage uplift factor on the test-cycle based fuel efficiency figure. This is included in an attempt to factor in a range of considerations that affect the performance of vehicles in the real-world versus the specific conditions used in the calculation of fuel consumption using regulatory (or other) test-cycles. Real-world versus test-cycle efficiency and the assumptions used in developing suitable uplift factors are discussed in more detail in Section 3.2.3.

2.3 Vehicle Characteristics

In order to generate the characteristics of future vehicles of different powertrain types it is necessary to have both an accurate description of the current baseline vehicles and likely trends in key vehicle characteristics. These characteristics have been broadly split into two categories for further discussion:

- **Basic characteristics:** these are the core characteristics that define the base vehicle technology starting point in terms of price, efficiency, weight/size and performance.
- **Technology specific characteristics:** these are often time dependant characteristics that influence the overall specification and performance of vehicles with different powertrain types – e.g. all electric range, degree of hybridisation (DOH), proportion of operation in different fuel modes (e.g. for PHEVs, dual fuel diesel-natural gas trucks).

2.3.1 Basic characteristics

Table 2.5 provides a summary of the basic vehicle characteristics and their reason for inclusion. The following sections provide an overview of the specific assumptions that were used in the analysis subdivided into light duty (cars, vans and motorcycles) and heavy duty (trucks, buses and coaches) vehicles.

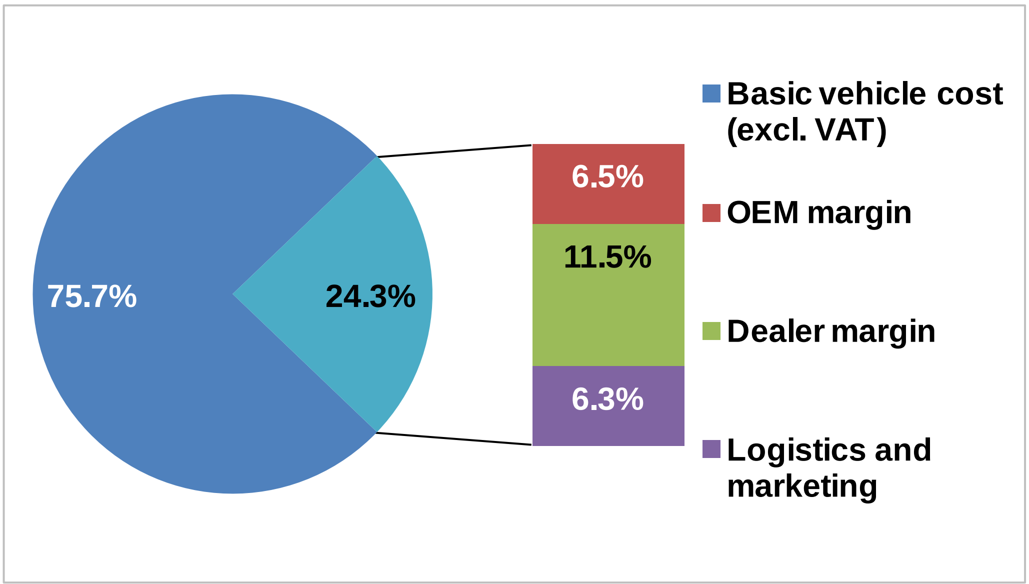
Table 2.5: Summary of basic vehicle characteristics used in the analysis

Element	Purpose for inclusion
Basic capital price, excluding VAT (£)	Used in combination to estimate the basic capital cost of a vehicle minus the manufacturer and dealer margins, from the basic capital price, excluding VAT.
Average margin for vehicle manufacture and sales (%)	
Base new vehicle efficiency (MJ/km)	The starting point for all new vehicle efficiency calculations on a test-cycle basis (i.e. excluding real world impacts on fuel consumption).
Max power (kW)	Used in the calculation of capital costs for components that scale in cost approximately with kW output (e.g. engines, motors, fuel cells, etc).
Kerb and/or gross weight (kg)*	Used in combination with max power to project likely future changes in kW that will affect total capital costs.
Power/Weight (kW/kg)	
Average annual km /year	To allow the estimation annual fuel costs**.
New vehicle lifetime, years	To allow the estimation of lifetime fuel costs**.

Notes: * Kerb weight is used for light duty vehicles and motorcycles. Gross weight has been used for heavy duty vehicles, as this is more relevant for power/weight ratio based calculations for these types of vehicles. Kerb weight is used for scaling costs of aftertreatment systems and non-battery electric powertrain costs for heavy duty vehicles – judged as a better measure of the physical size of the vehicle for these elements (giving more realistic variations than GVW, compared to other datasets).
** This calculation is useful to get a closer idea on the likely overall changes in total costs over time and in the cost-effectiveness of different powertrains, which is particularly helpful in understanding likely take-up rates of technologies in commercial vehicles.

For the average margin for vehicle manufacture and sales, it is assumed that the figure developed by EE (2011) for passenger cars is broadly applicable to other vehicle types in the absence of alternative sources. This figure of 24.3% (see Figure 2.1) has been used in preference to a slightly lower value of 16.8% from TNO (2006), since it has been more recently developed and tested with stakeholders in the UK. The main difference between the two estimates is an additional 6.3% for logistics and marketing is included in the EE (2011) estimate. It was identified at the workshop organised to discuss draft results with key experts (held on 2 February 2012 at CCC's offices) that the margins for different modes would likely be quite different (likely to be higher for heavy duty vehicles, which are sold in much lower numbers and usually with relatively bespoke specifications). However, no specific information could be identified that would allow the development/utilisation of figures different from those provided in EE (2011).

Figure 2.1: Estimated breakdown of basic vehicle cost for passenger cars



Source: EE (2011)

2.3.1.1 Light Duty Vehicles and Motorcycles

The following Table 2.6 provides a summary of the assumptions and sources for the basic vehicle characteristics of light duty vehicles and motorcycles used in this study. For passenger cars, the base data is mainly based on analysis for the Low Carbon Vehicle Partnership from EE (2011) on the UK car market for the average of C+D market segments (lower medium and upper medium cars). Van power and weight assumptions are based on a detailed dataset (based on outputs from the SMMT's MVRIS database[2]) on van new registrations previously used by in analysis for DfT (AEA, 2009). For motorcycles, estimates are based on a range of sources for different motorcycle sizes scaled using data from DfT licensing statistics (2011).

As already indicated, it is assumed that the margin for vehicle manufacture and sales figure developed by EE (2011) for cars is broadly applicable to other vehicle types in the absence of alternative sources.

Table 2.6: Assumptions on basic light duty vehicle and motorcycle characteristics used in the analysis

Mode	Element	Powertrain	2010 Figure	Source
Car	Basic capital price (£)	All	£17,817	(1)
	Average margin (%)	All	24.3%	(1)
	New vehicle efficiency (MJ/km)	Petrol ICE	2.321	(2)
		Diesel ICE	1.863	(2)
	New vehicle lifetime (years)	All	14	(3)
	Average annual distance (km)	All	14,434	(11)
	Max power (kW)	Petrol	112	(4)
		Diesel	106	(4)
	Power/Weight (kW/kg)	Petrol	0.0796	(1)
		Diesel	0.0753	(1)
	Total vehicle kerb weight (kg)	Petrol	1407	(1)
		Diesel	1407	(1)
Van	Basic capital price (£)	All	£15,000	(3)
	Average margin (%)	All	24.3%	(5)
	New vehicle efficiency (MJ/km)	Petrol ICE	2.381	(6)

[2] https://www.smmt.co.uk/members-lounge/member-services/market-intelligence/vehicle-data/mvris-new-vehicle-registrations-uk/

Mode	Element	Powertrain	2010 Figure	Source
		Diesel ICE	2.429	(6)
	New vehicle lifetime (years)	All	14	(3)
	Average annual distance (km)	All	23,000	(11)
	Max power (kW)	Petrol	69	(7)
		Diesel	82	(7)
	Power/Weight (kW/kg)	Petrol	0.0502	(7)
		Diesel	0.0459	(7)
	Kerb weight (kg)	Petrol	1,375	(7)
		Diesel	1,786	(7)
Motorcycles	Basic capital price (£)	All	£7,720	(8)
	Average margin (%)	All	24.3%	(5)
	New vehicle efficiency (MJ/km)	Petrol ICE	1.272	(9)
	New vehicle lifetime (years)	All	12	(3)
	Average annual distance (km)	All	5,500	(11)
	Max power (kW)	Petrol	67.5	(10)
	Power/Weight (kW/kg)	Petrol	0.4062	(10)
	Kerb weight (kg)	Petrol	166	(10)

Notes:

(1) EE (2011)

(2) Calculated from average new car CO_2 emission factors in gCO_2/km for the C+D market segments from SMMT (2011) and petrol/diesel CO_2 conversion factors from DCF (2011)

(3) AEA indicative estimate for typical UK vehicle broadly consistent with UK statistics

(4) Power for average petrol/diesel car from EE (2011) scaled to relative difference in petrol/diesel car power from TNO (2011)

(5) Assumed similar to that for cars from EE (2011)

(6) Estimated relative to car efficiencies from average fleet emission factor for average car versus average van for fuel type from DCF (2011)

(7) Average based on 2008 MVRIS database for new van registrations in the UK

(8) Indicative estimate calculated from DfT vehicle licensing statistics (DfT, 2011) for top 10 models and Motorcycle News (MCN 2011) for motorcycle specifications and prices

(9) Based on NAEI speed-emission calculations for motorcycle fleet (test-cycle based)

(10) Estimated from DfT vehicle licensing statistics dataset (DfT, 2011) and data from MCN (2011)

(11) Based on DfT statistics (2011) for cars, vans (estimated similar to 3.5-7.5t truck) and motorbikes.

2.3.1.2 Heavy Duty Vehicles

The following Table 2.7 provides a summary of the assumptions and sources for the basic vehicle characteristics of heavy duty vehicles used in this study. Typical truck prices are based on a dataset sourced from the UK's Freight Transport Association (FTA) that is provided in FBP (2010). Other vehicle characteristics are largely based on datasets and analysis from recent work for the European Commission by AEA and Ricardo (AEA-Ricardo, 2011). Base datasets for construction vehicles are based on those of small/large rigid trucks and articulated trucks, weighted using information on the split of construction body types from DfT (2011) licensing statistics for rigid trucks (see Table 2.8) and CLEAR (2010) for semi-trailers for articulated trucks (tipper trailers account for around 8.3% of new trailer registrations).

As already indicated, it is assumed that the margin for vehicle manufacture and sales figure developed by EE (2011) for cars is broadly applicable to other vehicle types in the absence of alternative sources.

Note: The test-cycle based vehicle efficiencies for trucks are indicative and are based on average truck activity on urban/rural/motorway roads. In reality there are very significant operational/mission characteristics for different types of truck which have a marked impact on their fuel consumption. The figures are not equivalent to those for passenger cars and vans.

Table 2.7: Assumptions on basic heavy duty vehicle characteristics used in the analysis

Mode	Element	Powertrain	2010 Figure	Source
Small Rigid Truck	Basic capital price (£)	All	£36,445	(1)
	Average margin (%)	All	24.3%	(2)
	Base new vehicle efficiency (MJ/km)	Diesel ICE	6.637	(3)
	New vehicle lifetime (years)	All	12	(4)
	Average annual distance (km)	All	24,029	(16)
	Max power (kW)	All	155.3	(5)
	Power/Weight (kW/kg)	All	0.0155	(6)
	Gross vehicle weight (kg)	All	10,000	(4)
	Kerb weight (kg)	All	5,840	(3)
Large Rigid Truck	Basic capital price (£)	All	£59,676	(1)
	Average margin (%)	All	24.3%	(2)
	Base new vehicle efficiency (MJ/km)	Diesel ICE	11.382	(3)
	New vehicle lifetime (years)	All	10	(4)
	Average annual distance (km)	All	41,779	(16)
	Max power (kW)	All	249.6	(5)
	Power/Weight (kW/kg)	All	0.0104	(7)
	Gross vehicle weight (kg)	All	24,000	(8)
	Kerb weight (kg)	All	9,650	(3)
Articulated Truck	Basic capital price (£)	All	£76,368	(1)
	Average margin (%)	All	24.3%	(2)
	Base new vehicle efficiency (MJ/km)	Diesel ICE	13.986	(3)
	New vehicle lifetime (years)	All	10	(4)
	Average annual distance (km)	All	90,000	(16)
	Max power (kW)	All	317.4	(5)
	Power/Weight (kW/kg)	All	0.0079	(9)
	Gross vehicle weight (kg)	All	40,000	(8)
	Kerb weight (kg)	All	13,960	(3)
Construction Truck	Basic capital price (£)	All	£62,272	(10)
	Average margin (%)	All	24.3%	(2)
	Base new vehicle efficiency (MJ/km)	Diesel ICE	12.073	(11)
	New vehicle lifetime (years)	All	10	(4)
	Average annual distance (km)	All	46,577	(16)
	Max power (kW)	All	228.8	(5)
	Power/Weight (kW/kg)	All	0.0104	(12)
	Gross vehicle weight (kg)	All	22,000	(8)
	Kerb weight (kg)	All	8,850	(3)
Bus	Basic capital price (£)	All	£130,000	(13)
	Average margin (%)	All	24.3%	(2)
	Base new vehicle efficiency (MJ/km)	Diesel ICE	12.861	(3)
	New vehicle lifetime (years)	All	15	(4)
	Average annual distance (km)	All	55,785	(16)
	Max power (kW)	All	152	(15)
	Power/Weight (kW/kg)	All	0.0101	(15)
	Gross vehicle weight (kg)	All	15,000	(15)
	Kerb weight (kg)	All	9,000	(15)
Coach	Basic capital price (£)	All	£130,000	(17)
	Average margin (%)	All	24.3%	(2)
	Base new vehicle efficiency (MJ/km)	Diesel ICE	12.694	(3)
	New vehicle lifetime (years)	All	15	(4)
	Average annual distance (km)	All	61,067	(16)

Mode	Element	Powertrain	2010 Figure	Source
	Max power (kW)	All	220	(15)
	Power/Weight (kW/kg)	All	0.0122	(15)
	Gross vehicle weight (kg)	All	18,000	(15)
	Kerb weight (kg)	All	11,000	(15)

Notes:

(1) FBP (2010)
(2) Assumed similar to that for cars from EE (2011)
(3) Estimate based on AEA-Ricardo (2011) analysis
(4) AEA estimate for typical vehicle based on UK statistics (EU statistics for bus lifetimes)
(5) Calculated from max power and power/weight ratio
(6) Based on data for a 7.5t vehicle from AEA-Ricardo (2011), estimate 0.5% p.a. increase in power
(7) Based on an average of data for a 18t and 26t vehicle for 2010 from AEA-Ricardo (2011); estimate 0.5% p.a. power increase to 2050
(8) Estimated from DfT Licensing Statistics (2011) datasets
(9) Based on data for an average 44t vehicle for 2010 from AEA-Ricardo (2011); estimate 0.5% p.a. power increase to 2050
(10) Estimated from FBP (2010) and DfT Licensing Statistics (2011) datasets
(11) DfT (2010) - freight best practice programme publication on tipper trucks
(12) AEA estimate - assumed to be similar to large rigid truck
(13) AEA (2007)
(14) Estimate based on an average of small and large rigid trucks
(15) Calculated based on averaged bus or coach data from Alexander Dennis (2012)
(16) Based on DfT statistics (2011) for heavy trucks. Construction trucks estimated based on approximate split of rigid and articulated vehicles available from DfT statistics (2011) and CLEAR (2010). Annual km for buses and coaches based on datasets sourced for the UK in AEA-Ricardo (2011).
(17) AEA estimate – assumed to be similar to bus

Table 2.8: Rigid goods vehicles1 over 3.5 tonnes licensed by gross weight and body type, Great Britain, annually: 2010 *

1000s vehicles by Body Type	Up to 7.5 t	Over 7.5t up to 15 t	Over 15 t up to 18 t	Over 18 t up to 26 t	Over 26 t	Total[2]
Box Van	48.7	8.4	13.0	2.7	0.2	**73.0**
Tipper	17.7	1.3	4.2	4.8	14.9	**42.8**
Curtain Sided	10.7	2.1	9.7	5.3	0.2	**28.1**
Dropside Lorry	10.5	1.8	4.7	3.2	0.2	**20.4**
Flat Lorry	6.7	1.7	3.4	5.4	1.3	**18.5**
Refuse Disposal	0.9	1.1	1.7	10.8	1.6	**16.1**
Insulated Van	5.6	2.7	3.9	2.1	0.1	**14.4**
Skip Loader	1.0	0.6	5.6	1.1	3.3	**11.6**
Goods	3.0	0.9	1.2	1.5	0.8	**7.4**
Panel Van	7.1	0.1	0.1	0.0	0.0	**7.3**
Tanker	0.4	0.5	2.3	2.8	1.2	**7.3**
Street Cleansing	2.3	2.4	0.4	0.1	0.0	**5.1**
Livestock Carrier	3.5	0.3	0.1	0.2	0.0	**4.2**
Car Transporter	1.1	0.4	1.0	1.3	0.2	**4.1**
Concrete Mixer	0.0	0.1	0.4	2.0	1.2	**3.8**
Tractor	0.2	0.1	0.3	0.8	2.1	**3.5**
Skeletal Vehicle	0.6	0.3	0.5	0.3	0.3	**1.9**
Tower Wagon	1.7	0.1	0.0	0.0	0.0	**1.8**
Luton Van	1.3	0.1	0.1	0.0	0.0	**1.6**
Special Purpose	0.5	0.3	0.3	0.2	0.1	**1.3**
Specially Fitted Van	0.7	0.2	0.2	0.1	0.0	**1.2**
Van	1.1	0.1	0.1	0.0	0.0	**1.2**
Not Recorded	0.6	0.2	0.2	0.1	0.0	**1.1**
Truck	0.6	0.1	0.2	0.1	0.1	**1.0**
Others	2.2	0.9	1.3	0.8	0.5	**5.8**
Overall Total	**128.5**	**26.6**	**54.9**	**45.9**	**28.5**	**284.4**

1000s vehicles by Body Type	Up to 7.5 t	Over 7.5t up to 15 t	Over 15 t up to 18 t	Over 18 t up to 26 t	Over 26 t	Total[2]
% Overall Total	45.2%	9.4%	19.3%	16.1%	10.0%	**100%**
Construction Total	**18.7**	**1.9**	**10.2**	**7.9**	**19.5**	**58.3**
% Construction Total	32.1%	3.3%	17.5%	13.6%	33.4%	**100%**
% Overall Total	6.6%	0.7%	3.6%	2.8%	6.8%	**20.5%**
Study Category	**Small Rigid**		**Large Rigid**			

Source: DfT Licensing statistics (2011)

Notes: * Body types with cells highlighted in green are assumed to be in the construction vehicles category for the purposes of this study.

2.3.2 Technology specific characteristics

The following section provides a summary of the key technology specific attributes used to define the relative performance and costs of different powertrain options, why they are needed and general sources for assumptions and trajectories to 2050 (where relevant). A summary description of these elements is provided in Table 2.9 below.

Table 2.9: Summary of technology specific characteristics used in the analysis

Element	Description and purpose
ICE range (km) (by powertrain type)	This is the assumption on required vehicle range operating in ICE mode. May also be used to allow for initial reduced ranges of natural gas fuelled vehicles if appropriate. It is used in combination with the calculated vehicle efficiency to calculate the required sizing of liquid fuel tanks and natural gas storage tanks in the calculation of the capital costs of these components.
Hydrogen range (km) (by powertrain type)	This is the assumption on required vehicle range operating on hydrogen fuel. It is used in combination with the calculated vehicle efficiency to calculate the required sizing of hydrogen storage tanks in the calculation of their capital costs.
Electric range (km) (by powertrain type)	This is the assumption on required vehicle range operating on stored electricity. It is used in combination with the calculated vehicle efficiency and usable SOC (see below) to calculate the required sizing of batteries/electric storage (in kWh) in the calculation of their capital costs.
Distance in fuel mode 1 (%) (by powertrain type)	For powertrain types that can operate using more than one fuel (i.e. dual-fuel (ICE/H2/NG), this is the average percentage of the total km travelled by the vehicle in fuel mode 1. For the purposes of the study analysis, fuel mode 1 is taken to be petrol/diesel/hydrogen as appropriate for PHEVs, REEVs and dual-fuel diesel-natural gas powertrains, as appropriate. This factor is used in the calculation of the average net vehicle efficiencies (and greenhouse gas emissions from fuel consumption) of different powertrain options.

Element	Description and purpose
Basic real-world % increase (by powertrain type)	This is an estimate of the typical differential between the vehicle efficiency on typical/regulatory test cycles versus performance in real-world driving conditions. There is some evidence that the differential is larger for some powertrain technologies, compared to conventional ICE equivalents. These assumptions are used to provide an adjustment to the test-cycle based calculations as the final stage in the analysis, so that a closer view can be obtained on the relative performance of different powertrain options. There is also some evidence that there is a larger differential between test-cycle and real-world performance for the most efficient vehicles within a given powertrain type. Additional scaling factors are therefore also be applied on top of these basic factors to account for a further widening of differentials after additional efficiency technologies have been applied.
ICE sizing as % max power (by powertrain type)	This is defined in the analysis calculations as the percentage of the vehicle's total combined peak/maximum power (i.e. ICE kW + electric motor kW) provided by the internal combustion engine. It is therefore the opposite of the degree of hybridisation (defined as the percentage of the total vehicle peak power provided by the electric motor). It is used to calculate the required ICE and electric motor power sizing in the calculation of their capital costs.
Battery usable SOC for electric range	This is the safety margin built into battery sizing calculations for a given range requirement and vehicle efficiency (in MJ/km) to take into account battery degradation over the usual working life of the vehicle and provide a buffer for hybrid operation use. This is used in the calculation of the battery capital costs.
Ratio fuel cell size to max power	This is the reduction in fuel cell size/power rating possible for H2FC REEV powertrains due to the different operational requirements versus a regular H2FC vehicle (i.e. in an REEV the fuel cell doesn't have to provide the full peak power). This is used in the calculation of the fuel cell capital costs.
% Max power ICE for electrified drivetrains (by powertrain type)	This represents the total combined peak power output of the electric motor and ICE (where relevant) as a proportion of the peak power of the comparable conventional ICE vehicle. For HEVs, PHEVs and REEVs the proportions are typically: 125% for HEV/PHEV and 138% for REEVs. For fuel cell and battery electric vehicles, there is a reduced electric engine peak power rating (typically 85-90%) needed to achieve comparable performance to a conventional ICE. Most electric motors deliver full torque over a wide RPM range, so the performance per kW peak power is not equivalent to an ICE, which has a limited torque curve. This is used in the scaling of electric motor and ICE power ratings for the calculation of the capital costs.
# New vehicles/year	Approximate figures on the numbers of new vehicles and the total UK fleet size for a given vehicle category are used in the estimation of future capital cost reductions of fuel efficiency technology based on their levels of deployment into the new vehicle fleet using learning rate methodologies.
# Fleet vehicles	

2.3.2.1 Light Duty Vehicles and Motorcycles

The following section provides a summary of the data sources for assumptions used to define the key technology specific attributes used in the calculations for light duty vehicles and motorcycles. A summary of these sources is provided in Table 2.10 below. Full details on the specific values for the period 2010-2050 used in the analysis for light duty vehicles and motorcycles is provided in Appendix 1.

In general data has been sourced from EE (2011) or TNO (2011) as the most current relevant data sources for passenger cars. It is assumed in the absence of conflicting specific information that in most cases the technology specific characteristics are analogous for vans (there is good evidence for this in other related studies considering both cars and vans by TNO and AEA) and for motorcycles (where there is very little or no information available in the literature at all).

In general there is little detailed information on real-world uplift factors used to convert test-cycle based fuel consumption into real-world values, so the figures used are generally approximations based on a number of sources. This subject is discussed in more detail in Section 3.2.3.

Table 2.10: Summary of key data sources for the technology specific characteristics used in the analysis of light duty vehicles and motorcycles

Element	Cars	Vans	Motorcycles
ICE range (km) (by powertrain type)	EE (2011), JEC (2011), NGVA (2012)	NGVA (2012)	AEA estimate
Hydrogen range (km) (by powertrain type)	EE (2011)	Assume similar to cars	AEA estimate
Electric range (km) (by powertrain type)	EE (2011)	Assume similar to cars	AEA estimate
Distance in fuel mode 1 (%) (by powertrain type)	EE (2011)	Assume similar to cars	N/A
Basic real-world % increase (by powertrain type)	(1)	(1)	(2)
ICE sizing as % max power (by powertrain type)	Based on TNO (2011)	Assume similar to cars	Assume similar to cars
Battery usable SOC for electric range	(3)	Assume similar to cars	Assume similar to cars
Ratio fuel cell size to max power	EE (2011)	Assume similar to cars	N/A
% Max power ICE for electrified drivetrains (by powertrain type)	Estimate based on TNO (2011)	Assume similar to cars	Assume similar to cars
# New vehicles/year	DfT vehicle licensing statistics (2011)		
# Fleet vehicles	Estimated based on # new vehicles and average vehicle lifetime.		

Notes:

(1) ICE = from TNO (2011); HEV and BEV = AEA estimates based on LowCVP (2011) and Cenex (2012); PHEV/REEV = assume average of HEV and BEV; H2FC = assume similar to BEV.

(2) Based on the differential between the test-cycle based CO_2 emission factor from the UK NAEI and the average real-world based emission factor from DCF (2011).

(3) Figure of 70% from TNO (2011) for 2010, which is assumed to increase after 2020 to reach 90% by 2050.

2.3.2.2 Heavy Duty Vehicles

The following section provides a summary of the data sources for assumptions used to define the key technology specific attributes used in the calculations for light duty vehicles and motorcycles. A summary of these sources is provided in Table 2.10 below. Full details on the specific values for the period 2010-2050 used in the analysis for heavy duty vehicles is provided in Appendix 1.

In general, where data is absent, assumptions have been developed using those for light duty vehicle technologies as a basis.

No specific information on real-world uplift factors used to convert test-cycle based fuel consumption into real-world values for heavy duty vehicles, so the base ICE figures used are generally approximations based on calculations of test-cycle based estimates (from speed-emission curve calculations used in the AEA-Ricardo, 2011) and comparison with real-world fuel consumption estimates from DfT. This subject is discussed in more detail in Section 3.2.3.

Table 2.11: Summary of key data basis/sources for the technology specific characteristics used in the analysis of heavy duty vehicle

Element	Heavy Duty Trucks				Buses/Coaches	
	Small Rigid	Large Rigid	Articulated	Construction	Bus	Coach
ICE range (km) (by powertrain type)	Based on data from NGVA (2012)					
Hydrogen range (km) (by powertrain type)	Assume similar range to ICE					
Electric range (km) (by powertrain type)	Assume as for cars	HEVs – as for cars	HEVs – as for cars	HEVs – as for cars	Assume as for cars	HEVs – as for cars
Distance in fuel mode 1 (%) (by powertrain type)	Average distance using natural gas for dual-fuel trucks is based on AEA-Ricardo (2011) and NREL (2000) , with some scaling to account for different usage in different duty cycles (i.e. substitution at the high end of the range for articulated trucks, and at the low end for small rigid trucks and buses in mainly urban duty cycles).					
Basic real-world % increase (by powertrain type)	(1), (2)	(1), (2)	(1), (2)	(1), (2)	(2), (3)	(4)
ICE sizing as % max power (by powertrain type)	Assume similar to cars technologies					
Battery usable SOC for electric range	Assume similar to cars technologies					
Ratio fuel cell size to max power	N/A	N/A	N/A	N/A	N/A	N/A
% Max power ICE for electrified drivetrains (by powertrain type)	Assume similar to cars technologies					
# New vehicles/year	Approximation based on # fleet vehicles and average vehicle lifetime.					
# Fleet vehicles	Estimated based on DfT Vehicle Licensing Statistics (2011)					

Notes:

(1) ICE = Calculated by comparing test-cycle based fuel consumption to DfT fuel consumption statistics (2011).

(2) HEV / BEV = based on 25% of the increase for cars. FHV / HHV = assume similar to HEV. H2FC = assume similar to BEV.

(3) ICE = Calculated from test-cycle based basic fuel efficiency figure relative to Bus Service Operators Grant (BSOG) fuel consumption calculations from DfT (2011) sourced for the updates to DCF (2011).

(4) Assume uplifts for coaches are similar to those for large rigid trucks.

2.4 Efficiency Improvement Technologies

This section provides a summary of the specific efficiency improvement technologies identified and used in the analysis and their classification into five different categories. The assumed efficiency improvements, capital costs and deployment rates of the different technologies are detailed in the corresponding Chapter 3, Chapter 4 and Chapter 5, respectively. The categorisation for the energy improvement technologies is as follows:

Category	Abbreviation	Coverage
• Powertrain efficiency	PtrainE	All engine, transmission and other driveline efficiency technologies
• Aerodynamics	Aero	Technologies focussing on reducing aerodynamic drag
• Weight reduction	Weight	Technical options for weight reduction
• Rolling resistance	Rres	Technologies aimed at reducing rolling resistance
• Other options	Other	Technologies that do not readily fit into the other categories

The following Table 2.9 provides a summary of the technological options identified and used in the analysis for cars and vans. These options are generally consistent with those identified and used in the most recent analysis for the European Commission on car regulatory CO_2 emissions targets (TNO, 2011) and also for related previous (AEA-TNO, 2009) and ongoing work for vans. This study provides a comprehensive update to previous work carried for the EC in this area (TNO, 2006), which was used as the basis for the assumptions in CCC's Marginal Abatement Cost-Curve Model (AEA, 2009). The review of the available literature as part of this study has confirmed this is the most comprehensive, up-to-date and relevant dataset available that covers all the major technological options that are being developed for near-medium term application in light duty vehicles. A short description/definition of the technical option is provided in Table 2.9 where it is not immediately obvious from the name what it covers. A specific definition of the different technology options was not in general provided in TNO (2011).

Table 2.12: Summary of the efficiency improvement technologies included in the car and van analysis

Efficiency Improvement Technology	Category	#	Additional description/notes
Petrol - low friction design and materials	PtrainE	1	Includes a range of options/low friction components for reducing friction in the engine and transmission, e.g. low tension piston rings, low friction coatings, improved lubricants.
Petrol - gas-wall heat transfer reduction	PtrainE	2	Includes a range of technical options, such as: charge motion systems (decreased combustion duration), fast warm-up, insulation (coolant) and variable compression ratios.
Petrol - direct injection (homogeneous)	PtrainE	3	A variant of fuel injection where the fuel is highly pressurised and injected directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that happens in the intake tract, or cylinder port.
Petrol - direct injection (stratified charge)	PtrainE	4	In some applications, gasoline direct injection (GDI) enables a stratified fuel charge (ultra lean burn) combustion for improved fuel efficiency, and reduced emission levels at low load.

Efficiency Improvement Technology	Category	#	Additional description/notes
Petrol - thermodynamic cycle improvements	PtrainE	5	Includes multi-port injection such as HCCI (homogeneous charge compression ignition) technologies. HCCI has characteristics of both homogeneous charge spark ignition (gasoline engines) and stratified charge compression ignition (diesel engines).
Petrol - cam-phasing	PtrainE	6	VVA, also known as variable valve timing (VVT), is a generalized term used to describe any mechanism or method that can alter the shape or timing of a valve lift event within an internal combustion engine (Wiki, 2012a). Cam-phasing is the simplest form of VVT, with more sophisticated systems also providing variable lift to further improve efficiency.
Petrol - Variable valve actuation and lift	PtrainE	7	
Diesel - Variable valve actuation and lift	PtrainE	8	
Diesel - combustion improvements	PtrainE	9	Further non-specific technology improvements to the combustion efficiency of diesel engines.
Mild downsizing (15% cylinder content reduction)	PtrainE	10	Reduced cylinder size, with additional boost (via turbo- or super- charging) to reach a similar peak power output.
Medium downsizing (30% cylinder content reduction)	PtrainE	11	
Strong downsizing (≥45% cylinder content reduction)	PtrainE	12	
Reduced driveline friction	PtrainE	13	General improvements made to the whole driveline to reduce friction.
Optimising gearbox ratios / down-speeding	PtrainE	14	Changing gearbox ratios to be more optimised towards fuel efficiency by using longer gear ratios leading to lower engine operation speeds (downspeeding). This shifts engine operation into the map area of highest efficiency, improving fuel economy.
Automated manual transmission (AMT)	PtrainE	15	An automated transmission based on a manual, which has mechanical efficiency similar to a manual transmission but with automated gear shifts to optimise engine speed.
Dual clutch transmission	PtrainE	16	A type of semi-automatic or automated manual transmission that utilises two separate clutches for odd and even gear sets. Many also have the ability to allow the driver to manually shift gears, albeit still carried out by the transmission's electro-hydraulics.
Start-stop hybridisation	PtrainE	17	A start-stop (or stop-start) system automatically shuts down and restarts the engine to reduce the time the engine spends idling, thereby reducing fuel consumption and emissions.
Regenerative breaking (smart alternator)	PtrainE	18	This system adds regenerative braking to a start-stop system to recover additional energy from braking using a smart alternator, which can be stored in a battery in order to provide electrical power to auxiliaries. This reduces the need for energy to be collected directly from the engine operation, improving overall system efficiency.

Efficiency Improvement Technology	Category	#	Additional description/notes
Aerodynamics improvement	Aero	1	Improvement to the vehicles overall aerodynamics through improvements to its aerodynamic profile (/shape) as well as using other options, such as smoother undercarriages, aerodynamic hub caps/wheels, wheel well farings, etc.
Low rolling resistance tyres	Rres	1	Tyres designed to minimise rolling resistance whilst still maintaining the required levels of grip.
Mild weight reduction (~10% reduction in BIW*)	Weight	1	Reduction in BIW* through, for example: use of AHSS (advanced high strength steels), aluminium, or composite materials (in the future).
Medium weight reduction(~25% reduction in BIW*)	Weight	2	
Strong weight reduction (~40% reduction in BIW*)	Weight	3	
Lightweight components other than BIW*	Weight	4	Using lightweighting in areas other than those included in BIW*.
Thermo-electric waste heat recovery	Other	1	This is the conversion of waste heat energy to electricity using a thermo-electric substance, where a change in temperature across a semiconductor material creates a voltage.
Secondary heat recovery cycle	Other	2	Secondary heat (i.e. waste heat) can be recovered, for example using the organic Rankine cycle, where an organic substance is used as working medium instead of water (i.e. steam).
Auxiliary systems efficiency improvement	Other	3	Includes improving air conditioning and other energy using auxiliary systems.
Thermal management	Other	4	Closed-loop control of the coolant circuits for instantaneous adaptation to current operating conditions.

Notes: * Body in white or BIW refers to the stage in automotive design or automobile manufacturing in which a car body's sheet metal components have been welded together - but before moving parts (doors, hoods, and deck lids as well as fenders) the motor, chassis sub-assemblies, or trim (glass, seats, upholstery, electronics, etc.) have been added and before painting. (Wiki, 2012)

Regulatory interest in GHG reductions from motorcycles and mopeds has yet to significantly develop on this mode, since it comprises a very small proportion of overall energy consumption and emissions. Therefore, information is much less readily available in the public domain on the technical possibilities to improve their energy efficiency. The following Table 2.13 provides a summary of the options identified based on information available in the public domain (e.g. in reports from the IEA (2009) and ICCT (2011)), or through drawing parallels with the options available for passenger cars. As for car and van technologies, a short description/definition of the technical option is provided in where it is not immediately obvious from the name what it covers.

Table 2.13: Summary of the efficiency improvement technologies included in the motorcycle analysis

Efficiency Improvement Technology	Category	#	Additional description/notes
Air assisted direct injection for 2-stroke engines	PtrainE	1	Similar to technology for cars and vans
Electronic port fuel injection for 4-stroke engines	PtrainE	2	Similar to technology for cars and vans
Swirl control valve	PtrainE	3	While idling and during low engine speed operation, the swirl control valve closes. Thus the velocity of the air in the intake passage increases, promoting the vaporization of the fuel and producing a swirl in the combustion chamber. Because of this operation, this system tends to increase the burning speed of the gas mixture, improve fuel consumption, and increase the stability in running conditions.
Variable ignition timing	PtrainE	4	Using a throttle sensor position and the engine speed sensor, the load can be estimated and the spark timing adjusted for better fuel economy (ICCT, 2011).
Engine friction reduction	PtrainE	5	Assume similar to cars and vans
Optimising transmission systems	PtrainE	6	Similar to cars and vans
Start-stop hybridisation	PtrainE	7	Similar to technology for cars and vans
Aerodynamics improvement	Aero	1	More challenging than cars and vans due to reduced possibilities to reduce drag from the rider without the use of encasing shells (unlikely to be popular).
Low rolling resistance tyres	Rres	1	Friction levels per unit weight are twice as high as those used on cars - but high friction is important for safety (IEA, 2009). Improvements are therefore limited in scope.
Light weighting	Weight	1	Similar to cars and vans
Thermo-electric waste heat recovery	Other	1	Assume similar to cars and vans

For heavy duty vehicles there have been a range of recent studies investigating the technical options for improving efficiency and reducing GHG emissions. As for passenger cars there are several specific studies that have been completed recently relevant to the UK/European situation that provide a comprehensive list of the different technology options being developed, which include AEA-Ricardo (2011), Ricardo (2009) and TIAX (2011). These sources have therefore been used as a basis for the list of technological options presented in Table 2.14. As for light duty vehicles and motorcycles, a short description/definition of the technical option is provided in where it is less obvious from the name what it covers, and a more detailed technical description of each technology is also available in AEA-Ricardo (2011).

Table 2.14: Summary of the efficiency improvement technologies included in the heavy duty vehicle analysis

Efficiency Improvement Technology	Category	#	Additional description/notes
General improvements	PtrainE	1	General incremental improvements to vehicle and powertrain (other than the headline technologies listed in this table), and impacts of additional AQ pollutant control (as defined by Ricardo in AEA-Ricardo (2011)*. It is assumed that all the underlying technologies are utilised fully by 2030 (and also no further Euro standards) - hence no further efficiency improvement after then.
Mechanical Turbocompound	PtrainE	2	Exhaust gas energy recovery with additional exhaust turbine, which is linked to a gear drive and transfers the energy on to the crankshaft providing extra torque.
Electrical Turbocompound	PtrainE	3	Exhaust turbine in combination with an electric generator / motor to recover exhaust energy: (i) Recovered energy can be stored or used by other electrical devices; (ii) Motor during transients to accelerate.
Heat Recovery (Bottoming Cycles)	PtrainE	4	Exhaust gas energy recovery with heat exchangers. Sometimes called “bottoming cycles”, this concept uses exhaust gas heat in an exchanger to drive an additional power turbine to generate energy. Similar to the secondary heat recovery cycle for light duty vehicles.
Controllable Air Compressor	PtrainE	5	Air compressor with electric / air actuated clutch to de-connect compressor in idle status or when compressor not required.
Automated Transmission	PtrainE	6	Replacement of manual transmissions with automated transmission based on a manual (AMT) which has similar mechanical efficiency to a manual transmission but automated gear shifts to optimise engine speed.
Stop / Start System	PtrainE	7	System uses a high-voltage e-motor mounted to the crankshaft to operate stop / start, i.e. stopping the engine running whenever the vehicle is stationary, along with regenerative braking.
Pneumatic Booster – Air Hybrid	PtrainE	8	Compressed air from vehicle braking system is injected rapidly into the air path and allows a faster vehicle acceleration, which allows an earlier gear shift (short shifting), resulting in the engine operating more in an efficient engine speed / load range.
Aerodynamic Fairings	Aero	1	Additional add-ons to cabs that help reduce aerodynamics drag and improve fuel consumption. Includes cab deflectors and cab collars and can be added as aftermarket additions.
Spray Reduction Mud Flaps	Aero	2	The mud flap separates the water from the air through a series of vertical passages created by vanes which makes the spray change direction a number of times eliminating the water.
Aerodynamic Trailers / Bodies	Aero	3	Trailers / bodies designed to improve vehicle aerodynamics, e.g.: teardrop shapes, or those integrating multiple aerodynamic features into a complete package.
Aerodynamics (Irregular Body Type)	Aero	4	A package of more limited set of aerodynamic options can be applied to certain vehicle types that are limited by their specific functionality/shape (e.g. tankers and container carriers) or variable loads (e.g. flat bed).
Active Aero	Aero	5	Active aerodynamics to reduce vehicle drag where air is blown from trailer/body trailing edge and over trailer/body roof to reduce drag caused by low pressure region behind trailer/body.
Low Rolling Resistance Tyres	Rres	1	Tyres designed to minimise rolling resistance whilst still maintaining the required levels of grip.

Efficiency Improvement Technology	Category	#	Additional description/notes
Single Wide Tyres	Rres	2	Replacement of dual tyres on an axle with a lower aspect ratio single wide tyre.
Automatic Tyre Pressure Adjustment	Rres	3	Automatic Tyre Monitoring/Pressure Adjustment systems use the air compressor on the vehicle to automatically monitor and adjust tyre pressures to optimum levels for load and terrain conditions.
Light weighting	Weight	1	Apply aluminium alloys intensively in tractor chassis and body, trailer and powertrain. Use of aluminium alloy may achieve total combined unit weight savings of up to 2,000kg –estimate for tractor body and chassis ~900 kg.
Predictive Cruise Control	Other	1	Development of systems that use electronic horizon data to improve the fuel efficiency of vehicles. Combining GPS with Cruise Control to better understand the road ahead for optimal speed control. Based on lower cost and energy savings estimates from TIAX (2011).
Smart Alternator, Battery Sensor & AGM Battery	Other	2	Control alternator voltage to that required for the current battery condition and vehicle mode to maximise overall electrical generation efficiency: Typically, an absorbent glass mat (AGM) battery is used to decouple alternator and vehicle electrical loads with State of Charge (SOC) varying between 50-75% according to vehicle mode. In overrun, a high alternator voltage and fast charging is used to maximise brake energy regeneration. To reduce engine load in acceleration, the alternator voltage is reduced below that required for the current battery condition such that discharge occurs.
Alternative Fuel Bodies	Other	3	Replacement of existing power sources for vehicle bodies which use diesel for power. For body types with high auxiliary requirements like RCVs, refrigerated transport (and some construction vehicles), additional efficiency gains can be achieve by powering these systems via electric battery storage, rather than off the ICE. This option is therefore only suitable to vehicles with high-powered electrical systems, i.e. HEVs / BEVs.
Advanced Predictive Cruise Control	Other	4	Based on a more sophisticated system with higher costs and energy savings from AEA-Ricardo (2011)

Source: Descriptive text/notes taken directly from AEA-Ricardo (2011) for the most part.

Notes: * Business as usual scenario of fuel consumption of new vehicles - assuming no incentives or legislative CO_2 for HDV:
(a) *All:* Natural p.a. improvement in powertrain efficiency includes transmission and engine auxiliaries;
(b) *Long-haul:* Significant additional impacts of using vehicle aids by 2030
(c) *Coaches/Regional Distribution:* Some additional aero improvements and weight reduction
(d) *Buses:* Forecast reduction in vehicle mass to increase fuel economy of vehicles
(e) *All:* 3% penalty from increasing emissions legislation in 2013 and then potential Euro VII at ~2018.

3 Efficiency Assumptions

This chapter provides a more detailed summary of the methodological approach, calculations, data sources and assumptions used in the development of the study dataset for technology efficiencies.

3.1 Calculation Methodology

The study methodology estimates two classes of efficiency improvements over time: first non-specific general improvements to powertrain technologies (such as improvements to electric engine or fuel cell efficiency) that impact on the overall efficiency of the basic powertrain. The methodology used for these technologies are discussed in Section 3.1.1. The second are the specific technologies identified that can improve the efficiency of a range of aspects of the vehicles performance (including the powertrain). The methodologies for these technologies are dealt with separately in Section 3.1.2. Finally, the key assumptions and data sources used in the calculations are detailed in Section 3.2

3.1.1 Basic Components

This section provides a summary of the methodology for calculation of the change in the efficiency of powertrains from 2010-2050, providing the specific formulas used for calculating this in the study analysis.

The basic 2010 energy consumption (in MJ/km) of individual vehicle powertrains is calculated using the powertrain efficiency improvement relative to the reference powertrain, which is defined as:

- *Petrol ICE*: for all petrol-based powertrains, NG ICE powertrains, and all motorcycle technologies;
- *Diesel ICE*: for all diesel-based powertrains, DNG ICE powertrains and all other powertrain technologies, except for motorcycle powertrains and NG ICE (as above);

The assumptions used for these 2010 basic powertrain efficiencies is provided in Section 0.

The basic improvement to the powertrain efficiency from 2010 – 2050 is calculated based on the net change in the efficiency of its component parts. For a given year, an approximation for the overall powertrain efficiency is calculated as follows, by powertrain type:

Powertrain	**Summary calculation for powertrain efficiency (for a given year)**
ICE / FHV / HHV / HEV	**Total Efficiency (%)** = ICE Eff.(%) x Fuel tank Eff.(%) x Hybrid system improvement % (where appropriate)
BEV	**Total Efficiency (%)** = Elec motor Eff.(%) x Elec drivetrain Eff.(%) x Battery Eff.(%)
H2FC	**Total Efficiency (%)** = Fuel cell Eff.(%) x Elec motor Eff.(%) x Elec drivetrain Eff.(%) x Battery Eff.(%) x H2 storage Eff.(%)
Petrol/Diesel/H2 PHEV / REEV	**Total Efficiency (%)** = (Elec drive Eff.(%) x %km in Elec drive) x (NonElec drive Eff.(%) x (1 - %km in Elec drive))
	Where:
	Elec drive Eff.(%) = as for BEV Eff.(%) ;
	NonElec drive Eff.(%) = as for HEV Eff.(%) OR H2FC Eff.(%)

The overall efficiency improvement of the basic powertrain is then calculated from:

Total Efficiency Improvement (%) [2010-20XX]

= Powertrain Eff.(%) [20XX] / Powertrain Eff.(%) [2010]

3.1.2 Efficiency Improvement Technologies

The methodology employed for combining individual effects of technologies via individual technology performance and deployment levels 2010-2050 is summarised in this section.

Individual efficiency improvement technology (EIT) efficiencies are calculated in a multiplicative way based on the net increased percentage penetration/deployment in the new vehicle fleet versus 2010 levels from 2010 - 2050 (see Section 5.2 on the assumptions for this aspect). Total efficiency improvement for EITs are therefore calculated as follows:

$$\textbf{Total EIT Eff.Saving (\%)} = 1 - \big((1 - \text{EIT}_{[1]}\ \text{Eff.Saving(\%)} \times \%\ \text{Deployment EIT}_{[1]}) \\ \times (1 - \text{EIT}_{[2]}\ \text{Eff.Saving(\%)} \times \%\ \text{Deployment EIT}_{[2]}) \\ \times (1 - \text{EIT}_{[3]}\ \text{Eff.Saving(\%)} \times \%\ \text{Deployment EIT}_{[3]}) \\ \times \text{etc} \big)$$

Where:

$\text{EIT}_{[1]}$ Eff.Saving(%) = Total efficiency saving of efficiency improvement technology 1

% Deployment $\text{EIT}_{[1]}$ = Net increased percentage deployment of EIT 1 versus 2010

For PHEV and REEV powertrain types, the efficiency savings for the energy consumption of the vehicle running on either battery electric mode or other mode (i.e. using petrol ICE / diesel ICE or H2FC) are tracked separately. This is because some technologies (e.g. those improving the efficiency of ICEs) will not improve the efficiency of the battery electric mode. The overall vehicle efficiency is calculated at the end using the relative % distances travelled in electric/other drive modes.

3.2 Key Sources and Assumptions

3.2.1 Basic components

This section provides a summary of sources and assumptions for the performance of basic component elements which are generally consistent across modes and powertrains. However, there are also mode specific powertrain efficiency factors also detailed in this section.

3.2.1.1 Mode independent basic components

The study analysis assumptions for the basic component efficiencies are presented in Table 3.1. These technology efficiencies are either indicative estimates or have been sourced from a range of other sources (summarised in the table). As described in the previous section 3.2.1, these are used primarily to estimate future improvements at the basic powertrain level.

Table 3.1: Summary of basic component efficiency assumptions used in the study analysis

Area	Category	Unit	2010	2020	2030	2040	2050	Source/Notes
Battery **(all types)**	**Best**	%	86%	87%	88%	89%	90%	AEA (2008)
	Low	%	86%	86%	86%	86%	86%	AEA indicative estimate
	High	%	86%	87.5%	89%	90.5%	92%	AEA indicative estimate
H2 storage	All	%	99%	99%	99%	99%	99%	Science (2003)
CNG storage	All	%	99%	99%	99%	99%	99%	Science (2003)
Petrol ICE powertrain	All	%	22%	22%	22%	22%	22%	Indicative estimate
NG ICE powertrain	All	%	22%	22%	22%	22%	22%	As for petrol
NG ICE (HDV)	All	%	22%	22%	22%	22%	22%	As for NG ICE
Diesel ICE powertrain	All	%	25%	25%	25%	25%	25%	Indicative estimate
Diesel ICE (HDV)	All	%	25%	25%	25%	25%	25%	As for Diesel ICE
DNG ICE	All	%	25%	25%	25%	25%	25%	As for heavy duty diesel
Electric motor	**Best**	%	92.0%	92.8%	93.5%	94.3%	95.0%	JEC (2011), AEA (2008)
	Low	%	92.0%	92.5%	93.0%	93.5%	94.0%	AEA indicative estimate
	High	%	92.0%	93.0%	94.0%	95.0%	96.0%	AEA indicative estimate
Fuel cell	**Best**	%	54.0%	56.5%	59.0%	61.5%	64.0%	AEA (2008)
	Low	%	54.0%	55.5%	57.0%	58.5%	60.0%	AEA indicative estimate
	High	%	54.0%	57.5%	61.0%	64.0%	64.0%	AEA indicative estimate
Electric powertrain	LDV	%	95%	95%	95%	95%	95%	Indicative estimate based on IEA (2012, forthcoming).
	HDV	%	95%	95%	95%	95%	95%	
	Motorcycle	%	95%	95%	95%	95%	95%	
Battery charger	LDV	%	87.2%	90.0%	92.7%	95.3%	97.8%	Calculated from efficiency
	HDV	%	87.2%	90.0%	92.7%	95.3%	97.8%	of Battery and Battery +
	Motorcycle	%	87.2%	90.0%	92.7%	95.3%	97.8%	Charger
Battery + Charger	LDV	%	75.0%	78.8%	82.5%	86.3%	90.0%	Cenex (2012), AEA (2008)
	HDV	%	75.0%	78.8%	82.5%	86.3%	90.0%	As for LDVs
	Motorcycle	%	75.0%	78.8%	82.5%	86.3%	90.0%	As for LDVs

3.2.1.2 Mode specific basic components

The mode specific basic component efficiencies include the overall efficiency assumptions for individual powertrain types, which are presented Table 3.3 for light duty vehicles and motorcycles, and Table 3.5 for heavy duty vehicles.

The figures for LDVs are based primarily on TNO (2011) and AEA-TNO (2009), with the exception of H2 fuel cell vehicles, which were estimated based on a range of values available in the literature (Honda, 2012; EERE, 2010). The savings listed in the table for LDVs indicate efficiencies relative to the base technology – which is petrol ICE for petrol-based technologies, and diesel ICE for everything else. Efficiencies of diesel ICE versus petrol ICE are around 25%, calculated from the relative energy consumption (in MJ/km) of petrol and diesel C+D class vehicles (see Section 2.3 on vehicle characteristics). The efficiency improvements listed for PHEV and REEVs are combined average efficiencies based on relative % distance travelled in ICE/fuel cell mode and battery electric mode. In the model analysis the efficiencies of running on full battery electric mode and the alternative mode are tracked separately, with efficiency benefits assumed to be in line with BEVs and HEVs (or H2FCs as appropriate) respectively.

Table 3.2: Summary of the light duty vehicle and motorcycle powertrain efficiency assumptions used in the study analysis

Component	Type	T#	2010 Efficiency improvements over the base technology*, %		
			Cars	Vans	Motorcycles
Petrol ICE	Ptrain	1	0.0%	0.0%	0.0%
Diesel ICE	Ptrain	2	0.0%	0.0%	N/A
Petrol HEV	Ptrain	3	25.0%	25.0%	25.0%
Diesel HEV	Ptrain	4	22.0%	18.0%	N/A
Petrol PHEV**	Ptrain	5	46.9%	46.9%	N/A
Diesel PHEV**	Ptrain	6	45.2%	45.2%	N/A
Petrol REEV**	Ptrain	7	56.6%	56.6%	N/A
Diesel REEV**	Ptrain	8	55.5%	55.5%	N/A
BEV	Ptrain	9	76.0%	76.0%	76.0%
H2FC	Ptrain	10	53.7%	53.7%	53.7%
H2FC-PHEV**	Ptrain	11	63.3%	63.3%	N/A
H2FC-REEV**	Ptrain	12	67.5%	67.5%	N/A
NG ICE	Ptrain	13	-24.6%	-15.0%	N/A

Sources: Calculated from on data provided in TNO (2011) and AEA-TNO (2009), except for H2FC, which is based on a range of estimates available in the literature on the current efficiency of fuel cell vehicles.

Notes: * Base technology referenced against is petrol for petrol fuelled vehicles and diesel for all other powertrain types.
** Efficiency improvements listed for PHEV and REEVs are combined average efficiencies based on relative % distance travelled in ICE mode (= HEV efficiency assumed for petrol/diesel, and H2FC efficiency assumed for H2FC PHEV/REEV) and battery electric mode (= BEV efficiency assumed).

The figures for HDVs in Table 3.5 are based primarily on AEA-Ricardo (2011), with the exception of H2 fuel cell vehicles, which were assumed to be similar to the LDV estimates.

Table 3.3: Summary of the heavy duty vehicle powertrain efficiency assumptions used in the study analysis

Component	Type	T#	2010 Efficiency improvements over the base technology, %					
			Small Rigid Truck	Large rigid Truck	Articulated Truck	Construction Truck	Bus	Coach
Diesel ICE	Ptrain	1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Diesel FHV	Ptrain	2	15.0%	7.5%	5.0%	6.3%	20.0%	7.5%
Diesel HHV	Ptrain	3	10.0%	5.0%	3.3%	4.3%	15.0%	5.6%
Diesel HEV	Ptrain	4	20.0%	10.0%	7.0%	8.5%	30.0%	10.0%
BEV	Ptrain	5	70.0%	N/A	N/A	N/A	70.0%	N/A
H2FC	Ptrain	6	53.7%	53.7%	53.7%	53.7%	53.7%	53.7%
DNG ICE (2)	Ptrain	7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NG ICE (2)	Ptrain	8	-15.0%	-15.0%	-15.0%	-15.0%	-15.0%	-15.0%

Sources: Based on efficiencies provided in AEA-Ricardo (2011), except for H2FC, which is based on a range of estimates available in the literature on the current efficiency of fuel cell vehicles.

3.2.2 Efficiency Improvement Technologies

This section provides a summary of the sources and assumptions for the performance of mode specific efficiency improvement technologies.

The study analysis assumptions for the efficiency improvement technology costs for cars and vans are presented in Table 3.4. These technology costs have been sourced primarily from TNO (2011) and AEA-TNO (2009). There are a range of sources available in the literature that have been reviewed and considered (see Section 8 of this report), providing estimates on technology cost and performance. However, these two sources were selected for use in this study as the most up-to-date, relevant (i.e. specific to the European market and conditions), comprehensive (covering all the significant technologies/types being considered/developed) and consistent.

Ideally it would also be desirable to account for greater benefits of measures resulting in improved rolling resistance (including weight reduction) for electric powertrains/vehicles[3]: For conventional ICE powertrains, most of the energy losses over the NEDC are due to the ICE - around 70% of total losses, with rolling resistance around 5-6% of total losses. However, for electric vehicles the drivetrain is highly efficient, so that rolling resistance losses are a much higher proportion of the total (maybe over 50% of all losses). Hence, since weight reduction essentially acts to reduce rolling resistance losses it has a proportionally higher impact in reducing electric powertrain energy consumption. However, it was not possible to take this to be taken it into account within the study's analysis – partly due to a lack of suitable data for quantification, and partly due to the significant additional complexity that this would have entailed in the study calculation framework.

Table 3.4: Summary of the technology efficiency assumptions for the car and van analysis

Efficiency Improvement Technology	Category	#	Efficiency Improvement, %	
			Cars[(1)]	Vans[(2)]
Petrol - low friction design and materials	PtrainE	1	2.0%	1.5%
Petrol - gas-wall heat transfer reduction	PtrainE	2	3.0%	3.0%
Petrol - direct injection (homogeneous)	PtrainE	3	5.3%	5.5%
Petrol - direct injection (stratified charge)	PtrainE	4	9.3%	9.5%
Petrol - thermodynamic cycle improvements	PtrainE	5	14.5%	15.0%
Petrol - cam-phasing	PtrainE	6	4.0%	4.0%
Petrol - Variable valve actuation and lift	PtrainE	7	10.5%	11.0%
Diesel - Variable valve actuation and lift	PtrainE	8	1.0%	1.0%
Diesel - combustion improvements	PtrainE	9	2.0%	1.5%
Mild downsizing (15% cylinder content reduction)	PtrainE	10	5.5%	2.7%
Medium downsizing (30% cylinder content reduction)	PtrainE	11	8.5%	9.3%
Strong downsizing (≥45% cylinder content reduction)	PtrainE	12	17.5%	18.5%
Reduced driveline friction	PtrainE	13	1.0%	1.0%
Optimising gearbox ratios / down-speeding	PtrainE	14	4.0%	2.7%
Automated manual transmission	PtrainE	15	5.0%	4.0%
Dual clutch transmission	PtrainE	16	6.0%	5.0%
Start-stop hybridisation	PtrainE	17	5.0%	4.0%
Regenerative breaking (smart alternator)	PtrainE	18	7.0%	6.0%
Aerodynamics improvement	Aero	1	1.8%	1.1%
Low rolling resistance tyres	Rres	1	3.0%	3.0%
Mild weight reduction (~10% reduction in BIW*)	Weight	1	2.0%	1.5%
Medium weight reduction(~25% reduction in BIW*)	Weight	2	6.0%	6.1%
Strong weight reduction (~40% reduction in BIW*)	Weight	3	12.0%	11.0%
Lightweight components other than BIW	Weight	4	2.0%	1.5%
Thermo-electric waste heat recovery	Other	1	2.0%	2.0%
Secondary heat recovery cycle	Other	2	2.0%	2.0%
Auxiliary systems efficiency improvement	Other	3	12.0%	11.0%
Thermal management	Other	4	2.5%	2.5%

Notes:

(1) Data based on average of C and D class cars from TNO (2011)
(2) Data from TNO (2011) for large cars was used to update the older/previous assumptions for vans by scaling data from AEA-TNO (2009) – which contained comparable data for both car and van technologies..

[3] Personal communication with Angela Johnson of Ricardo, following the workshop held on 2 February 2012 at CCC's offices.

The study analysis assumptions for the efficiency improvement technology performance for motorcycles and mopeds are presented in Table 3.5. These have been sourced from a limited range of identified literature including principally publications by the IEA (2009) and ICCT (2011), together with indicative AEA estimates for technologies based on those for petrol cars where no suitable data in the literature could be identified.

Table 3.5: Summary of the technology efficiency assumptions for the motorcycle analysis

Efficiency Improvement Technology	Category	#	Efficiency Improvement, %
Air assisted direct injection for 2-stroke engines (1)	PtrainE	1	30.0%
Electronic port fuel injection for 4-stroke engines (1)	PtrainE	2	20.0%
Swirl control valve (1)	PtrainE	3	7.0%
Variable ignition timing (2)	PtrainE	4	8.5%
Engine friction reduction (2)	PtrainE	5	4.0%
Optimising transmission systems (2)	PtrainE	6	0.5%
Start-stop hybridisation (2)	PtrainE	7	5.0%
Aerodynamics improvement (2)	Aero	1	0.9%
Low rolling resistance tyres(2)	Rres	1	1.5%
Light weighting(2)	Weight	1	2.0%
Thermo-electric waste heat recovery (3)	Other	1	2.0%

Source: (1) ICCT (2011); (2) Estimates by AEA based on data for cars for measures without efficiency values identified by IEA (2009), ICCT (2011) and other sources. (3) AEA estimate based on car option.

The study analysis assumptions for the efficiency improvement technology costs for heavy duty vehicles are presented in Table 3.6. These have generally been sourced from recent work carried out by AEA and Ricardo for the European Commission (AEA-Ricardo, 2011), which further updated analysis Ricardo had previously carried out for DfT (Ricardo, 2009). For the purposes of this studies analysis, the categories provided in AEA 2011 have been mapped onto the vehicle categories used in this study as follows:

AEA-Ricardo (2011) category		*Study category*
Urban Delivery	=	Small rigid truck
Regional Delivery	=	Large rigid truck
Long haul	=	Articulated
Construction	=	Construction

TIAX recently carried out a review of the AEA-Ricardo (2011) study assumptions and modelling results on behalf of ICCT, which was completed in December 2011 (TIAX, 2011). This study utilised the efficiency and cost assumptions TIAX developed for the recent US review of heavy duty vehicles (NAS, 2010) that fed into the recent development of regulations aimed at significantly improving HDV efficiency in the US. The TIAX (2011) study findings were generally in close consistency with the AEA-Ricardo (2011) work – within the range of the analysis uncertainty[4]. However, there were significant variations between the costs and performance of predictive cruise control technology between the two studies.

For predictive cruise control, it appears that there may be differences in the sophistications of the systems evaluated in AEA-Ricardo (2011) and TIAX (2011), since there were also significant deviations in capital costs (the more efficient system being significantly higher costs)[5]. Therefore, two levels of predictive cruise control have been used in this study's analysis. In addition, there were no figures available in AEA-Ricardo (2011) for mechanical turbocompounding, therefore estimates were made based on the difference between mechanical and electrical turbocompounding from ICCT (2009).

[4] Confirmed in personal communications between AEA and the lead author of the TIAX (2011) study in December 2011.
[5] Based on personal communications between AEA and the TIAX (2011) lead author. As part of their work for NAS (2010) study, which fed into the work for ICCT, they gathered data from a wide range of US manufacturers, upon which their study costs and efficiencies are largely based.

Table 3.6: Summary of the technology efficiency assumptions for the HDV analysis

Technology	Cat.	#	Efficiency Improvement, %					
			Small Rigid	Large Rigid	Articulated Truck	Construction Truck	Bus	Coach
General improvements (2010-2020)*	PtrainE	1	-3.0%	0.2%	2.3%	-3.0%	0.9%	0.2%
General improvements (2020-2030)*	PtrainE	1	3.0%	6.2%	8.3%	3.0%	5.1%	6.2%
Mechanical Turbocompound	PtrainE	2	0.7%	0.7%	2.0%	1.8%	0.7%	1.7%
Electrical Turbocompound	PtrainE	3	1.0%	2.5%	3.0%	2.8%	1.0%	2.5%
Heat Recovery (Bottoming Cycles)	PtrainE	4	1.5%	2.5%	5.0%	3.8%	1.5%	2.5%
Controllable Air Compressor	PtrainE	5	0.0%	1.0%	1.5%	1.3%	0.0%	1.0%
Automated Transmission	PtrainE	6	5.0%	1.5%	1.5%	1.5%	5.0%	1.5%
Stop / Start System	PtrainE	7	6.0%	3.0%	1.0%	2.0%	4.0%	3.0%
Pneumatic Booster – Air Hybrid	PtrainE	8	1.5%	1.5%	3.5%	2.5%	0.0%	1.5%
Aerodynamic Fairings	Aero	1	0.0%	1.0%	0.4%	0.7%	0.0%	1.0%
Spray Reduction Mud Flaps	Aero	2	1.0%	2.0%	3.5%	2.8%	1.0%	2.0%
Aerodynamic Trailers / Bodies	Aero	3	1.0%	11.0%	11.0%	5.8%	N/A	4.1%
Aerodynamics (Irregular Body Type)	Aero	4	1.0%	6.5%	5.0%	2.8%	N/A	N/A
Active Aero	Aero	5	1.0%	5.0%	8.0%	0.0%	1.0%	5.0%
Low Rolling Resistance Tyres	Rres	1	1.0%	3.0%	5.0%	4.0%	1.0%	3.0%
Single Wide Tyres	Rres	2	4.0%	6.0%	5.0%	5.5%	4.0%	6.0%
Automatic Tyre Pressure Adjustment	Rres	3	1.0%	2.0%	3.0%	2.5%	1.0%	2.0%
Light weighting	Weight	1	4.0%	2.2%	2.2%	0.3%	6.0%	2.2%
Predictive Cruise Control	Other	1	N/A	1.5%	1.5%	1.5%	N/A	1.5%
Smart Alternator, Battery Sensor & AGM Battery	Other	2	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Alternative Fuel Bodies *	Other	3	15.0%	15.0%	15.0%	7.5%	N/A	N/A
Advanced Predictive Cruise Control	Other	4	N/A	5.0%	5.0%	5.0%	N/A	5.0%

Source: Based on datasets from AEA-Ricardo (2011), ICCT (2009) and TIAX (2011).

Notes: * These are general incremental improvements to vehicle and powertrain (other than the headline technologies listed in this table), and impacts of more AQ pollutant control (as defined in AEA-Ricardo, 2011). The % improvements quoted are net per decade (unlike other technology options). However it is assumed that all the underlying technologies are utilised fully by 2030 (and no further Euro standards after 2020) - hence there is no further change after then. For some vehicle types the impacts of additional AQ pollutant control on fuel consumption outweigh the efficiency improvements.
** AEA estimate for saving for alternative fuel bodies for construction trucks (mostly tippers) 50% of other truck types (including RCVs and refrigerated vehicles, where auxiliary loads are estimated to be significantly higher on average).

3.2.3 Real-World Efficiencies

It is currently widely acknowledged that there is a significant (and potentially widening) differential between the performance of road vehicles on regulatory or other test-cycles and in real-world conditions of use. This differential is due to a range of factors including the use of accessories (air con, lights, heaters etc), vehicle payload (most significant for vans and heavy duty trucks), poor maintenance (tyre under inflation, maladjusted tracking, etc), gradients (tests effectively assume a level road), weather, more aggressive/harsher driving style, differences in operational usage cycles, etc. (DCF, 2011a). Real-world uplifts in the order of 15-18% for existing vehicle fleets are currently factored into most major modelling exercises (DCF, 2011a). However, there is some evidence that the size of the discrepancy between test-cycles and real-world performance is increasing for LDVs (LowCVP, 2011).

A review of the evidence available has not provided very significant amount of new information in this area. TNO (2011) uses an uplift of 19.5% on new car efficiencies, which is, if anything on the low side when compared to a recent review by Ricardo for LowCVP (2011).

A summary of the results of LowCVP (2011) are summarised in Table 3.7. In this study, Ricardo compared the NEDC reported gCO_2/km performance for 2-3 of the most popular /representative vehicle models in each market segment with those from Autocar magazine tests. However, such magazine tests may not be truly representative of the average driving behaviour on UK roads. Therefore the TNO (2011) factor has been selected for the purposes of this study's analysis to represent most appropriate real-world uplift to apply to 2010 new passenger cars (and vans) for conventional ICE technologies.

Table 3.7: Summary of the differences found between gCO_2/km values from NEDC and Autocar Magazine tests

Market Segment	Av. Difference NEDC to Autocar Test	2010 Registrations*	
	%	Number, #	Proportion, %
A: Mini	27.3%	53,269	2.7%
B: Small	20.7%	739,615	36.8%
C: Lower Medium	24.5%	532,881	26.5%
D: Upper Medium	17.5%	253,584	12.6%
E: Executive	22.5%	98,872	4.9%
F: Luxury	23.7%	7,655	0.4%
G: Sports	18.0%	44,679	2.2%
SUV	21.3%	153,220	7.6%
MPV	32.7%	124,206	6.2%
Weighted Average	**22.3%**	**2,007,981**	**100%**

Sources: Calculations based on data from LowCVP (2011). Vehicle registrations data from SMMT (2011).

Notes: Comparisons were made by Ricardo between NEDC and Autocar test results for 2-3 of the most popular /representative vehicle models in each category.

In general it does appear from limited information available (e.g. LowCVP, 2011) that the real-world performance is further away from the NEDC figures for the most efficient vehicles. For non-conventional powertrain technologies, there is little evidence available on real-world differences. Other than the LowCVP (2011) study (which also considered a limited range of hybrid and electric vehicles) and recent work by Cenex (2009), there is mostly anecdotal information that uplifts are generally greater than for conventional technologies. However, analysis by Cenex of data from the current UK trials of electric vehicles (funded by TSB) has indicated that the average differential between manufacturer claims on typical range, and those achieve during the trials was almost 25%. We have used this figure, together with what other little information is available to estimate modified uplifts for the purposes of this study for passenger cars, which are presented in Table 3.8.

A further consideration is that there are losses associated with charging the batteries of hybrid and electric vehicles. For regular HEVs, these losses are fully accounted for within the vehicle's operation. However, for PHEVs, REEVs and BEVs these losses are not accounted for by simple comparison of the stored energy capacity of the battery and the observed vehicle range, although they directly affect the actual amount of energy consumed. According to Cenex, the best combined charging and battery efficiencies they have observed on modern EVs is in the low 80%s, more typically around 75% and occasionally even lower.[6]

These losses are not accounted for in the real-world uplifts, since they are not on the vehicle-side. However they should be accounted for separately in any overall analysis carried out involving such vehicles – potentially through incorporation into the efficiencies of delivering electricity to plug-in vehicles (i.e. in addition to electricity grid transmission and distribution losses), such as within/on top of electricity GHG emission factors utilised.

For other road transport modes, there is also very little or no information available on differences between test-cycle based data and the real world. This is a particular problem for HDVs, where regulatory tests are on the engine only. Full-body test-cycle methodologies are currently still under development at a European level (partly driven by the desire to more effectively assess and potentially regulate HDV energy consumption/GHG emissions) with likely introduction towards the end of the decade (AEA-Ricardo, 2011). The situation is also complicated by the huge diversity of HDVs in both their configurations and duty cycles.

[6] Personal communication between AEA and Steve Carol (Cenex), i.e. these figures include all the 'lost' energy that comes out of the wall socket but doesn't end up coming out of the battery to power the vehicle.

However, test-cycle assessments have been carried out on road transport vehicles recently by TRL in order to develop/update the speed-emission curves (see DfT, 2009) that are used in the compilation of the UK's National Atmospheric Emissions Inventory (NAEI). These include fuel consumption and CO_2 emission functions used in the GHG inventory which is part of the NAEI. Similar speed-emission/fuel consumption functions are also used in road transport emissions modelling outside of the UK (e.g. in the COPERT model, widely used in Europe to help countries compile their road transport emissions inventories).

Therefore, in order to develop suitable 'real-world' uplifts for this study's analysis, we have compared such speed-fuel consumption curve developed estimates (from AEA-Ricardo, 2011) for the UK situation with available data (mainly from DfT statistics) on actual real-world fuel consumption of vehicles in different categories. The results of this analysis are also presented in Table 3.8, with a summary of the main sources and assumptions for the different real-world uplift factors provided in the accompanying Table 3.9.

Note: The test-cycle based vehicle efficiencies for trucks are based on average truck activity on urban/rural/motorway roads. In reality there are very significant operational/mission characteristics for different types of truck which have a very marked impact on their fuel consumption (e.g. predominantly urban driving for smaller trucks). The actual real-world fuel consumption data used to generate the 'real-world' uplifts intrinsically includes these operational differences for different sizes of vehicles, which in some cases results in very significant or very small real-world uplifts. The real-world uplift figures for HDVs are therefore indicative for the purposes of the modelling and not equivalent to those for cars and vans.

Table 3.8: Summary of the basic real-world efficiency uplift assumptions used in the study analysis for different vehicle powertrains

Type	2010 Basic Real-world efficiency uplifts, %								
	Car	Van	Motor-cycle	Small Rigid Truck	Large rigid Truck	Articulated Truck	Construction Truck	Bus	Coach
ICE	19.5%	19.5%	30.2%	41.3%	9.0%	0.0%	9.0%	8.8%	9.0%
FHV				42.5%	10.1%	1.1%	10.1%	9.9%	10.1%
HHV				42.5%	10.1%	1.1%	10.1%	9.9%	10.1%
HEV	21.7%	21.7%	30.2%	42.5%	10.1%	1.1%	10.1%	9.9%	10.1%
PHEV**	22.6%	22.6%							
REEV**	23.5%	23.5%							
BEV	24.6%	24.6%	24.6%	43.9%				11.4%	
H2FC	24.6%	24.6%	24.6%	43.9%	11.5%	2.6%	11.5%	11.4%	11.5%

Sources: Summarised in Table 3.9.

Table 3.9: Summary of the sources/methods used to estimate the basic real-world efficiency uplift assumptions used in the study analysis for different vehicle powertrains

Type	Sources and assumptions for 2010 Basic Real-world efficiency uplifts, %								
	Car	Van	Motor-cycle	Small Rigid Truck	Large rigid Truck	Articulated Truck	Construction Truck	Bus	Coach
ICE	(1)	(1)	(2)	(3)	(3)	(3)	(3)	(4)	(5)
FHV				(6)	(6)	(6)	(6)	(6)	(6)
HHV				(6)	(6)	(6)	(6)	(6)	(6)
HEV	(7)	(7)	(7)	(8)	(8)	(8)	(8)	(8)	(8)
PHEV**	(9)	(9)	(9)						
REEV**	(9)	(9)	(9)						
BEV	(7)	(7)	(7)	(8)				(8)	
H2FC	(10)	(10)	(10)	(10)	(11)	(11)	(11)	(10)	(11)

Sources:

(1) TNO (2011), for new cars
(2) AEA estimate based on NAEI data vs DCF (2011) (reported fuel consumption data)
(3) Estimated by comparing test-cycle based efficiencies relative to DfT fuel consumption stats (2011)
(4) Estimated by comparing test-cycle based efficiencies relative to BSOG fuel consumption calculations from DfT (2011)
(5) Assumed to be the same as for large rigid trucks (similar duty cycle)

(6) Assumed to be similar to HEVs
(7) AEA estimate based on limited survey of current passenger car models from LowCVP (2011), and information on average EVs from Cenex (2012) based on the UK's current EV trials.
(8) AEA estimate based on 50% of the differential between car ICE and HEV increase from LowCVP (2011), since small rigid trucks and buses are used in urban cycles where hybrid/BEV is optimal and other vehicle types have already reduced efficiency assumptions generally based on real-world performance assumptions for hybrids from AEA-Ricardo (2011).
(9) Indicative estimate based on the corresponding figures for HEVs and BEVs weighted by the % km distance travelled in ICE mode and full electric mode respectively.
(10) Assumed to be similar to the uplift for BEVs.
(11) Assumed to be similar to the uplift for hybrid vehicles.

In addition to the development/understanding of test-cycle and real-world differences for existing vehicles and technologies, CCC have indicated they wish to get a better understanding on whether these differentials are likely to get larger as vehicles of a given powertrain type get more efficient.

As already indicated, and illustrated in Table 3.8, the most efficient technologies appear to have the largest differentials. Recent work by Cenex (2009) assessing the performance of current electric vehicles has provided some insights as to some of the reasons for the discrepancy. The findings from this work suggests that a significant proportion of the additional energy consumption is due to the hotel power requirements (energy consumption) of auxiliaries – particularly air conditioning/heating – which are not included in current test-procedures for light-duty vehicles. The hotel power requirements for EVs, HEVs and pure ICEs will remain essentially similar i.e. independent of drive-train technology. They will therefore account for larger proportion of the total energy consumption of more efficient vehicles. Improvements in the efficiency of such auxiliaries might therefore be expected to reduce this differential in the future. Such issues are likely to be less important for HDVs.

In addition, there are certain flexibilities in the existing NEDC test procedures for LDVs that if taken advantage of by manufacturers, could potentially lead to apparently greater levels of improvements than are found in real-world conditions. This topic is currently the subject of investigation in work recently started for the EC that AEA is contributing to.

In order to provide an estimate for the increasing gap between test-cycle and real-world performance as additional efficiency improvement technologies are utilised, we have developed the percentage reduction factors presented in Table 3.10, based on data from TNO (2011). These figures represent the percentage by which the total improvement in energy efficiency calculated from the combination of individual technologies should be reduced to account for both overlap in their impacts (where effects are on the same source of energy loss) and real-world performance. They are applied as in the following example:

Real world improvement through application of technologies A–C =

Total estimated test-cycle improvement from A-C (%) x (1 – *RWF*)

Where:

RWF = Real-world reduction factor from Table 3.10.

Table 3.10: Additional real-world correction factors used in the study analysis

Area	RW safety margin, % reduction in overall vehicle efficiency improvement				
	2010	2020	2030	2040	2050
Petrol technologies*	3.0%	6.0%	9.0%	12.0%	15.0%
Diesel technologies**	1.0%	2.0%	3.0%	4.0%	5.0%

Sources: Based on the estimate of the safety margin for the end of the cost-curves from TNO (2011).

Notes: These figures represent the percentage by which the total improvement in energy efficiency calculated from the combination of individual technologies should be reduced to account for both overlap in their impacts and real-world performance.
* The petrol margin also used for 'other' LDV technologies (i.e. BEV, H2FC, and the electric operation of PHEV/REEV) since it is higher and therefore is assumed to better reflect the greater discrepancy to real-world performance for the most efficient light duty vehicles.
** The diesel margin is used for all HDV technologies, reflecting anticipated lower significance for them.

4 Capital Cost Assumptions

This chapter provides a more detailed summary of the methodological approach, calculations, data sources and assumptions used in the development of the study dataset for technology capital costs.

4.1 Calculation Methodology

4.1.1 Methodologies for projecting capital costs

The future costs associated with technological options for reducing CO_2 will evolve as a direct consequence of the scale of application (willingness to pay, economies of scale and learning effects) and time (innovation). Decreases in the costs of technology arise due to a combination of direct and indirect factors including:

Direct factors

- Improvements in production processes (i.e. over time, and with increases in the scale of manufacturing, production processes can become more efficient, thereby reducing costs);
- Technological or manufacturing innovations may lead to reductions in unit costs (e.g. new materials or production processes);
- A move to mass production from low-volume production;

Indirect factors

- Subsidies and financial incentives to promote technology (e.g. electric car discount or 0% VED on green cars); and
- Greater demand or change in consumer behaviour (mainly influenced by environmental policies).

To capture the impact of the above factors a number of different methods, theories, estimates and assumptions have been used in the literature (Table 4.1).

When considering a purchase, capital cost is always the primary factor for the mass market. However, the potential for lower running costs is largely ignored by the mass market i.e. life cycle costing (or Net Present Value) is rarely considered at the point of purchase. The challenge for OEMs is to achieve manufacturing efficiencies with alternative powertrain by bringing down the capital cost, for example the cost of batteries in electric powertrains.

Decreases in the marginal costs of technology due to the factors above can be quantitatively described using learning rate theory. Learning rate theory enables changes in the costs associated with a particular technology to be quantified in relation to levels of deployment in the market. The application of learning rate theory is not straightforward in practice, because there are a number of unknown factors that cannot be foreseen with absolute accuracy. In particular, it is difficult to predict future innovations and, with respect to vehicle technologies, the rate at which costs will decrease is highly dependent on the levels of activity and investment in research and development made by vehicle manufacturers.

Table 4.1: Summary of alternative potential options for forward projecting capital costs

Methods, estimates, theories & Assumptions	Description	Impact on capital cost
Penetration rates	A measure of the amount of sales or adoption of a product or service compared to the total market for that product or service.	High (or faster) penetration rates can bring down capital cost, as higher sales volumes drive cost reduction due to economies of scale and development of the product to reduce cost. Can be used in conjunction with learning rates
Economies of scale	Cost advantages due to expansion of production or market	Greater economies of scale can reduce capital costs
Cost of sub-components	Available information on capital costs of sub-components	Possible to estimate total product cost from cost of sub-components and estimates of other cost components, e.g. margin and assembly costs
Cost trajectories based on learning rates	Decreases in the marginal costs of technology due to innovation, economies of scale and improvement in production process over time is defined as learning rate	Learning rate methods assume that production costs fall in a logarithmic trajectory with total cumulative production volumes (i.e. when cumulative production volumes double, costs fall by a given proportion). This has been observed in practice with many technologies as they reach maturity, but is less representative of very early stages where innovation is more significant in cost reduction than accumulated learning. Moreover, the drivers of cost reduction mentioned above go beyond pure economies of scale and some take time in order to be realised. In other words there is an implicit time dimension in learning rate theory that needs to be taken into account when applying learning rate equations, as very rapid growth in production volumes (which in itself may be unlikely due to logistic and market reasons) may not be accompanied by a quick reduction in cost.

In developing a dataset on technology capital cost projections for this study, a pragmatic approach has been used on the basis of a combination of (i) limitations of data/information in the literature, (ii) the short study period, and (iii) study resources in relation to the wide range of technologies and vehicle types/combinations covered. The approach utilises some of the different methods, theories, estimates and assumptions described in Table 4.1 above. The core of the methodology revolves around developing an estimate of the total production cost using the costs of sub-components. In general, two broad approaches have been adopted dependant on the type of technology to estimate the future costs of these sub-components. These are defined as follows, with a summary of the rational used for the approach taken:

A. ***Basic Components:*** These are the mostly mode-independent costs for powertrain-level technologies (i.e. for conventional ICEs, HEVs, PHEVs, BEVs, H2FC vehicles, etc.). For example they include cost per kW power required for engines, electric motors, fuel cells, and cost per kWh for batteries, natural gas or H_2 storage:
   - The available information from the literature for these technologies generally provides estimates based on current prices and future cost reductions (with built in assumptions on various levels of deployment/innovation or meeting future research targets). Figures typically have a wide range of values in the literature and depend on a lot of assumptions / different sources, methodologies.

- Since this study was not developing a dataset of powertrain penetration levels, it is not possible to directly model potential cost reductions using learning rates – also this has to an extent already been done by others in the literature. Therefore we have used existing estimates for these costs (often with upper/lower values) and their projections from 2010-2030/2050. These have been mainly sourced from the Element Energy report for LowCVP (EE, 2011), which carried out a comprehensive review of the literature and developed datasets to 2030. These have been extrapolated out to 2050 using other available information sources.
- Generally overall technology costs for a given vehicle class are calculated by scaling to the vehicle characteristics – i.e. required peak power rating (for ICE/motors, etc), MJ/km and range (for energy storage), though some are essentially fixed values for a particular mode category (e.g. after treatment costs for LDV, HDV, motorcycles). This is discussed further in the Section 4.1.2.

B. ***Efficiency Improvement Technologies:*** These are mode-specific technology costs applied below/onto different powertrain options (i.e. as indicated above):
   - For these, information from the literature does not usually provide very much detail on the basis for cost estimates developed, though a few of the key sources referenced provide higher-level details. Generally capital cost estimates from the literature have been put together assuming mass deployment (though with further cost reduction possible in the future at a lower rate). Even so it is not always clear whether data are on a consistent basis even within the same study.
   - Since assumptions/estimates are being made for this study on levels of deployment of technologies within modes technology learning rates have been used in combination with indicative figures for 'mass-deployment' to estimate more modest future cost reductions trajectories. This is discussed further in the Section 4.1.3.

Total vehicle costs are calculated according to the following formula:

Total Vehicle Cost (£) = Powertrain cost (£) + Energy storage cost (£) + Glider cost (£) + Total efficiency improvement technology costs (£)

The methodology for calculating the individual component costs is outlined in the following sections.

Where the figures that have been sourced were in US$ or Euro currencies, the following exchange rates have been applied:

	Pound, £	Euro, €	USD, $
Pound, £		1.25	1.8
Euro, €	0.800		1.440
USD, $	0.556	0.694	

4.1.2 Basic Components

This section provides a summary of the methodology of calculation of change in costs of basic powertrains from 2010-2050, providing the specific formulas used for calculating the capital cost of the powertrain, energy storage and glider.

4.1.2.1 Powertrain costs

Powertrain costs for different vehicle types and powertrains are calculated mainly from mode-independent costs for powertrain-level technologies as follows by powertrain type:

Powertrain	Summary calculation for powertrain cost (for a given year)
Petrol ICE /Diesel ICE	**Total Cost (£)** = Power (kW) x ICE cost (£/kW)* + ICE aftertreatment cost (£)**
DNG ICE	As for ICE + Dual fuel system cost (£)***
NG ICE	As for ICE + NG system premium***
FHV	**Total Cost (£)** = Power (kW) x FHV ICE kW size (%) x ICE cost (£/kW)* + ICE aftertreatment cost (£)** + Flywheel hybrid system cost (£)***
HHV	Similar format to FHV
HEV	**Total Cost (£)** = Power (kW) x HEV ICE kW size (%) x ICE cost (£/kW)* + (Power (kW) x (1 - HEV ICE kW size(%)) x HEV Motor kW size (%) x Electric motor cost (£/kW)) + ICE aftertreatment cost (£)** + Electric drivetrain cost (£)**
PHEV	Similar format to HEV, but with PHEV ICE kW size (%)
REEV	Similar format to HEV, but with REEV ICE kW size (%)
BEV	**Total Cost (£)** = Power (kW) x BEV Motor kW size (%) x Electric motor cost (£/kW) + Electric drivetrain cost (£)**
H2FC	**Total Cost (£)** = Power (kW) x H2FC Motor kW size (%) x Electric motor cost (£/kW) + Electric drivetrain cost (£)**
H2FC PHEV /REEV	As for H2FC

Notes: * Separate costs for petrol/natural gas ICE and for diesel/dual-fuel ICE; also different costs for LDV and for HDV diesel ICE and NG ICE engine costs
** Separate fixed costs for LDVs and for Motorcycles; HDV scaled to kerb weight. -50% aftertreatment costs for petrol vehicles or natural gas fuelled vehicles
*** By HDV vehicle type

4.1.2.2 Energy storage costs

Energy storage costs for different vehicle types and powertrains are calculated mainly from vehicle range and energy efficiency assumptions using mode-independent costs for energy storage technologies, as follows by powertrain type:

Powertrain	Summary calculation for energy storage cost (for a given year)
Petrol ICE /Diesel ICE	**Total Cost (£)** = ICE Range (km) x Vehicle efficiency (MJ/km) x Fuel tank cost (£/MJ)
DNG ICE	**Total Cost (£)** = ICE Range (km) x Vehicle efficiency (MJ/km) x Diesel tank cost (£/MJ) + ICE Range (km) x Vehicle efficiency (MJ/km) x NGas tank cost (£/MJ)*
NG ICE	**Total Cost (£)** = ICE Range (km) x Vehicle efficiency (MJ/km) x NGas tank cost (£/MJ)*
FHV	As for Petrol/Diesel ICE
HHV	As for Petrol/Diesel ICE
HEV	**Total Cost (£)** = ICE Range (km) x Vehicle efficiency (MJ/km) x Fuel tank cost (£/MJ) + (Electric Range (km) x Vehicle efficiency (MJ/km) x Battery cost (£/MJ)***) / Battery usable SOC for electric range (%)

PHEV / REEV	**Total Cost (£)** = ICE Range (km) x Vehicle efficiency (MJ/km) x Fuel tank cost (£/MJ) + (Electric Range (km) x Vehicle efficiency (MJ/km) x Battery cost (£/MJ)***) / Battery usable SOC for electric range (%) + Battery charger (£)**
BEV	**Total Cost (£)** = (Electric Range (km) x Vehicle efficiency (MJ/km) x Battery cost (£/MJ)***) / Battery usable SOC for electric range (%) + Battery charger (£)**
H2FC, H2FC PHEV /REEV	**Total Cost (£)** = ICE Range (km) x Vehicle efficiency (MJ/km) x H2 storage cost (£/MJ) + (Electric Range (km) x Vehicle efficiency (MJ/km) x Battery cost (£/MJ)***) / Battery usable SOC for electric range (%) + Battery charger (£)

Notes: * Similar costs assumed for CNG or LNG storage per MJ fuel
** Separate fixed costs for an LDV charger, for an HDV charger and for a Motorcycle charger.
*** Using different costs for (a) BEV (car/motorcycle), BEV (van/HDV), Non-BEV (car/motorcycle), Non-BEV (van/HDV). Where: 'Non-BEV' includes all HEV, H2FC, PHEV and REEV.
**** Vehicle efficiency (MJ/km) is based on the calculated real-world value/basis

4.1.2.3 Glider cost

The glider cost is simply calculated according to the following formula:

Glider Cost (£) = Basic capital cost (£) – Powertrain cost (£) – Energy storage cost (£)

Where:

Basic capital cost (£) = Basic capital price (£) / (1 + Total manuf.+ dealer margin)

4.1.3 Efficiency Improvement Technologies

The methodologies employed for calculating the effects of multiple technologies and estimating cost reduction 2010-2050 are summarised in the following sub-sections.

4.1.3.1 Combining individual technology costs

Individual efficiency improvement technology (EIT) costs are calculated in an additive way based on the net increased percentage penetration/deployment in the new vehicle fleet versus 2010 levels from 2010 - 2050 (see Section 5.2 on the assumptions for this aspect). Total costs for efficiency improvement technologies are therefore calculated as follows:

Total EIT costs (£) = $EIT_{[1]}$ Cost (£) x % Deployment $EIT_{[1]}$
+ $EIT_{[2]}$ Cost (£) x % Deployment $EIT_{[2]}$
+ $EIT_{[3]}$ Cost (£) x % Deployment $EIT_{[3]}$
+ etc

Where:

$EIT_{[1]}$ Cost (£) = Total cost of efficiency improvement technology 1
% Deployment $EIT_{[1]}$ = Net increased percentage deployment of EIT 1 versus 2010

4.1.3.2 Estimating future technology cost reduction

The future cost reductions of individual efficiency improvement technologies from 2010 - 2050 is estimated using a learning rate methodology. This method allows the calculation of cost reductions based on assumptions on the deployment of a particular technology, the learning rate and initial level of deployment. Box 4.1 provides a summary of learning rate methodology, as applied in the CCC's transport MACC model (AEA, 2009).

Box 4.1: The utilisation of learning rates in CCC's transport MACC model (AEA, 2009)*

Learning rates in the existing transport MACC model are presented as decimal numbers between 0 and 1. A learning rate of 1 indicates a technology is in mass manufacture and there will not be further decrease in cost with increases in production levels. A learning rate of 0.95 for a particular technology indicates that the marginal cost of a vehicle equipped with that technology will reduce by 5% every time cumulative production levels double; a learning rate of 0.60 indicates that the marginal cost will decrease by 40% each time cumulative production levels double. The formula used to calculate the learning rates is as follows:

$$C_t = C_o \times \left(\frac{M_t}{M_o}\right)^b \quad \text{and} \quad b = \frac{\ln PR}{\ln 2}$$

Where

C_0	= Marginal capital cost in year 0 (starting year)
C_t	= Marginal capital cost at mass manufacture
M_0	= Estimate of cumulative production volumes in year 0 (starting year)
M_t	= Estimate of cumulative production volumes at mass production
PR	= Estimate of the learning rate
ln	= Natural log

The more mature technologies such as conventional petrol engines are at or close to mass-production, and so the range of learning rates will be small. In contrast, EVs and PHEVs are some way from mass production so there is far more uncertainty regarding the rate at which costs will reduce. As a result the range of learning rates will be significantly greater.

Finally it should be noted that technology learning is a global phenomenon that is ultimately linked to global production volumes. For reasons of expediency in the existing transport MACC model learning rates are however related to UK sales. This implicitly assumes that the increase in UK sales is a proportionate reflection of global trends, and may also quickly and implicitly result in an extension of learning rates to large global production volumes (if for instance a UK production volume of 100,000 corresponds to a global production volume which is likely to be an order of magnitude bigger).

Notes: Corrected from the original report wording to reflect cumulative production basis of calculations.

A similar methodology has been applied in this study's analysis, with a 2010 base. In general, where cost estimates have been provided on the basis of mass deployment - as is the case for the TNO (2011) dataset used as a basis for cars and vans – installed capacity has been set at a higher level for consistency, to ensure lower rates of future learning. The specific assumptions on learning rates and initial stock are presented in Section 4.2.2. The technology deployment assumptions are summarised in Chapter 5.

4.2 Key Sources and Assumptions

4.2.1 Basic components

This section provides a summary of sources and assumptions for basic component elements which are generally consistent across modes and powertrains.

The study analysis assumptions for the basic component capital costs are presented in Table 4.3. These technology costs have been sourced primarily from Element Energy's recent report for the LowCVP (EE, 2011), which carried out a comprehensive review of the material in this area available from the literature, and from TNO (2011) for a selection of specific elements. The figures provided for batteries are based mainly on a separate study commissioned by CCC investigating the anticipated future potential in this area that was recently completed (CCC/EE, 2012), supplemented with data from EE(2011).

In addition to these mode-independent component costs, there were a number of powertrain technologies for heavy duty vehicles that were not fully definable using these generic figures and vehicle characteristics. These are presented instead in the following Table 4.2 and are based primarily on AEA-Ricardo (2011) with some scaling of technology costs to different vehicle sizes.

Note there appears to currently be a significant degree of uncertainty in the expected cost of flywheel hybrid vehicle (FHV) technology at mass deployment. The current values provided in Table 4.2 are therefore indicative estimates based on a weighed (70:30) average of low estimates based on AEA-Ricardo (2011) which are for mass-deployment, and high estimates based on ETI (2012), which are for current conversions of London buses and are likely to be higher than the costs expected at mass deployment.

Table 4.2: Summary of the additional heavy duty powertrain technology capital cost assumptions used in the study analysis

Component	Type	T#	2010 Cost					
			Small Rigid Truck	Large rigid Truck	Articulated Truck	Construction Truck	Bus	Coach
Diesel ICE	Ptrain	1	(1)	(1)	(1)	(1)	(1)	(1)
Diesel FHV [2]	Ptrain	2	£8,089	£9,898	£13,636	£11,767	£9,898	£9,898
Diesel HHV	Ptrain	3	£8,630	£8,630	£14,547	£11,588	£10,560	£10,560
Diesel HEV	Ptrain	4	(1)	(1)	(1)	(1)	(1)	(1)
BEV	Ptrain	5	(1)	N/A	N/A	N/A	(1)	N/A
H2FC	Ptrain	6	(1)	(1)	(1)	(1)	(1)	(1)
DNG ICE [3]	Ptrain	7	£16,998	£20,800	£28,688	£24,601	£14,160	£20,800
NG ICE [3]	Ptrain	8	£16,998	£20,800	£28,688	£24,601	£14,160	£20,800

Sources: Based on costs provided in AEA-Ricardo (2011), scaled to different vehicle sizes.

Notes: (1) Calculated entirely based on individual components – see Section 4.1.
(2) Based on a weighted average of low figure based on AEA-Ricardo (2011) and high figure based on data supplied by ETI (2012) for conversions of London buses by Williams Hybrid Power.
(3) Partially calculated based on individual components – see Section 4.1.

Table 4.3: Summary of the basic component technology capital cost assumptions used in the study analysis

Area	Category	Unit	2010	2020	2030	2040	2050	Sources and other notes
Battery (BEV) (car/motorcycle)	**Best**	**£/kWh**	**403.6**	**176.9**	**117.8**	**103.3**	**88.9**	From CCC/EE (2012) to 2030, interpolate to DfT figure at 2050
	Low	£/kWh	342.0	176.9	100.0	94.4	88.9	EE (2011) to 2030, interpolate to DfT figure at 2050
	High	£/kWh	1369.0	833.0	530.0	465.0	400.0	EE (2011) to 2030, extrapolate based on best case
Battery (PHEV, other) (car/motorcycle)	**Best**	**£/kWh**	**737.3**	**300.4**	**234.7**	**205.9**	**177.1**	From CCC/EE (2012) to 2030, interpolate to DfT figure at 2050
	Low	£/kWh	624.7	300.4	199.3	188.2	177.1	Indicative estimate relative to differentials for EV batteries for cars
	High	£/kWh	1369.0	833.0	530.0	465.0	400.0	Indicative estimate relative to differentials for EV batteries for cars
Battery (BEV) (van/HDV)	**Best**	**£/kWh**	**325.9**	**140.5**	**95.1**	**92.0**	**88.9**	From CCC/EE (2012) interpolate relative to DfT figure at 2050 for cars
	Low	£/kWh	276.2	140.5	80.7	84.1	88.9	Indicative estimate relative to differentials for EV batteries for cars
	High	£/kWh	1105.6	661.4	427.9	414.0	400.0	Indicative estimate relative to differentials for EV batteries for cars
Battery (PHEV, other) (van)	**Best**	**£/kWh**	**414.2**	**183.3**	**146.3**	**128.4**	**110.4**	From CCC/EE (2012) interpolate relative to DfT figure at 2050 for cars
	Low	£/kWh	351.0	183.3	124.2	117.3	110.4	Indicative estimate relative to differentials for EV batteries for cars
	High	£/kWh	1369.0	833.0	530.0	465.0	400.0	Indicative estimate relative to differentials for EV batteries for cars
H2 storage	**Best**	**£/kWh**	**47.0**	**17.0**	**8.0**	**8.0**	**8.0**	EE (2011) to 2030, assume flat 2030
	Low	£/kWh	35	10	5	5	5	EE (2011) to 2030, assume flat 2030
	High	£/kWh	59	16	10	10	10	EE (2011) to 2030, assume flat 2030
CNG storage	**Best**	**£/kWh**	**3.7**	**3.7**	**3.7**	**3.7**	**3.7**	Based on JEC WTW (2005)
	Low	£/kWh	3.7	3.7	3.7	3.7	3.7	
	High	£/kWh	3.7	3.7	3.7	3.7	3.7	
Petrol ICE	**Best**	**£/kW**	**23.3**	**23.3**	**23.3**	**23.3**	**23.3**	TNO (2011), flat 2020-2050
	Low	£/kW	22.6	22.6	22.6	22.6	22.6	TNO (2011), flat 2020-2050
	High	£/kW	28	28	28	28	28	EE (2011) to 2030, assume flat 2030-2050
NG ICE	**Best**	**£/kW**	**23.3**	**23.3**	**23.3**	**23.3**	**23.3**	As for Petrol
	Low	£/kW	22.6	22.6	22.6	22.6	22.6	As for Petrol
	High	£/kW	28	28	28	28	28	As for Petrol
NG ICE (heavy duty)	**Best**	**£/kW**	**45.1**	**45.1**	**45.1**	**45.1**	**45.1**	Scaled up from NG ICE using differential between Diesel ICE and Diesel ICE (heavy duty)
	Low	£/kW	38.7	38.7	38.7	38.7	38.7	
	High	£/kW	60.3	60.3	60.3	60.3	60.3	
Diesel ICE	**Best**	**£/kW**	**28.9**	**28.9**	**28.9**	**28.9**	**28.9**	TNO (2011) to 2020, flat 2020-2050
	Low	£/kW	28	28	28	28	28	TNO (2011) to 2020, flat 2020-2050
	High	£/kW	29.7	29.7	29.7	29.7	29.7	TNO (2011) to 2020, flat 2020-2050

Area	Category	Unit	2010	2020	2030	2040	2050	Sources and other notes
Diesel ICE (heavy duty)	**Best**	**£/kW**	**56.0**	**56.0**	**56.0**	**56.0**	**56.0**	Based on information provided by Ricardo (2012)
	Low	£/kW	48.0	48.0	48.0	48.0	48.0	
	High	£/kW	64.0	64.0	64.0	64.0	64.0	
DNG ICE	**Best**	**£/kW**	**56.0**	**56.0**	**56.0**	**56.0**	**56.0**	As for Diesel (heavy duty)
	Low	£/kW	48.0	48.0	48.0	48.0	48.0	As for Diesel (heavy duty)
	High	£/kW	64.0	64.0	64.0	64.0	64.0	As for Diesel (heavy duty)
Electric motor	**Best**	**£/kW**	**33.0**	**17.7**	**11.4**	**11.4**	**11.4**	EE(2011), TNO (2011) flat 2030-2050
	Low	£/kW	22	10	5	5	5	TNO (2011), EE (2011)
	High	£/kW	53	25	25	25	25	EE (2011) to 2030, assume flat 2030-2050
Fuel cell	**Best**	**£/kW**	**811**	**250**	**75**	**53**	**48**	EE (2011), amended to reflect a more gradual rate of cost reduction 2010-2050: E (2011) 2020 estimates moved to 2030, 2030 estimates moved to 2040 and then extrapolated to 2050 to reflect expected further cost reduction. New figures for 2020 are approximately interpolated.
	Low	£/kW	391	100	35	34	34	
	High	£/kW	902	300	99	70	64	
ICE aftertreatment	LDV	£/vehicle		£706	£686	£667	£648	EE (2011) extrapolated 2030-2050 (assume for diesel, with petrol ~50%)
	HDV	£/tonne kerb weight		£0.502	£0.488	£0.474	£0.460	Calculated based on EE (2011), extrapolated 2030-2050
	Motorcycle	£/vehicle		£177	£172	£167	£162	Assume 25% LDV
Electric powertrain	LDV	£/vehicle	£1,350	£1,080	£864	£691	£553	TNO (2011) to 2030, extrapolated 2030-2050
	HDV	£/tonne kerb weight	£0.959	£0.768	£0.614	£0.491	£0.393	Calculated based on TNO (2011) to 2030, extrapolated 2030-2050
	Motorcycle	£/vehicle	£338	£270	£216	£173	£138	Assume 25% of LDV figure
Battery charger	LDV	£/vehicle	£279	£279	£227	£227	£227	EE (2011) to 2030, assume flat 2030-2050
	HDV	£/vehicle	£558	£558	£454	£454	£454	Assume 200% of LDV
	Motorcycle	£/vehicle	£140	£140	£114	£114	£114	Assume 50% of LDV

4.2.2 Efficiency Improvement Technologies

This section provides a summary of the sources and assumptions for mode specific efficiency improvement technologies.

The study analysis assumptions for the efficiency improvement technology costs for cars and vans are presented in Table 4.4. As for the corresponding efficiency figures, these technology costs have been sourced primarily from TNO (2011) and AEA-TNO (2009). There are a range of sources available in the literature that have been reviewed and considered (see Section 8 of this report), providing estimates on technology cost and performance. However, these two sources were selected for use in this study as the most up-to-date, relevant (i.e. specific to the European market and conditions), comprehensive (covering all the significant technologies/types being considered/developed) and consistent.

Table 4.4: Summary of the technology cost assumptions for the car and van analysis

Efficiency Improvement Technology	Category	#	Capital Cost, £		Learning Rate(3),(4)
			Cars(1)	Vans(2)	Cars and Vans
Petrol - low friction design and materials	PtrainE	1	£28	£22	0.95
Petrol - gas-wall heat transfer reduction	PtrainE	2	£40	£54	0.95
Petrol - direct injection (homogeneous)	PtrainE	3	£144	£120	0.95
Petrol - direct injection (stratified charge)	PtrainE	4	£440	£385	0.95
Petrol - thermodynamic cycle improvements	PtrainE	5	£390	£321	0.95
Petrol - cam-phasing	PtrainE	6	£64	£64	0.95
Petrol - Variable valve actuation and lift	PtrainE	7	£224	£191	0.95
Diesel - Variable valve actuation and lift	PtrainE	8	£224	£224	0.95
Diesel - combustion improvements	PtrainE	9	£40	£36	0.95
Mild downsizing (15% cylinder content reduction)	PtrainE	10	£220	£36	0.95
Medium downsizing (30% cylinder content reduction)	PtrainE	11	£378	£479	0.95
Strong downsizing (≥45% cylinder content reduction)	PtrainE	12	£520	£626	0.95
Reduced driveline friction	PtrainE	13	£40	£36	0.95
Optimising gearbox ratios / down-speeding	PtrainE	14	£48	£40	0.95
Automated manual transmission	PtrainE	15	£240	£222	0.95
Dual clutch transmission	PtrainE	16	£580	£528	0.95
Start-stop hybridisation	PtrainE	17	£170	£170	0.95
Regenerative breaking (smart alternator)	PtrainE	18	£320	£326	0.90
Aerodynamics improvement	Aero	1	£44	£48	0.95
Low rolling resistance tyres	Rres	1	£30	£29	0.95
Mild weight reduction (~10% reduction in BIW*)	Weight	1	£141	£136	0.95
Medium weight reduction(~25% reduction in BIW*)	Weight	2	£352	£323	0.95
Strong weight reduction (~40% reduction in BIW*)	Weight	3	£880	£764	0.90
Lightweight components other than BIW	Weight	4	£132	£125	0.95
Thermo-electric waste heat recovery	Other	1	£800	£1,078	0.85
Secondary heat recovery cycle	Other	2	£160	£216	0.90
Auxiliary systems efficiency improvement	Other	3	£360	£496	0.95
Thermal management	Other	4	£120	£162	0.95

Notes:

(3) Data based on average of C and D class cars from TNO (2011)
(4) Data from TNO (2011) for large cars was used to update the older/previous assumptions for vans by scaling data from AEA-TNO (2009) – which contained comparable data for both car and van technologies..
(5) Initial stock estimates were set to 200,000 for cars and 100,000 for vans to
(6) Learning rates applied in a consistent way to those developed in AEA (2009).

The study analysis assumptions for the efficiency improvement technology costs for motorcycles and mopes are presented in Table 4.5. These have been sourced from a limited range of identified literature including principally publications by the IEA (2009) and ICCT (2011), together with indicative AEA estimates for technologies based on those for petrol cars where no suitable data in the literature could be identified.

Table 4.5: Summary of the technology cost assumptions for the motorcycle analysis

Efficiency Improvement Technology	Category	#	Capital Cost, £	Learning Rate
Air assisted direct injection for 2-stroke engines (1)	PtrainE	1	£22	0.95
Electronic port fuel injection for 4-stroke engines (1)	PtrainE	2	£71	0.95
Swirl control valve (1)	PtrainE	3	£20	0.95
Variable ignition timing (2)	PtrainE	4	£189	0.95
Engine friction reduction (2)	PtrainE	5	£64	0.95
Optimising transmission systems (2)	PtrainE	6	£20	0.95
Start-stop hybridisation (2)	PtrainE	7	£290	0.95
Aerodynamics improvement (2)	Aero	1	£44	1.00
Low rolling resistance tyres(2)	Rres	1	£15	0.95
Light weighting(2)	Weight	1	£176	0.95
Thermo-electric waste heat recovery (3)	Other	1	£400	0.95

Source: (1) ICCT (2011); (2) Estimates by AEA based on data for cars for measures without cost values identified by IEA (2009), ICCT (2011) and other sources. (3) AEA estimate based on car option.

The study analysis assumptions for the efficiency improvement technology costs for heavy duty vehicles are presented in Table 2.14. As for the corresponding efficiency figures, these have generally been sourced from recent work carried out by AEA and Ricardo for the European Commission (AEA-Ricardo, 2011). However, in some cases scaling has been applied where technologies had the same costs across widely different sizes/types of vehicle. As indicated in the earlier section on vehicle efficiencies, for the purposes of this studies analysis, the categories provided in AEA-Ricardo (2011) have been mapped onto the vehicle categories used in this study as follows:

AEA-Ricardo (2011) category		*Study category*
Urban Delivery	=	Small rigid truck
Regional Delivery	=	Large rigid truck
Long haul	=	Articulated
Construction	=	Construction

TIAX recently carried out a review of the AEA-Ricardo (2011) study assumptions and modelling results on behalf of ICCT, which was completed in December 2011 (TIAX, 2011). This study utilised the efficiency and cost assumptions TIAX developed for the recent US review of heavy duty vehicles (NAS, 2010) that fed into the recent development of regulations aimed at significantly improving HDV efficiency in the US. The TIAX (2011) study findings were generally in close consistency with the AEA-Ricardo (2011) work – within the range of the analysis uncertainty[7]. However, there were significant variations between the costs for light-weighting and for predictive cruise control between the two studies.

For the purposes of the study analysis we have utilised the costs based on the TIAX (2011) report for light-weighting, since the AEA-Ricardo (2011) estimates were extremely low

[7] Confirmed in personal communications between AEA and the lead author of the TIAX (2011) study in December 2011: *"the biggest differences are most likely a result the differences in vehicle size and not in technology costs"*.

compared to other estimates in the literature on the cost of light-weighting. For predictive cruise control, it appears that there may be differences in the sophistications of the systems evaluated in AEA-Ricardo (2011) and TIAX (2011), since there were also significant deviations in efficiency (the more efficient system providing greater savings)[8]. Therefore, two levels of predictive cruise control have been used in this study's analysis. In addition, there were no figures available in AEA-Ricardo (2011) for mechanical turbocompounding, therefore estimates were made based on the difference between mechanical and electrical turbocompounding from ICCT (2009).

Table 4.6: Summary of the technology cost assumptions for the heavy duty vehicle analysis

Technology	Cat.	#	Capital Cost, £						LR
			Small Rigid	Large Rigid	Articulated Truck	Construction Truck	Bus	Coach	
General improvements	PtrainE	1	£583	£583	£583	£583	£583	£583	0.95
Mechanical Turbocompound	PtrainE	2	£1,824	£1,824	£2,639	£2,435	£2,232	£2,232	0.95
Electrical Turbocompound	PtrainE	3	£4,576	£5,600	£6,623	£6,112	£5,600	£5,600	0.95
Heat Recovery (Bottoming Cycles)	PtrainE	4	£7,564	£9,256	£10,948	£10,102	£9,256	£9,256	0.95
Controllable Air Compressor	PtrainE	5	£112	£112	£152	£132	£112	£112	0.95
Automated Transmission	PtrainE	6	£2,800	£2,800	£3,773	£3,286	£2,800	£2,800	0.95
Stop / Start System	PtrainE	7	£418	£512	£752	£632	£512	£512	0.95
Pneumatic Booster – Air Hybrid	PtrainE	8	£523	£640	£757	£698	£640	£640	0.95
Aerodynamic Fairings	Aero	1	£771	£944	£944	£944	£280	£280	0.95
Spray Reduction Mud Flaps	Aero	2	£11	£11	£11	£2,800	£11	£11	0.95
Aerodynamic Trailers / Bodies	Aero	3	£1,200	£2,800	£2,800	£704	N/A	£2,800	0.95
Aerodynamics (Irregular Body Type)	Aero	4	£320	£704	£704	£11	N/A	N/A	0.95
Active Aero*	Aero	5	£817	£1000	£1000	£1000	£1000	£1000	0.90
Low Rolling Resistance Tyres	Rres	1	£200	£280	£280	£280	£280	£280	0.95
Single Wide Tyres	Rres	2	£660	£660	£1,040	£850	£660	£660	0.95
Automatic Tyre Pressure Adjustment	Rres	3	£7,708	£9,432	£11,156	£10,294	£9,432	£9,432	0.90
Light weighting	Weight	1	£577	£1,845	£1,826	£1,836	£9,223	£5,534	0.95
Predictive Cruise Control	Other	1	N/A	£62	£62	£62	N/A	£62	0.95
Smart Alternator, Battery Sensor & AGM Battery	Other	2	£418	£512	£752	£632	£512	£512	0.95
Alternative Fuel Bodies	Other	3	£9,153	£11,200	£13,247	£12,223	N/A	N/A	0.95
Advanced Predictive Cruise Control	Other	4	N/A	£1,120	£1,120	£1,120	N/A	£1,120	0.90

Source: Based on datasets from AEA-Ricardo (2011), ICCT (2009) and TIAX (2011).
* Active aero cost based on estimate provided by SMMT (2012).

Notes: The initial deployment rate of most technical measures were set at lower rates compared to LDVs, reflecting the different basis of the AEA-Ricardo (2011) cost estimates and the greater potential for cost reduction through a combination learning and mass deployment. Measures such as aerodynamic farings and low rolling resistance tyres were set at slightly higher initial deployment reflecting their already significant presence in the marketplace and fewer opportunities for cost reduction.

[8] Based on personal communications between AEA and the TIAX (2011) lead author. As part of their work for NAS (2010) study, which fed into the work for ICCT, they gathered data from a wide range of US manufacturers, upon which their study costs and efficiencies are largely based.

5 Technology Compatibility and Deployment Assumptions

This chapter provides a more detailed summary of the methodological approach and assumptions used in the development of the study dataset for technology deployment.

5.1 Compatibility and Stackability

In developing the study calculation methodology it was important to factor in the following two elements:

1) *Compatibility*: The ability for a particular powertrain type to utilise a particular technical option (e.g. technologies improving the efficiency of the ICE or conventional transmission are not compatible/relevant to BEVs);
2) *Stackability*:
    a) The ability for two or more technologies to be simultaneously applied to a vehicle at all (e.g. cannot simultaneously apply two direct injection technologies);
    b) Even if the technologies can technically be simultaneously applied, whether their effects overlap in a significant way so as to substantially reduce their combined overall efficiency benefit versus simple combination of their basic impacts.

It was therefore important to consider both of these issues in developing the technology deployment/penetration assumptions that form the basis for the efficiency and capital cost calculations.

The following Table 5.1, Table 5.2 and Table 5.3 provide summary of matrices of compatibility/stackability assumptions for LDV, HDV and motorcycle technologies utilised in the study calculations. These have been developed from a consideration of the above effects in order to provide a reasonable safety margin in the over-estimation of potential efficiency improvements. The assumptions have also been discussed with/checked by Duncan Kay, a senior consultant at AEA who was previously an automotive engineer working in fuel economy technologies at Ford.

Table 5.1: Summary of Light Duty Vehicle (car and van) technology compatibility / stackability

#	Type	T#	Technology Name	1 Petrol - low friction design and materials	2 Petrol - gas-wall heat transfer reduction	3 Petrol - direct injection (homogeneous)	4 Petrol - direct injection (stratified charge)	5 Petrol - thermodynamic cycle improvements	6 Petrol - cam-phasing	7 Petrol - variable valve actuation and lift	8 Diesel - variable valve actuation and lift	9 Diesel - combustion improvements	10 Mild downsizing (15% cylinder content reduction)	11 Medium downsizing (30% cylinder content reduction)	12 Strong downsizing (>=45% cylinder content reduction)	13 Reduced driveline friction	14 Optimising gearbox ratios / downspeeding	15 Automated manual transmission	16 Dual clutch transmission	17 Start-stop hybridisation	18 Regenerative braking (smart alternator)	19 Aerodynamics improvement	20 Low rolling resistance tyres	21 Mild weight reduction	22 Medium weight reduction	23 Strong weight reduction	24 Lightweight components other than BIW	25 Thermo-electric waste heat recovery	26 Secondary heat recovery cycle	27 Auxiliary systems efficiency improvement	28 Thermal management	1 Petrol ICE	2 Diesel ICE	3 Petrol HEV	4 Diesel HEV	5 Petrol PHEV	6 Diesel PHEV	7 Petrol REEV	8 Diesel REEV
1	PtrainE	1	Petrol - low friction design and materials	X							X	X																					X		X		X		X
2	PtrainE	2	Petrol - gas-wall heat transfer reduction		X	X	X	X		X	X	X																					X		X		X		X
3	PtrainE	3	Petrol - direct injection (homogeneous)		X	X	X	X		X	X	X								X													X		X		X		X
4	PtrainE	4	Petrol - direct injection (stratified charge)		X	X	X	X		X	X	X								X													X		X		X		X
5	PtrainE	5	Petrol - thermodynamic cycle imporvements		X	X	X	X		X	X	X																					X		X		X		X
6	PtrainE	6	Petrol - cam-phasing						X		X	X																					X		X		X		X
7	PtrainE	7	Petrol - variable valve actuation and lift		X	X	X	X		X	X	X																					X		X		X		X
8	PtrainE	8	Diesel - variable valve actuation and lift	X	X	X	X	X	X	X	X																					X		X		X		X	
9	PtrainE	9	Diesel - combustion improvements	X	X	X	X	X	X	X		X																				X		X		X		X	
10	PtrainE	10	Mild downsizing (15% cylinder content reduction)										X	X	X																								
11	PtrainE	11	Medium downsizing (30% cylinder content reduction)										X	X	X																								
12	PtrainE	12	Strong downsizing (>=45% cylinder content reduction)										X	X	X																								
13	PtrainE	13	Reduced driveline friction													X																							
14	PtrainE	14	Optimising gearbox ratios / downspeeding														X	X	X															X	X	X	X	X	X
15	PtrainE	15	Automated manual transmission														X	X	X															X	X	X	X	X	X
16	PtrainE	16	Dual clutch transmission														X	X	X															X	X	X	X	X	X
17	PtrainE	17	Start-stop hybridisation			X	X													X														X	X	X	X	X	X
18	PtrainE	18	Regenerative braking (smart alternator)																		X													X	X	X	X	X	X
19	Aero	1	Aerodynamics improvement																			X																	
20	Rres	1	Low rolling resistance tyres																				X																
21	Weight	1	Mild weight reduction																					X	X	X													
22	Weight	2	Medium weight reduction																					X	X	X													
23	Weight	3	Strong weight reduction																					X	X	X													
24	Weight	4	Lightweight components other than BIW																								X												
25	Other	1	Thermo-electric waste heat recovery																									X											
26	Other	2	Secondary heat recovery cycle																										X										
27	Other	3	Auxiliary systems efficiency improvement																											X									
28	Other	4	Thermal management																												X								

Notes: X = not compatible/stackable

Table 5.2: Summary of Heavy Duty Vehicle (all trucks, buses and coaches) technology compatibility / stackability

#	Type	T#	Technology Name	1 General improvements (+ impact AQ emission control)	2 Mechanical Turbocompound	3 Electrical Turbocompound	4 Heat Recovery (Bottoming Cycles)	5 Controllable Air Compressor	6 Automated Transmission	7 Stop / Start System	8 Pneumatic Booster – Air Hybrid	9 Aerodynamic Fairings	10 Spray Reduction Mud Flaps	11 Aerodynamic Trailers / Bodies	12 Aerodynamics (Irregular Body Type)	13 Active Aero	14 Low Rolling Resistance Tyres	15 Single Wide Tyres	16 Automatic Tyre Pressure Adjustment (ATPA)	17 Light weighting	18 Predictive Cruise Control	19 Smart Alternator, Battery Sensor & AGM Battery	20 Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	21 Advanced Predictive Cruise Control	1 Diesel ICE	2 Diesel FHV	3 Diesel HHV	4 Diesel HEV	5 BEV	6 H2FC	7 DNG ICE	8 NG ICE
1	PtrainE	1	General improvements (+ impact AQ emission control)	X																									X	X		
2	PtrainE	2	Mechanical Turbocompound		X	X																						X	X	X		
3	PtrainE	3	Electrical Turbocompound		X	X																							X	X		
4	PtrainE	4	Heat Recovery (Bottoming Cycles)				X																						X	X		
5	PtrainE	5	Controllable Air Compressor					X																					X	X		
6	PtrainE	6	Automated Transmission						X																			X	X	X		
7	PtrainE	7	Stop / Start System							X	X															X	X	X	X	X		
8	PtrainE	8	Pneumatic Booster – Air Hybrid							X	X															X	X	X	X	X		
9	Aero	1	Aerodynamic Fairings									X																				
10	Aero	2	Spray Reduction Mud Flaps										X																			
11	Aero	3	Aerodynamic Trailers / Bodies											X	X																	
12	Aero	4	Aerodynamics (Irregular Body Type)											X	X																	
13	Aero	5	Active Aero													X																
14	Rres	1	Low Rolling Resistance Tyres														X															
15	Rres	2	Single Wide Tyres															X														
16	Rres	3	Automatic Tyre Pressure Adjustment (ATPA)																X													
17	Weight	1	Light weighting																	X												
18	Other	1	Predictive Cruise Control																		X			X								
19	Other	2	Smart Alternator, Battery Sensor & AGM Battery																			X							X	X		
20	Other	3	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)																				X		X	X					X	X
21	Other	4	Advanced Predictive Cruise Control																		X			X								

Notes: X = not compatible/stackable

Table 5.3: Summary of motorcycle and moped technology compatibility / stackability

				1	2	3	4	5	6	7	8	9	10	11	1	2	3	4
#	**Type**	**T#**	**Technology Name**	Air assisted direct injection for 2-stroke engines	Electronic port fuel injection for 4-stroke engines	Swirl control valve	Variable ignition timing	Engine friction reduction	Optimising transmission systems	Start-stop hybridisation	Aerodynamics improvement	Low rolling resistance tyres	Light weighting	Thermo-electric waste heat recovery	Petrol ICE	Petrol HEV	BEV	H2FC
1	PtrainE	1	Air assisted direct injection for 2-stroke engines	X	X												X	X
2	PtrainE	2	Electronic port fuel injection for 4-stroke engines	X	X												X	X
3	PtrainE	3	Swirl control valve			X											X	X
4	PtrainE	4	Variable ignition timing				X										X	X
5	PtrainE	5	Engine friction reduction					X									X	X
6	PtrainE	6	Optimising transmission systems						X							X	X	X
7	PtrainE	7	Start-stop hybridisation							X						X	X	X
8	Aero	1	Aerodynamics improvement								X							
9	Rres	1	Low rolling resistance tyres									X						
10	Weight	1	Light weighting										X					
11	Other	1	Thermo-electric waste heat recovery											X				

Notes: X = not compatible/stackable

5.2 Deployment

This section summarises the basis for development/source of the technology deployment rates used in the development of the efficiency and cost trajectories. This used a combination of existing estimates (e.g. AEA-Ricardo, 2011 for HDVs) and/or estimates based on combination of current regulatory targets, expert judgement on potential/likely rates of technology deployment.

One of the basic starting assumptions for the analysis is that (where they are compatible with the powertrain) individual efficiency technologies are deployed at the same average rate across all powertrains. For example, if VVTL (variable valve timing and lift) is taken up at a rate of 20% in petrol ICE cars, it will also be applied in the calculations at the same 20% rate for HEVs, and not at all for BEVs (where it is incompatible). In reality there may be some strategising in the application of such technologies between different compatible powertrain technologies, but it is impossible to accurately predict what might be the result. Using this simplified assumption also facilitates comparisons of the potential efficiency improvements between different powertrain types.

Three other principal considerations were also applied in developing the deployment trajectories:

1) *Maximising reductions in GHG/energy consumption*: One of the stipulations in the study specification was to develop trajectories that should be consistent with the goal of progressively reducing new vehicle CO_2 as far as is practicable by 2050.
2) *Cost-effectiveness*: In general it is assumed that those technological options that are the most cost-effective (e.g. in £ per % reduction in energy consumption) will be applied first/at a higher rate, with less cost-effective technologies being applied later in order to achieve greater levels of reduction in later periods.
3) *Maximum deployment*: Besides the issues of compatibility and stackability of technologies, for some technologies it is not possible to deploy them at 100% rate across the entirety of the vehicle category due to some practical limitations. For example, the 'Alternative Fuel Bodies' technology for heavy duty vehicles is only relevant/applicable for RCVs, refrigerated vehicles and some construction trucks. Since these have a finite share in the truck fleet, this forms an upper boundary above which the technology cannot be applied.

The following subsections provide more details on the specific assumptions utilised for light duty vehicles, motorcycles and heavy duty vehicles.

5.2.1 Light duty vehicles and motorcycles

For passenger cars, the assumptions on efficiency improvement technology deployment are presented in Table 5.4. The initial technology deployment rates have been developed in line with the expectation that the EU-wide 2020 regulatory target (95gCO_2/km) is likely to be largely be achieved by improvements to conventional vehicles, rather than significant introduction of increasingly electrified powertrains (i.e. HEVs, PHEVs, REEVs and BEVs) on the basis of their current relative cost-effectiveness (TNO, 2011). It is currently anticipated that most of the benefits will be achieve through a combination engine and transmission improvements including direct injection (for petrol engines), engine downsizing + boost and stop-start, as well as others (Bosch, 2010). The UK currently has new car CO_2 emissions higher than the UK average and this seems unlikely to change in the short-term under the existing arrangements.

In terms of the likely rate of introduction of efficiency improvement technologies into the new vehicle fleet, the following Box 5.1 provides an extract from TNO (2011) summarising their findings in this area.

Box 5.1: Extract from TNO (2011) on the timing for vehicle and engine platform changes

For the OEMs, selected vehicle models and engine platforms analysed in this study the following conclusions could be drawn:

- On average vehicle models have a platform change every 6 – 8 years and are refreshed with a face-lift between 2-4 years after a platform change.
- Engine platforms have a long lifespan, typically 10 – 15 years but during that time will have minor or major upgrades and additional variants added. There is no typical timing pattern for the introduction of new variants or upgrades (it is dependent on the OEM and engine platform) but in general minor upgrades/variants to engine platforms are added fairly frequently (e.g. higher power variant) and major upgrades/variants added less frequently occurring anywhere from 3 to 7 years (e.g. a turbocharged variant of a naturally aspirated gasoline engine).
- Vehicle platform changes / facelifts and engine variants / upgrades are staggered so that changes to all vehicle models or all engine platforms are not all made within the same year.

For vans, the assumptions on efficiency improvement technology deployment are presented in Table 5.5. It is assumed that technologies are deployed in a similar way to the passenger car sector, but with a degree of lag in technological uptake reflecting the greater conservatism of this sector (i.e. uptake in vans follows confirmation of success in cars). The resulting trajectory in gCO_2/km (test-cycle) from 2010-2020 has been developed to be broadly in line with the EU-wide regulatory requirements (i.e. 147gCO_2/km).

For motorcycles, there is very limited information available in the literature, and currently no significant regulatory investigation/action on improving their fuel efficiency, since they only comprise a very limited proportion of overall energy consumption/GHG from road transport. However, it is anticipated that this situation will change and there will some benefits also to be transferred from technology development from petrol LDVs in certain areas. The technology deployment assumptions developed for motorcycles, presented in Table 5.6, therefore reflect the longer term goal of maximising efficiency improvement, but with somewhat lower ambition on improvements in the short term compared to other modes.

The deployment of the direct injection and port fuel injection technologies are limited by the proportion of motorcycles and mopeds with 2-stroke or 4-stroke engines in the fleet. 2-stroke engines are only generally used in some low-powered mopeds/scooters. In the absence of an alternative suitable source from the literature an assumption is used in the study calculations that 25% of all motorcycle engines are 2-stroke and 75% are 4-stroke.

Table 5.4: Deployment assumptions for passenger car efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050			2020	2030	2040	2050
Car	Petrol - low friction design and materials	PtrainE	1	10.0%	50.0%	90.0%	100.0%	100.0%	100%	£14	40.0%	80.0%	90.0%	90.0%
Car	Petrol - gas-wall heat transfer reduction	PtrainE	2	10.0%	40.0%	80.0%	100.0%	100.0%	100%	£13	30.0%	70.0%	90.0%	90.0%
Car	Petrol - direct injection (homogeneous)	PtrainE	3	10.0%	55.0%	45.0%	40.0%	30.0%	100%	£27	45.0%	35.0%	30.0%	20.0%
Car	Petrol - direct injection (stratified charge)	PtrainE	4		5.0%	10.0%	15.0%	20.0%	100%	£48	5.0%	10.0%	15.0%	20.0%
Car	Petrol - thermodynamic cycle improvements	PtrainE	5		0.0%	5.0%	10.0%	15.0%	100%	£27	0.0%	5.0%	10.0%	15.0%
Car	Petrol - cam-phasing	PtrainE	6	10.0%	40.0%	25.0%	10.0%	0.0%	100%	£16	30.0%	15.0%	0.0%	-10.0%
Car	Petrol - variable valve actuation and lift	PtrainE	7	5.0%	20.0%	35.0%	45.0%	55.0%	100%	£21	15.0%	30.0%	40.0%	50.0%
Car	Diesel - variable valve actuation and lift	PtrainE	8		10.0%	30.0%	70.0%	100.0%	100%	£224	10.0%	30.0%	70.0%	100.0%
Car	Diesel - combustion improvements	PtrainE	9	10.0%	60.0%	90.0%	100.0%	100.0%	100%	£20	50.0%	80.0%	90.0%	90.0%
Car	Mild downsizing (15% cylinder content reduction)	PtrainE	10	25.0%	60.0%	25.0%	5.0%	0.0%	100%	£40	35.0%	0.0%	-20.0%	-25.0%
Car	Medium downsizing (30% cylinder content reduction)	PtrainE	11	15.0%	30.0%	50.0%	55.0%	25.0%	100%	£44	15.0%	35.0%	40.0%	10.0%
Car	Strong downsizing (>=45% cylinder content reduction)	PtrainE	12	5.0%	10.0%	25.0%	40.0%	75.0%	100%	£30	5.0%	20.0%	35.0%	70.0%
Car	Reduced driveline friction	PtrainE	13	5.0%	40.0%	80.0%	100.0%	100.0%	100%	£40	35.0%	75.0%	95.0%	95.0%
Car	Optimising gearbox ratios / downspeeding	PtrainE	14	10.0%	60.0%	90.0%	100.0%	100.0%	100%	£12	50.0%	80.0%	90.0%	90.0%
Car	Automated manual transmission	PtrainE	15	5.0%	30.0%	50.0%	40.0%	20.0%	100%	£48	25.0%	45.0%	35.0%	15.0%
Car	Dual clutch transmission	PtrainE	16	1.0%	20.0%	40.0%	60.0%	80.0%	100%	£97	19.0%	39.0%	59.0%	79.0%
Car	Start-stop hybridisation	PtrainE	17	5.0%	75.0%	100.0%	100.0%	100.0%	100%	£34	70.0%	95.0%	95.0%	95.0%
Car	Regenerative braking (smart alternator)	PtrainE	18	1.0%	25.0%	60.0%	100.0%	100.0%	100%	£46	24.0%	59.0%	99.0%	99.0%
Car	Aerodynamics improvement	Aero	1	5.0%	30.0%	70.0%	90.0%	100.0%	100%	£25	25.0%	65.0%	85.0%	95.0%
Car	Low rolling resistance tyres	Rres	1	20.0%	100.0%	100.0%	100.0%	100.0%	100%	£10	80.0%	80.0%	80.0%	80.0%
Car	Mild weight reduction	Weight	1	5.0%	65.0%	60.0%	30.0%	0.0%	100%	£70	60.0%	55.0%	25.0%	-5.0%
Car	Medium weight reduction	Weight	2	3.0%	10.0%	25.0%	50.0%	50.0%	100%	£59	7.0%	22.0%	47.0%	47.0%
Car	Strong weight reduction	Weight	3	2.0%	3.0%	7.0%	20.0%	50.0%	100%	£73	1.0%	5.0%	18.0%	48.0%
Car	Lightweight components other than BIW	Weight	4		2.0%	10.0%	40.0%	90.0%	100%	£66	2.0%	10.0%	40.0%	90.0%
Car	Thermo-electric waste heat recovery	Other	1		0.0%	5.0%	20.0%	30.0%	100%	£400	0.0%	5.0%	20.0%	30.0%
Car	Secondary heat recovery cycle	Other	2		1.0%	5.0%	20.0%	30.0%	100%	£80	1.0%	5.0%	20.0%	30.0%
Car	Auxiliary systems efficiency improvement	Other	3	30.0%	60.0%	100.0%	100.0%	100.0%	100%	£30	30.0%	70.0%	70.0%	70.0%
Car	Thermal management	Other	4	25.0%	50.0%	75.0%	100.0%	100.0%	100%	£48	25.0%	50.0%	75.0%	75.0%

Notes: 2010 deployment levels partly informed by information supplied by SMMT following the presentation of draft project results in February 2012.

Table 5.5: Deployment assumptions for van efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050			2020	2030	2040	2050
Van	Petrol - low friction design and materials	PtrainE	1	5.0%	45.0%	80.0%	90.0%	90.0%	100%	£15	40.0%	75.0%	85.0%	85.0%
Van	Petrol - gas-wall heat transfer reduction	PtrainE	2	5.0%	30.0%	65.0%	85.0%	85.0%	100%	£18	25.0%	60.0%	80.0%	80.0%
Van	Petrol - direct injection (homogeneous)	PtrainE	3	5.0%	45.0%	30.0%	25.0%	15.0%	100%	£22	40.0%	25.0%	20.0%	10.0%
Van	Petrol - direct injection (stratified charge)	PtrainE	4	0.0%	0.0%	0.0%	5.0%	10.0%	100%	£41	0.0%	0.0%	5.0%	10.0%
Van	Petrol - thermodynamic cycle improvements	PtrainE	5	0.0%	0.0%	0.0%	5.0%	10.0%	100%	£21	0.0%	0.0%	5.0%	10.0%
Van	Petrol - cam-phasing	PtrainE	6	5.0%	35.0%	15.0%	0.0%	0.0%	100%	£16	30.0%	10.0%	-5.0%	-5.0%
Van	Petrol - variable valve actuation and lift	PtrainE	7	0.0%	10.0%	20.0%	30.0%	40.0%	100%	£17	10.0%	20.0%	30.0%	40.0%
Van	Diesel - variable valve actuation and lift	PtrainE	8	0.0%	0.0%	15.0%	55.0%	85.0%	100%	£224	0.0%	15.0%	55.0%	85.0%
Van	Diesel - combustion improvements	PtrainE	9	5.0%	50.0%	75.0%	85.0%	85.0%	100%	£24	45.0%	70.0%	80.0%	80.0%
Van	Mild downsizing (15% cylinder content reduction)	PtrainE	10	20.0%	50.0%	10.0%	0.0%	0.0%	100%	£13	30.0%	-10.0%	-20.0%	-20.0%
Van	Medium downsizing (30% cylinder content reduction)	PtrainE	11	10.0%	20.0%	35.0%	40.0%	10.0%	100%	£51	10.0%	25.0%	30.0%	0.0%
Van	Strong downsizing (>=45% cylinder content reduction)	PtrainE	12	0.0%	0.0%	10.0%	25.0%	60.0%	100%	£34	0.0%	10.0%	25.0%	60.0%
Van	Reduced driveline friction	PtrainE	13	0.0%	30.0%	65.0%	85.0%	85.0%	100%	£36	30.0%	65.0%	85.0%	85.0%
Van	Optimising gearbox ratios / downspeeding	PtrainE	14	5.0%	55.0%	80.0%	90.0%	90.0%	100%	£15	50.0%	75.0%	85.0%	85.0%
Van	Automated manual transmission	PtrainE	15	0.0%	20.0%	35.0%	25.0%	5.0%	100%	£55	20.0%	35.0%	25.0%	5.0%
Van	Dual clutch transmission	PtrainE	16	0.0%	10.0%	25.0%	45.0%	65.0%	100%	£106	10.0%	25.0%	45.0%	65.0%
Van	Start-stop hybridisation	PtrainE	17	0.0%	65.0%	85.0%	85.0%	85.0%	100%	£42	65.0%	85.0%	85.0%	85.0%
Van	Regenerative braking (smart alternator)	PtrainE	18	0.0%	15.0%	45.0%	85.0%	85.0%	100%	£54	15.0%	45.0%	85.0%	85.0%
Van	Aerodynamics improvement	Aero	1	0.0%	20.0%	55.0%	75.0%	85.0%	100%	£43	20.0%	55.0%	75.0%	85.0%
Van	Low rolling resistance tyres	Rres	1	15.0%	90.0%	85.0%	85.0%	85.0%	100%	£10	75.0%	70.0%	70.0%	70.0%
Van	Mild weight reduction	Weight	1	0.0%	5.0%	45.0%	15.0%	0.0%	100%	£90	5.0%	45.0%	15.0%	0.0%
Van	Medium weight reduction	Weight	2	0.0%	5.0%	10.0%	35.0%	35.0%	100%	£53	5.0%	10.0%	35.0%	35.0%
Van	Strong weight reduction	Weight	3	0.0%	5.0%	0.0%	13.0%	43.0%	100%	£69	5.0%	0.0%	13.0%	43.0%
Van	Lightweight components other than BIW	Weight	4	0.0%	5.0%	0.0%	30.0%	80.0%	100%	£82	5.0%	0.0%	30.0%	80.0%
Van	Thermo-electric waste heat recovery	Other	1	0.0%	0.0%	0.0%	15.0%	25.0%	100%	£539	0.0%	0.0%	15.0%	25.0%
Van	Secondary heat recovery cycle	Other	2	0.0%	0.0%	0.0%	15.0%	25.0%	100%	£108	0.0%	0.0%	15.0%	25.0%
Van	Auxiliary systems efficiency improvement	Other	3	25.0%	50.0%	85.0%	85.0%	85.0%	100%	£45	25.0%	60.0%	60.0%	60.0%
Van	Thermal management	Other	4	20.0%	40.0%	60.0%	85.0%	85.0%	100%	£65	20.0%	40.0%	65.0%	65.0%

Notes: 2010 deployment levels partly informed by information supplied by SMMT following the presentation of draft project results in February 2012.

Table 5.6: Deployment assumptions for motorcycle efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050			2020	2030	2040	2050
Motorcycle	Air assisted direct injection for 2-stroke engines *	PtrainE	1		10.0%	20.0%	25.0%	25.0%	25%	£1	10.0%	20.0%	25.0%	25.0%
Motorcycle	Electronic port fuel injection for 4-stroke engines *	PtrainE	2		10.0%	20.0%	35.0%	75.0%	75%	£4	10.0%	20.0%	35.0%	75.0%
Motorcycle	Swirl control valve	PtrainE	3		40.0%	80.0%	100%	100%	100%	£3	40.0%	80.0%	100%	100%
Motorcycle	Variable ignition timing	PtrainE	4		20.0%	30.0%	40.0%	50.0%	100%	£22	20.0%	30.0%	40.0%	50.0%
Motorcycle	Engine friction reduction	PtrainE	5		20.0%	50.0%	100%	100%	100%	£16	20.0%	50.0%	100%	100%
Motorcycle	Optimising transmission systems	PtrainE	6		5.0%	15.0%	40.0%	80.0%	100%	£40	5.0%	15.0%	40.0%	80.0%
Motorcycle	Start-stop hybridisation	PtrainE	7		10.0%	50.0%	100%	100%	100%	£58	10.0%	50.0%	100%	100%
Motorcycle	Aerodynamics improvement	Aero	1		1.0%	10.0%	30.0%	50.0%	100%	£50	1.0%	10.0%	30.0%	50.0%
Motorcycle	Low rolling resistance tyres	Rres	1		10.0%	75.0%	100%	100%	100%	£10	10.0%	75.0%	100%	100%
Motorcycle	Light weighting	Weight	1		5.0%	10.0%	20.0%	40.0%	100%	£88	5.0%	10.0%	20.0%	40.0%
Motorcycle	Thermo-electric waste heat recovery	Other	1		1.0%	5.0%	10.0%	20.0%	100%	£200	1.0%	5.0%	10.0%	20.0%

Notes: * Deployment limited by proportion of motorcycles and mopeds with 2-stroke or 4-stroke engines in the fleet. 2-stroke engines are only generally used in low-powered mopeds/scooters. In the absence of an alternative suitable source from the literature an assumption is made that 25% of all motorcycle engines are 2-stroke.

5.2.2 Heavy duty vehicles

The assumptions for deployment of heavy duty vehicle technologies have been based primarily on those developed by AEA and Ricardo for recent work on GHG reduction from HDVs for the European Commission (AEA-Ricardo, 2011), which ran up to 2030, together with consideration of alternative deployment scenarios from TIAX (2011) and ICCT (2009).

In this project two sets of assumptions were developed – 'Cost-Effective' and 'Challenge' scenarios. The assumptions used for this study's analysis are based on the 'Challenge' scenario, with some modifications to factor in changes to some of the core technology assumptions for this study (i.e. mainly capital costs, detailed in section 4.1.3). This is in line with the overall study objective for estimating the possibilities for reducing GHG as far as possible by 2050. Extrapolations on these scenarios from 2030-2050 were developed also based on this over-arching ethos and the other principal considerations mentioned earlier.

In terms of setting maximum limits for the deployment of certain technical options, the main options that are:

- *Aerodynamic bodies for regular body types:* limited by the % share of regular bodies of the whole new vehicle fleet.
- Aerodynamic bodies for regular body types: limited by the % share of irregular bodies of the whole new vehicle fleet.
- *Alternative fuel bodies:* assumed to be limited by the share of refrigerated vehicles/RCVs for regular trucks and by the share of tippers/concrete mixers for construction trucks.

The maximum deployment assumptions developed for these technologies were estimated according to statistics on different body types from DfT vehicle licensing statistics for rigid trucks, and from data from CLEAR (2010) on semi-trailer registrations sourced for the AEA-Ricardo (2011) project. These are presented in Table 5.7 below.

Table 5.7: Rigid truck and articulated trailer body types

	Small rigid trucks <15 t GVW	Large rigid trucks >15 t GVW	Construction (3)	Articulated trucks (4)
Number				
Regular body (1)	94.28	41.57	0	128.13
Irregular body (2)	40.19	50.09	73.61	42.24
Refrigerated/RCV/Street Cleansing	14.9	20.6	0	27.29
Tipper/Concrete Mixer	0	0	58.9	0
Total	***134.5***	***91.7***	***73.61***	***170.37***
Percentage				
Regular body (1)	70%	45%	0%	75%
Irregular body (2)	30%	55%	100%	25%
Refrigerated/RCV/Street Cleansing	11%	22%	0%	16%
Tipper/Concrete Mixer	0%	0%	80%	0%

Sources: Rigid trucks – based on DfT licensing statistics (2011) - Table VEH0522; Semi-trailers % split based on data on trailer registrations for the UK from CLEAR (2010) sourced for AEA-Ricardo (2011), and numbers calculated from total fleet of articulated trucks from DfT statistics.

Notes: (1) Sum of categories: box van, curtain sided, insulated van, goods, panel van, tower wagon, Luton van, van and truck; (2) All other categories, except construction; (3) Tipper, skip-loader or concrete mixer. (4) Excluding tipper truck trailer types – estimated at 8.3% based on CLEAR (2010).

Table 5.8: Deployment assumptions for small rigid truck efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050			2020	2030	2040	2050
Small rigid	General improvements (+ impact AQ emission control)	PtrainE	1		100%	100%	100%	100%	100%	£254	100%	100%	100%	100%
Small rigid	Mechanical Turbocompound	PtrainE	2		0.0%	10.0%	30.0%	40.0%	100%	£2,735	0.0%	10.0%	30.0%	40.0%
Small rigid	Electrical Turbocompound	PtrainE	3		0.0%	1.0%	15.0%	30.0%	100%	£4,576	0.0%	1.0%	15.0%	30.0%
Small rigid	Heat Recovery (Bottoming Cycles)	PtrainE	4		0.0%	0.0%	5.0%	20.0%	100%	£5,043	0.0%	0.0%	5.0%	20.0%
Small rigid	Controllable Air Compressor	PtrainE	5		0.0%	0.0%	0.0%	0.0%	100%	£-	0.0%	0.0%	0.0%	0.0%
Small rigid	Automated Transmission	PtrainE	6		20.0%	50.0%	100%	100%	100%	£560	20.0%	50.0%	100%	100%
Small rigid	Stop / Start System	PtrainE	7		100%	100%	100%	100%	100%	£70	100%	100%	100%	100%
Small rigid	Pneumatic Booster – Air Hybrid	PtrainE	8		0.0%	0.0%	0.0%	0.0%	100%	£349	0.0%	0.0%	0.0%	0.0%
Small rigid	Aerodynamic Fairings	Aero	1		0.0%	0.0%	20.0%	20.0%		£-	0.0%	0.0%	20.0%	20.0%
Small rigid	Spray Reduction Mud Flaps	Aero	2		2.5%	10.0%	50.0%	100%	100%	£11	2.5%	10.0%	50.0%	100%
Small rigid	Aerodynamic Trailers / Bodies	Aero	3		0.0%	0.0%	30.0%	70.0%	70%	£1,200	0.0%	0.0%	30.0%	70.0%
Small rigid	Aerodynamics (Irregular Body Type)	Aero	4		0.0%	0.0%	10.0%	30.0%	30%	£320	0.0%	0.0%	10.0%	30.0%
Small rigid	Active Aero	Aero	5		0.0%	20.0%	50.0%	70.0%	70%	£817	0.0%	20.0%	50.0%	70.0%
Small rigid	Low Rolling Resistance Tyres	Rres	1		50.0%	75.0%	50.0%	25.0%	100%	£200	50.0%	75.0%	50.0%	25.0%
Small rigid	Single Wide Tyres	Rres	2		0.0%	25.0%	50.0%	75.0%	100%	£165	0.0%	25.0%	50.0%	75.0%
Small rigid	Automatic Tyre Pressure Adjustment (ATPA)	Rres	3		50.0%	100%	100%	100%	100%	£7,708	50.0%	100%	100%	100%
Small rigid	Light weighting	Weight	1		4.0%	30.0%	60.0%	100%	100%	£144	4.0%	30.0%	60.0%	100%
Small rigid	Predictive Cruise Control	Other	1		0.0%	0.0%	20.0%	20.0%	100%	£-	0.0%	0.0%	20.0%	20.0%
Small rigid	Smart Alternator, Battery Sensor & AGM Battery	Other	2		20.0%	60.0%	100%	100%	100%	£279	20.0%	60.0%	100%	100%
Small rigid	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	Other	3		0.0%	5.0%	11.0%	11.0%	11%	£610	0.0%	5.0%	11.0%	11.0%
Small rigid	Advanced Predictive Cruise Control	Other	4		0.0%	0.0%	0.0%	0.0%	100%	£-	0.0%	0.0%	0.0%	0.0%

Table 5.9: Deployment assumptions for large rigid truck efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050	Max %		2020	2030	2040	2050
Large rigid	General improvements (+ impact AQ emission control)	PtrainE	1		100%	100%	100%	100%	100%	£254	100%	100%	100%	100%
Large rigid	Mechanical Turbocompound	PtrainE	2		0.0%	10.0%	20.0%	30.0%	100%	£2,735	0.0%	10.0%	20.0%	30.0%
Large rigid	Electrical Turbocompound	PtrainE	3		0.1%	1.0%	25.0%	50.0%	100%	£2,240	0.1%	1.0%	25.0%	50.0%
Large rigid	Heat Recovery (Bottoming Cycles)	PtrainE	4		0.1%	1.0%	10.0%	30.0%	100%	£3,702	0.1%	1.0%	10.0%	30.0%
Large rigid	Controllable Air Compressor	PtrainE	5		0.0%	20.0%	50.0%	100%	100%	£112	0.0%	20.0%	50.0%	100%
Large rigid	Automated Transmission	PtrainE	6		20.0%	50.0%	100%	100%	100%	£1,867	20.0%	50.0%	100%	100%
Large rigid	Stop / Start System	PtrainE	7		100%	100%	100%	100%	100%	£171	100%	100%	100%	100%
Large rigid	Pneumatic Booster – Air Hybrid	PtrainE	8		0.0%	0.0%	0.0%	0.0%	100%	£427	0.0%	0.0%	0.0%	0.0%
Large rigid	Aerodynamic Fairings	Aero	1		95.0%	100%	100%	100%	100%	£944	95.0%	100%	100%	100%
Large rigid	Spray Reduction Mud Flaps	Aero	2		5.0%	20.0%	80.0%	100%	100%	£6	5.0%	20.0%	80.0%	100%
Large rigid	Aerodynamic Trailers / Bodies	Aero	3		7.0%	40.0%	45.0%	45.0%	45%	£255	7.0%	40.0%	45.0%	45.0%
Large rigid	Aerodynamics (Irregular Body Type)	Aero	4		1.0%	20.0%	35.0%	55.0%	55%	£108	1.0%	20.0%	35.0%	55.0%
Large rigid	Active Aero	Aero	5		7.0%	40.0%	45.0%	45.0%	45%	£200	7.0%	40.0%	45.0%	45.0%
Large rigid	Low Rolling Resistance Tyres	Rres	1		95.0%	90.0%	60.0%	10.0%	100%	£93	95.0%	90.0%	60.0%	10.0%
Large rigid	Single Wide Tyres	Rres	2		5.0%	10.0%	40.0%	90.0%	100%	£110	5.0%	10.0%	40.0%	90.0%
Large rigid	Automatic Tyre Pressure Adjustment (ATPA)	Rres	3		50.0%	100%	100%	100%	100%	£4,716	50.0%	100%	100%	100%
Large rigid	Light weighting	Weight	1		4.0%	30.0%	60.0%	100%	100%	£839	4.0%	30.0%	60.0%	100%
Large rigid	Predictive Cruise Control	Other	1		50.0%	70.0%	20.0%	0.0%	100%	£41	50.0%	70.0%	20.0%	0.0%
Large rigid	Smart Alternator, Battery Sensor & AGM Battery	Other	2		30.0%	90.0%	100%	100%	100%	£341	30.0%	90.0%	100%	100%
Large rigid	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	Other	3		5.0%	10.0%	22.0%	22.0%	22%	£747	5.0%	10.0%	22.0%	22.0%
Large rigid	Advanced Predictive Cruise Control	Other	4		5.0%	30.0%	80.0%	100%	100%	£224	5.0%	30.0%	80.0%	100%

Table 5.10: Deployment assumptions for articulated truck efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050			2020	2030	2040	2050
Articulated	General improvements (+ impact AQ emission control)	PtrainE	1		100%	100%	100%	100%	100%	£254	100%	100%	100%	100%
Articulated	Mechanical Turbocompound	PtrainE	2		10.0%	20.0%	50.0%	20.0%	100%	£1,320	10.0%	20.0%	50.0%	20.0%
Articulated	Electrical Turbocompound	PtrainE	3		1.0%	10.0%	40.0%	80.0%	100%	£2,208	1.0%	10.0%	40.0%	80.0%
Articulated	Heat Recovery (Bottoming Cycles)	PtrainE	4		1.0%	10.0%	30.0%	40.0%	100%	£2,190	1.0%	10.0%	30.0%	40.0%
Articulated	Controllable Air Compressor	PtrainE	5		20.0%	50.0%	100%	100%	100%	£101	20.0%	50.0%	100%	100%
Articulated	Automated Transmission	PtrainE	6		100%	100%	100%	100%	100%	£2,515	100%	100%	100%	100%
Articulated	Stop / Start System	PtrainE	7		90.0%	50.0%	20.0%	10.0%	100%	£752	90.0%	50.0%	20.0%	10.0%
Articulated	Pneumatic Booster – Air Hybrid	PtrainE	8		10.0%	50.0%	80.0%	90.0%	100%	£216	10.0%	50.0%	80.0%	90.0%
Articulated	Aerodynamic Fairings	Aero	1		95.0%	100%	100%	100%	100%	£2,360	95.0%	100%	100%	100%
Articulated	Spray Reduction Mud Flaps	Aero	2		20.0%	80.0%	100%	100%	100%	£3	20.0%	80.0%	100%	100%
Articulated	Aerodynamic Trailers / Bodies	Aero	3		12.0%	50.0%	75.0%	75.0%	75%	£255	12.0%	50.0%	75.0%	75.0%
Articulated	Aerodynamics (Irregular Body Type)	Aero	4		10.0%	20.0%	25.0%	25.0%	25%	£141	10.0%	20.0%	25.0%	25.0%
Articulated	Active Aero	Aero	5		8.0%	50.0%	75.0%	75.0%	75%	£125	8.0%	50.0%	75.0%	75.0%
Articulated	Low Rolling Resistance Tyres	Rres	1		95.0%	90.0%	40.0%	0.0%	100%	£56	95.0%	90.0%	40.0%	0.0%
Articulated	Single Wide Tyres	Rres	2		5.0%	10.0%	60.0%	100%	100%	£208	5.0%	10.0%	60.0%	100%
Articulated	Automatic Tyre Pressure Adjustment (ATPA)	Rres	3		50.0%	100%	100%	100%	100%	£3,719	50.0%	100%	100%	100%
Articulated	Light weighting	Weight	1		4.0%	30.0%	60.0%	100%	100%	£830	4.0%	30.0%	60.0%	100%
Articulated	Predictive Cruise Control	Other	1		75.0%	50.0%	20.0%	0.0%	100%	£41	75.0%	50.0%	20.0%	0.0%
Articulated	Smart Alternator, Battery Sensor & AGM Battery	Other	2		45.0%	50.0%	70.0%	100%	100%	£501	45.0%	50.0%	70.0%	100%
Articulated	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	Other	3		5.0%	10.0%	16.0%	16.0%	16%	£883	5.0%	10.0%	16.0%	16.0%
Articulated	Advanced Predictive Cruise Control	Other	4		5.0%	50.0%	80.0%	100%	100%	£224	5.0%	50.0%	80.0%	100%

Table 5.11: Deployment assumptions for construction truck efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050			2020	2030	2040	2050
Construction	General improvements (+ impact AQ emission control)	PtrainE	1		100%	100%	100%	100%	100%	£658	100%	100%	100%	100%
Construction	Mechanical Turbocompound	PtrainE	2		7.5%	15.0%	30.0%	40.0%	100%	£1,328	7.5%	15.0%	30.0%	40.0%
Construction	Electrical Turbocompound	PtrainE	3		0.6%	5.5%	30.0%	50.0%	100%	£2,222	0.6%	5.5%	30.0%	50.0%
Construction	Heat Recovery (Bottoming Cycles)	PtrainE	4		0.6%	5.5%	10.0%	20.0%	100%	£2,694	0.6%	5.5%	10.0%	20.0%
Construction	Controllable Air Compressor	PtrainE	5		10.0%	35.0%	75.0%	100%	100%	£106	10.0%	35.0%	75.0%	100%
Construction	Automated Transmission	PtrainE	6		60.0%	75.0%	100%	100%	100%	£2,191	60.0%	75.0%	100%	100%
Construction	Stop / Start System	PtrainE	7		95.0%	50.0%	20.0%	10.0%	100%	£316	95.0%	50.0%	20.0%	10.0%
Construction	Pneumatic Booster – Air Hybrid	PtrainE	8		10.0%	50.0%	80.0%	90.0%	100%	£279	10.0%	50.0%	80.0%	90.0%
Construction	Aerodynamic Fairings	Aero	1		95.0%	100%	100%	100%	100%	£1,349	95.0%	100%	100%	100%
Construction	Spray Reduction Mud Flaps	Aero	2		2.5%	10.0%	50.0%	100%	100%	£1,018	2.5%	10.0%	50.0%	100%
Construction	Aerodynamic Trailers / Bodies	Aero	3		0.0%	0.0%	0.0%	0.0%	0%	£122	0.0%	0.0%	0.0%	0.0%
Construction	Aerodynamics (Irregular Body Type)	Aero	4		12.5%	40.0%	80.0%	100%	100%	£4	12.5%	40.0%	80.0%	100%
Construction	Active Aero	Aero	5		0.0%	0.0%	0.0%	0.0%	0%	£-	0.0%	0.0%	0.0%	0.0%
Construction	Low Rolling Resistance Tyres	Rres	1		95.0%	90.0%	40.0%	0.0%	100%	£70	95.0%	90.0%	40.0%	0.0%
Construction	Single Wide Tyres	Rres	2		5.0%	10.0%	60.0%	100%	100%	£155	5.0%	10.0%	60.0%	100%
Construction	Automatic Tyre Pressure Adjustment (ATPA)	Rres	3		50.0%	100%	100%	100%	100%	£4,118	50.0%	100%	100%	100%
Construction	Light weighting	Weight	1		1.0%	20.0%	50.0%	100%	100%	£6,119	1.0%	20.0%	50.0%	100%
Construction	Predictive Cruise Control	Other	1		62.5%	60.0%	20.0%	0.0%	100%	£41	62.5%	60.0%	20.0%	0.0%
Construction	Smart Alternator, Battery Sensor & AGM Battery	Other	2		35.0%	75.0%	80.0%	100%	100%	£421	35.0%	75.0%	80.0%	100%
Construction	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	Other	3		5.0%	10.0%	40.0%	80.0%	80%	£815	5.0%	10.0%	40.0%	80.0%
Construction	Advanced Predictive Cruise Control	Other	4		5.0%	40.0%	80.0%	100%	100%	£224	5.0%	40.0%	80.0%	100%

Table 5.12: Deployment assumptions for bus efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050	Max %		2020	2030	2040	2050
Bus	General improvements (+ impact AQ emission control)	PtrainE	1		100%	100%	100%	100%	100%	£254	100%	100%	100%	100%
Bus	Mechanical Turbocompound	PtrainE	2		0.0%	10.0%	30.0%	40.0%	100%	£3,347	0.0%	10.0%	30.0%	40.0%
Bus	Electrical Turbocompound	PtrainE	3		0.0%	1.0%	15.0%	30.0%	100%	£5,600	0.0%	1.0%	15.0%	30.0%
Bus	Heat Recovery (Bottoming Cycles)	PtrainE	4		0.0%	0.0%	5.0%	20.0%	100%	£6,171	0.0%	0.0%	5.0%	20.0%
Bus	Controllable Air Compressor	PtrainE	5		0.0%	0.0%	0.0%	0.0%	100%	£-	0.0%	0.0%	0.0%	0.0%
Bus	Automated Transmission	PtrainE	6		30.0%	80.0%	100%	100%	100%	£560	30.0%	80.0%	100%	100%
Bus	Stop / Start System	PtrainE	7		90.0%	100%	100%	100%	100%	£128	90.0%	100%	100%	100%
Bus	Pneumatic Booster – Air Hybrid	PtrainE	8		0.0%	0.0%	0.0%	0.0%		£-	0.0%	0.0%	0.0%	0.0%
Bus	Aerodynamic Fairings	Aero	1		0.0%	0.0%	0.0%	0.0%	100%	£-	0.0%	0.0%	0.0%	0.0%
Bus	Spray Reduction Mud Flaps	Aero	2		50.0%	100%	100%	100%	100%	£11	50.0%	100%	100%	100%
Bus	Aerodynamic Trailers / Bodies	Aero	3		0.0%	0.0%	0.0%	0.0%	100%	£-	0.0%	0.0%	0.0%	0.0%
Bus	Aerodynamics (Irregular Body Type)	Aero	4		0.0%	0.0%	0.0%	0.0%	0%	£-	0.0%	0.0%	0.0%	0.0%
Bus	Active Aero	Aero	5		0.0%	20.0%	50.0%	70.0%	100%	£1000	0.0%	20.0%	50.0%	70.0%
Bus	Low Rolling Resistance Tyres	Rres	1		25.0%	50.0%	80.0%	60.0%	100%	£280	25.0%	50.0%	80.0%	60.0%
Bus	Single Wide Tyres	Rres	2		0.0%	10.0%	20.0%	40.0%	100%	£165	0.0%	10.0%	20.0%	40.0%
Bus	Automatic Tyre Pressure Adjustment (ATPA)	Rres	3		50.0%	100%	100%	100%	100%	£9,432	50.0%	100%	100%	100%
Bus	Light weighting	Weight	1		4.0%	30.0%	60.0%	100%	100%	£1,537	4.0%	30.0%	60.0%	100%
Bus	Predictive Cruise Control	Other	1		0.0%	0.0%	20.0%	20.0%	100%	£-	0.0%	0.0%	20.0%	20.0%
Bus	Smart Alternator, Battery Sensor & AGM Battery	Other	2		15.0%	35.0%	70.0%	100%	100%	£341	15.0%	35.0%	70.0%	100%
Bus	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	Other	3		0.0%	0.0%	0.0%	0.0%	0%	£-	0.0%	0.0%	0.0%	0.0%
Bus	Advanced Predictive Cruise Control	Other	4		0.0%	0.0%	0.0%	0.0%	100%	£-	0.0%	0.0%	0.0%	0.0%

Table 5.13: Deployment assumptions for coach efficiency improvement technologies

Type	Sub-component	Type	T#	Total Deployment					Max %	£/% Eff	Additional Deployment (above 2010 levels)			
				2010	2020	2030	2040	2050	Max %		2020	2030	2040	2050
Coach	General improvements (+ impact AQ emission control)	PtrainE	1		100%	100%	100%	100%	100%	£254	100%	100%	100%	100%
Coach	Mechanical Turbocompound	PtrainE	2		5.0%	10.0%	25.0%	40.0%	100%	£1,339	5.0%	10.0%	25.0%	40.0%
Coach	Electrical Turbocompound	PtrainE	3		0.1%	1.0%	25.0%	50.0%	100%	£2,240	0.1%	1.0%	25.0%	50.0%
Coach	Heat Recovery (Bottoming Cycles)	PtrainE	4		0.1%	1.0%	10.0%	20.0%	100%	£3,702	0.1%	1.0%	10.0%	20.0%
Coach	Controllable Air Compressor	PtrainE	5		0.0%	20.0%	50.0%	100%	100%	£112	0.0%	20.0%	50.0%	100%
Coach	Automated Transmission	PtrainE	6		20.0%	50.0%	100%	100%	100%	£1,867	20.0%	50.0%	100%	100%
Coach	Stop / Start System	PtrainE	7		100%	100%	100%	100%	100%	£171	100%	100%	100%	100%
Coach	Pneumatic Booster – Air Hybrid	PtrainE	8		0.0%	0.0%	0.0%	0.0%	100%	£427	0.0%	0.0%	0.0%	0.0%
Coach	Aerodynamic Fairings	Aero	1		0.0%	0.0%	20.0%	60.0%	100%	£280	0.0%	0.0%	20.0%	60.0%
Coach	Spray Reduction Mud Flaps	Aero	2		5.0%	20.0%	80.0%	100%	100%	£6	5.0%	20.0%	80.0%	100%
Coach	Aerodynamic Trailers / Bodies	Aero	3		0.0%	10.0%	30.0%	90.0%	100%	£683	0.0%	10.0%	30.0%	90.0%
Coach	Aerodynamics (Irregular Body Type)	Aero	4		0.0%	0.0%	0.0%	0.0%	0%	£-	0.0%	0.0%	0.0%	0.0%
Coach	Active Aero	Aero	5		0.0%	10.0%	30.0%	90.0%	100%	£200	0.0%	10.0%	30.0%	90.0%
Coach	Low Rolling Resistance Tyres	Rres	1		95.0%	80.0%	40.0%	10.0%	100%	£93	95.0%	80.0%	40.0%	10.0%
Coach	Single Wide Tyres	Rres	2		0.0%	20.0%	60.0%	90.0%	100%	£110	0.0%	20.0%	60.0%	90.0%
Coach	Automatic Tyre Pressure Adjustment (ATPA)	Rres	3		50.0%	100%	100%	100%	100%	£4,716	50.0%	100%	100%	100%
Coach	Light weighting	Weight	1		4.0%	30.0%	60.0%	100%	100%	£2,516	4.0%	30.0%	60.0%	100%
Coach	Predictive Cruise Control	Other	1		50.0%	70.0%	20.0%	0.0%	100%	£41	50.0%	70.0%	20.0%	0.0%
Coach	Smart Alternator, Battery Sensor & AGM Battery	Other	2		30.0%	90.0%	100%	100%	100%	£341	30.0%	90.0%	100%	100%
Coach	Alternative Fuel Bodies (for RCV /Refrigeration /Tipper)	Other	3		0.0%	0.0%	0.0%	0.0%	0%	£-	0.0%	0.0%	0.0%	0.0%
Coach	Advanced Predictive Cruise Control	Other	4		5.0%	30.0%	80.0%	100%	100%	£224	5.0%	30.0%	80.0%	100%

6 Results: Cost and Efficiency Trajectories from 2010 to 2050

Objectives:

The purpose of Task 3 of the project was to utilise the information gathered in the Task 2 literature review to develop fuel efficiency and capital cost trajectories for different vehicle categories and technologies to 2050. Specific objectives of the task include:

- *Developing a trajectory of fuel efficiency and capital cost to 2050 for each technology in each category;*
- *Ensure the trajectory is consistent with the goal of progressively reducing new vehicle CO_2 to as far as is practicable by 2050;*

This chapter sets out the results of the analysis in line with these objectives.

Summary of Main Findings

⇒ For passenger cars and vans:

- Conventional powertrains have the greatest potential for % improvements in fuel efficiency in the long term (though being less efficient in absolute terms), versus increasingly electrified powertrain alternatives. The overall potential reduction in energy consumption 2010-2050 ranges from 27%-50% depending on powertrain.
- Capital cost differentials are expected to narrow substantially by 2030, with many alternatives becoming cost-competitive if fuel savings are included (depending on future tax rates for different fuels). Assumptions on electric driving range and battery cost reductions are critical factors. Under low cost assumptions BEV cars become comparable in price to ICEs by 2050, but under high cost assumptions H2FC variants become the more cost-effective ultra-low GHG option.
- The benefits of additional improvements to the ICE appear to be marginal for REEVs after 2020. Also the cost of efficiency improvements to BEVs beyond those to the basic powertrain are extremely high per gCO_2e/km abated. Therefore uptake of these may be more limited than for other powertrains, although the impacts on battery capacity/costs also need to be factored into the equation.

⇒ For motorcycles the reduction potential identified for different powertrain technologies is lower than cars and vans (10-36%), but may be due to insufficient information in the literature. BEV and HEV technologies may become cost-competitive with ICE by 2030.

⇒ For heavy duty vehicles in predominantly urban cycles (small rigid trucks and buses):

- Efficiency improvement benefits by 2050 are expected to reach 16-28%. These reductions are predominantly due to powertrain improvements, with lower levels of benefit from rolling resistance and lightweighting. The greatest benefits are therefore achieved through switching from conventional ICE to more efficient alternative powertrains.
- Purely in terms of capital costs, H2FC technology is the lowest cost ultra-low GHG option for the long-term, however the comparison with BEV changes if fuel costs are included. Factoring in likely future fuel costs brings most technologies to overall cost levels comparable with or lower than Diesel ICE by 2030 (depending on future fuel tax levels).

Summary of Main Findings

⇒ For heavy duty vehicles with the greatest proportions of their km outside of urban areas (large rigid, articulated and construction trucks, coaches):

- Efficiency improvement benefits by 2050 are expected to reach 23-43% (depending on type/powertrain). These reductions are mostly due to improvements in the powertrain and aerodynamics (except construction trucks), with lower levels of benefit from rolling resistance, lightweighting and other technologies.
- Capital costs of alternative powertrains drop to within 6-14% of Diesel ICE by 2050 (depending on vehicle type/powertrain). Factoring in likely future fuel costs brings most technologies to combined cost levels comparable with or lower than Diesel ICE by 2030 and essentially all by 2050 (depending on future fuel tax levels).
- DNG ICE powertrains appear to offer a cost effective alternative (under current tax levels) versus alternatives with substantial lifecycle GHG savings in the short-medium term, which could be further improved through the use of biomethane. In the long term H2FC offer greater GHG savings at similar capital costs.

This section provides a summary and short discussion of the main results of the analysis. A variety of charts and tables are included, illustrating the main results. The full details of the analysis results (including all the figures behind the presented charts) are available in the calculations spreadsheet supplied alongside this report.

An important factor to considering when viewing the presented charts on efficiency improvements is that split/allocation of efficiency savings between different technology categories is a result of the order in which the efficiency benefits are being applied in the calculations and therefore only indicative. In applying technical options successively, the observed actual MJ/km benefit per % improvement for each of the subsequently applied technology option will be smaller than for the one preceding it. Therefore if the options were applied in a different order the relative savings in MJ/km for each technology category would appear slightly different. Technologies are applied in the following category order in the study analysis calculations:

0. Core powertrain technology improvement
1. Powertrain efficiency
2. Aerodynamics
3. Rolling resistance
4. Weight reduction
5. Other measures

In addition to the assumptions presented in the earlier sections of the report, to aid the analysis of the results indicative assumptions on the future carbon intensity and price of different fuels were used, as summarised in Table 6.1. Note: the emission factors for electricity also factor in estimated losses from battery charging, based on earlier Table 3.1.

Table 6.1: Additional assumptions on the trajectory of carbon intensity and price of energy carriers from 2010-2050, excluding biofuel effects

Fuel		2010	2020	2030	2040	2050	Notes
	gCO_2/MJ *						
Petrol	Direct	68.75	68.75	68.75	68.75	68.75	
Diesel	Direct	71.39	71.39	71.39	71.39	71.39	
Natural Gas (CNG)	Direct	56.61	56.61	56.61	56.61	56.61	
LNG	Direct	56.61	56.61	56.61	56.61	56.61	
Electricity	Direct	0.00	0.00	0.00	0.00	0.00	
Hydrogen	Direct	0.00	0.00	0.00	0.00	0.00	
Petrol	Lifecycle	82.03	82.03	82.03	82.03	82.03	
Diesel	Lifecycle	86.86	86.86	86.86	86.86	86.86	
Natural Gas	Lifecycle	65.09	65.09	65.09	65.09	65.09	
LNG	Lifecycle	76.73	76.73	76.73	76.73	76.73	
Electricity	Lifecycle	149.95	93.27	49.25	10.64	6.42	(2)
Hydrogen	Lifecycle	112.74	86.73	60.73	34.72	8.72	(3)
	£/MJ	**2010**	**2020**	**2030**	**2040**	**2050**	
Petrol	Price	0.037	0.045	0.046	0.046	0.046	(2)
Diesel	Price	0.034	0.043	0.045	0.045	0.045	(2)
Natural Gas (CNG)	Price	0.018	0.024	0.025	0.025	0.025	(3)
LNG	Price	0.016	0.016	0.016	0.016	0.016	(4)
Electricity	Price	0.042	0.061	0.061	0.070	0.070	(2)
Hydrogen	Price	0.076	0.098	0.086	0.091	0.088	(2)

Sources: (1) 2011 Defra/DECC GHG Conversion Factors (DCF, 2011); (2) DECC (2011) plus additionally factoring in estimated losses from battery charging (see Table 3.1); (3) Estimate based on transition of production predominantly from natural gas in 2010 to 100% by electrolysis of grid electricity in 2050. (3) NGVA (2011); (4) Assume same as for CNG

Notes: * Excludes any potential impacts of biofuels on either net emissions or fuel prices.

6.1 Light Duty Vehicles and Motorcycles

This section provides a headline summary of some of the key results from the analysis.

6.1.1 Passenger Cars

Figure 6.2 to Figure 6.6 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to passenger cars on overall vehicle efficiency by powertrain type, direct gCO_2/km (for comparison with regulatory limit values for 2020), and net capital cost increases attributed to the different technology areas.

There are a number of key points to draw out of these charts under the best case cost assumptions:

i. The difference between conventional ICE powertrains and increasingly electrified alternative powertrains is expected to narrow significantly in the future, as there are still many options for improvements to engines and transmissions. The overall potential efficiency improvement seen by Petrol ICE between 2010 and 2050 is estimated at ~50%, compared to the BEV improvement of ~27%. Improvements to other powertrains are in-between depending on their relative degree of electrification.

ii. The relative costs of different powertrains is anticipated to very substantially narrow in the next 20 years, with the cost range of ICE, HEV, PHEV and REEV powertrains narrowing to less than £2800 by 2030 best cost estimates. Under the study assumptions BEVs and H2FCVs still have substantially reduced in cost, but still have significantly higher capital costs in 2030 (by a further ~£1000-£5600). There is a much lower level of cost reduction anticipated by 2050, with these technologies still being significantly more expensive than other options. The electric range assumption for BEVs also still has a significant impact here (assumed to reach 320km by 2050).

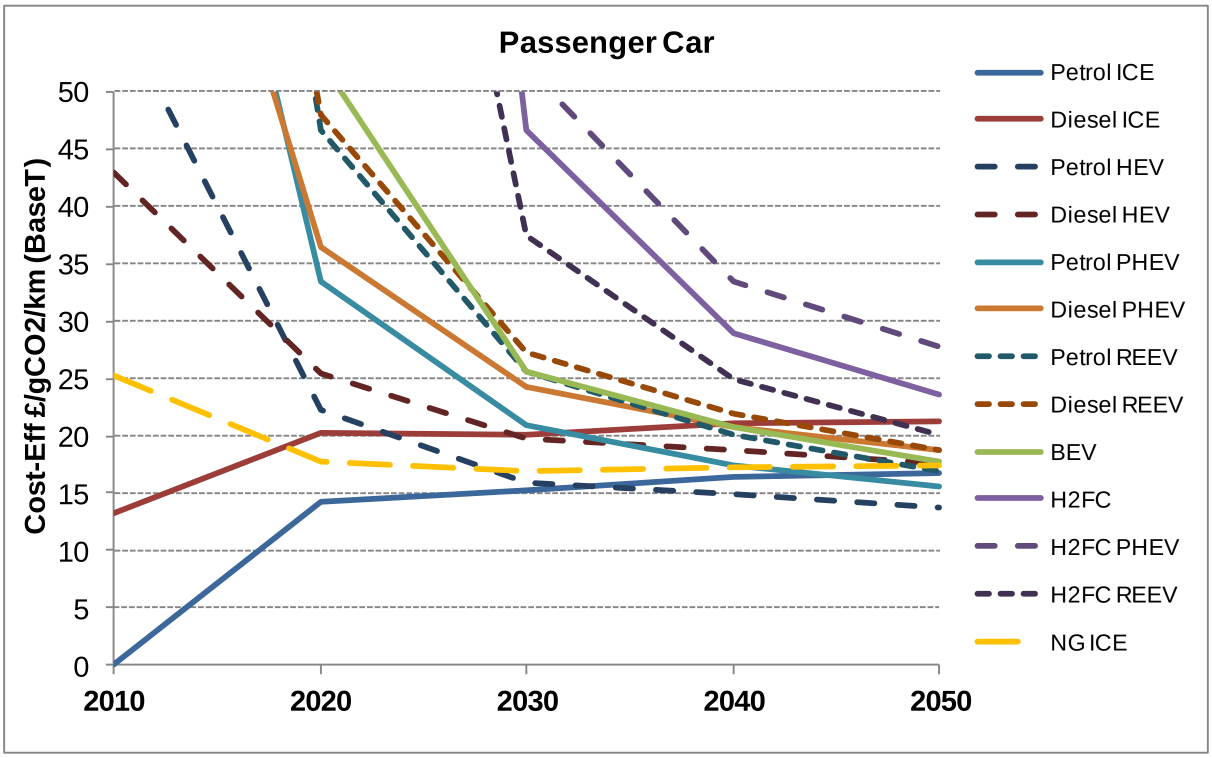
iii. If the lower price of electricity is factored into the comparisons, BEVs could become cost-competitive with ICEs much sooner, but this depends also on future taxation policy for electricity supplied for transport fuels (i.e. tax might be applied in future years to recover some of the revenue lost from reduced sales of conventional fuels).

iv. For PHEVs the benefits of improved ICE mode driving appear to still be relatively significant, at least up until 2030. However, for REEVs the benefits are more marginal due to the greater proportion of electric-only drive. For BEVs, cost in £ per gCO_2/km reduction for non-powertrain improvements is extremely high – especially in later periods (reaching £846/gCO_2e/km versus and average of £17/gCO_2e/km for petrol ICE technologies). This may suggest certain options are unlikely to be deployed at the same rate in the more carbon-efficient powertrains on this basis. However, it is also important to factor in the impact of reduced efficiency on the battery pack sizing and therefore total costs for a given range (i.e. the additional cost of the efficiency improvement technology is offset by reduced battery costs).

v. The cost-effectiveness of different powertrains versus the base 2010 petrol ICE technology appears to converge to a significant degree by 2030 and much further by 2050 for most powertrain types, as illustrated in Figure 6.1. The comparison will further improve when factoring in relative fuel costs.

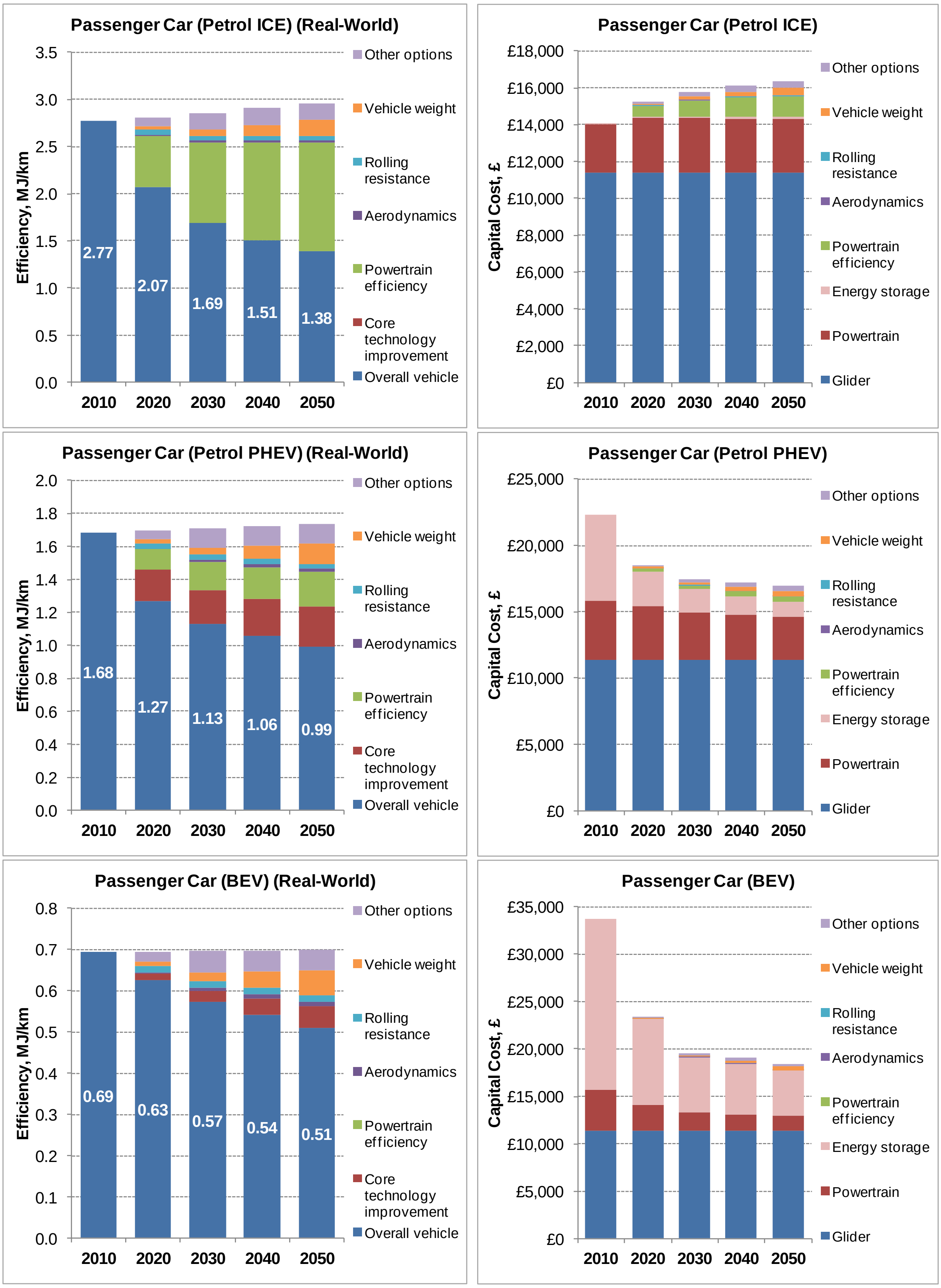
vi. The alternate base technology cost reduction scenarios presented in Figure 6.6 show that under low cost assumptions BEVs could reduce in cost to a similar level to conventional ICE vehicles by 2050. Under high cost assumptions, their costs could be significantly higher, with H2FCVs providing a more cost-effective ultra-low GHG option instead.

Figure 6.1: Trajectory for Passenger Car Efficiency improvement cost-effectiveness by technology, £ per gCO_2e/km reduction *



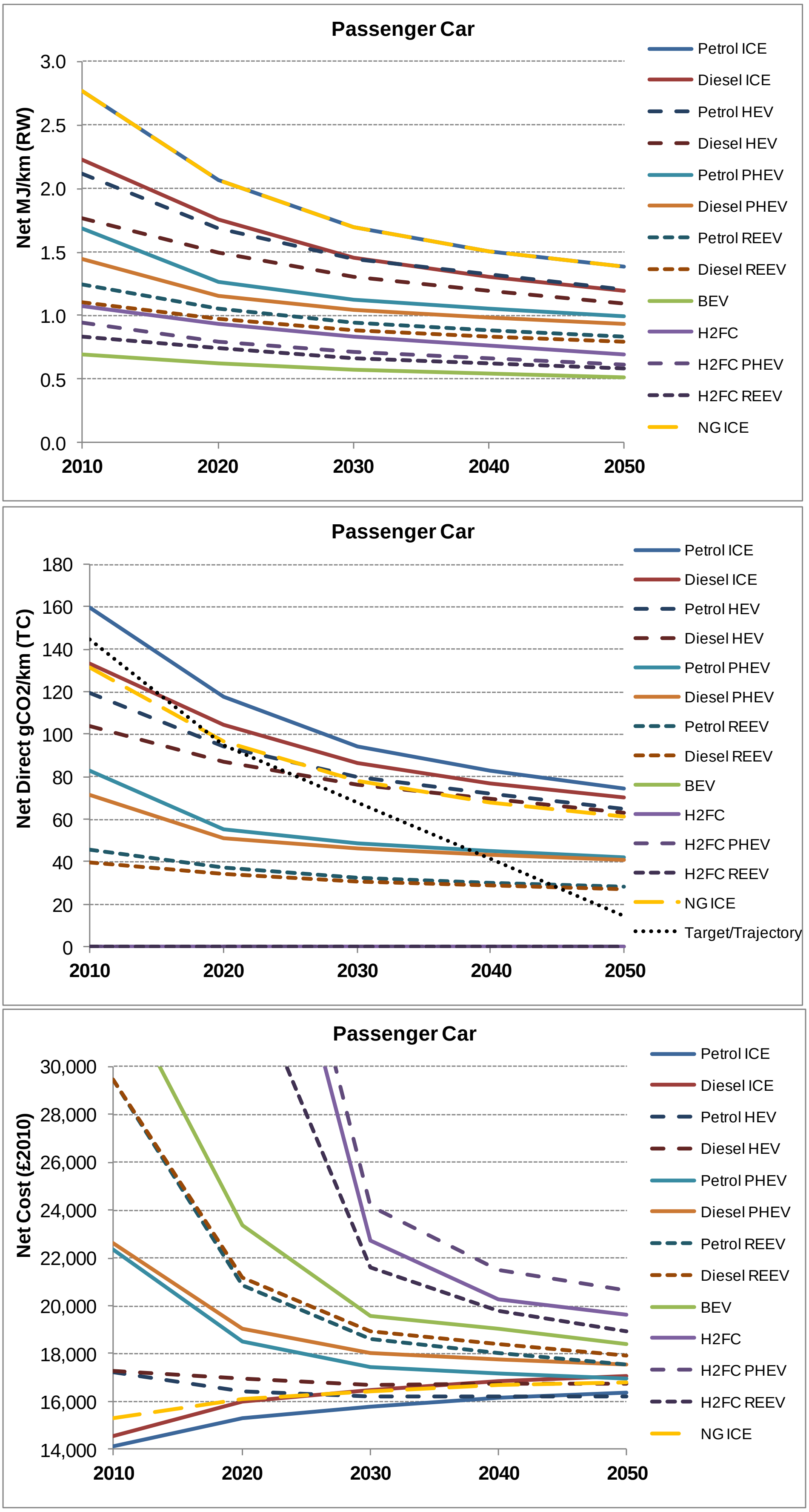
Notes: * Based on lifecycle GHG emissions estimates for different fuels

Figure 6.2: Trajectory for Passenger Car Efficiency and Costs for Petrol ICE, PHEV and BEV



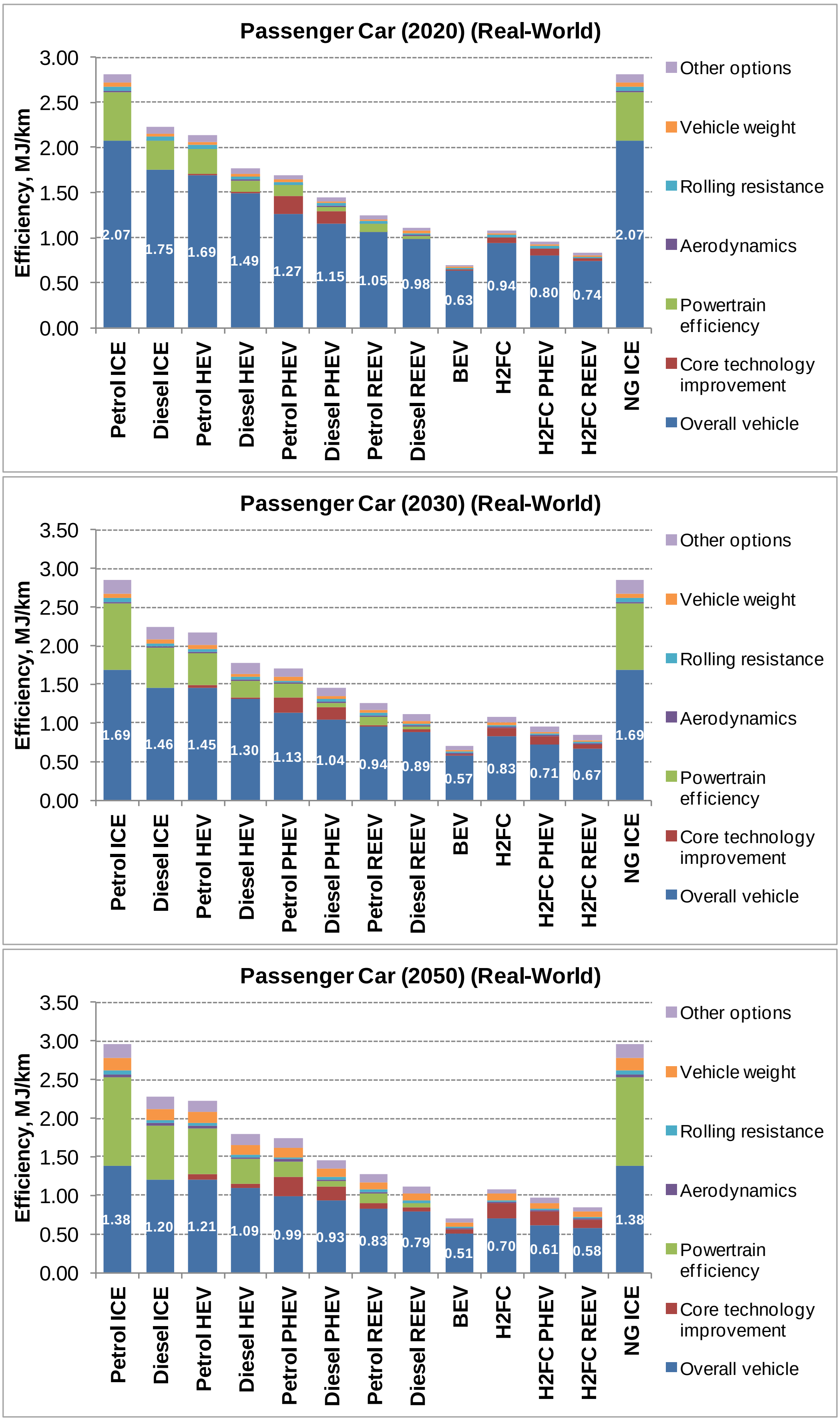
Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.3: Trajectory for Passenger Car Efficiency, Direct gCO_2/km and Cost by technology



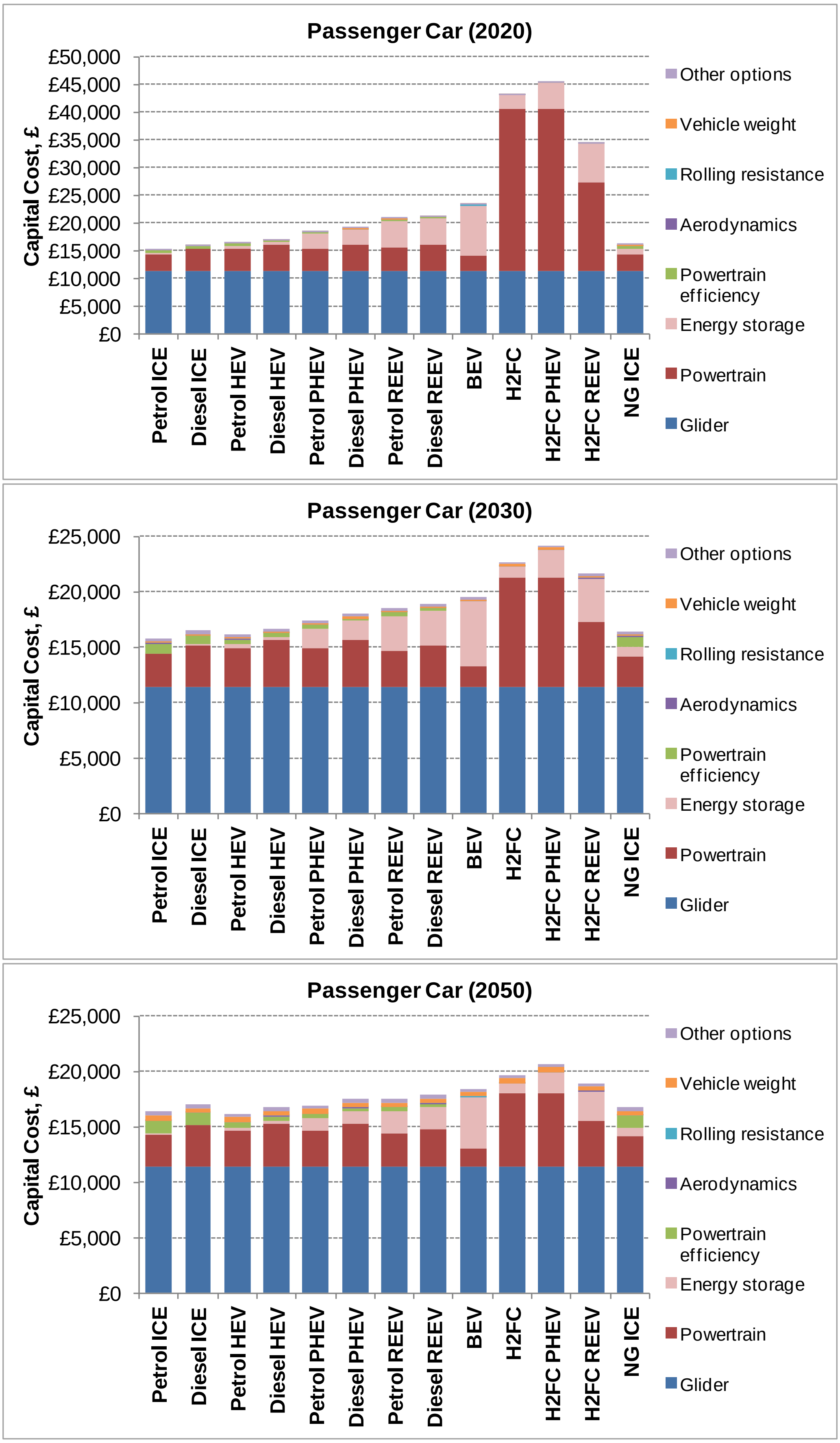
Notes: The 'Target/Trajectory' marks the 2020 gCO_2/km regulatory targets, and a continued indicative trajectory to 90% reduction in direct gCO_2/km by 2050 relative to 2010.

Figure 6.4: Analysis results for Passenger Car Efficiency for 2020, 2030 and 2050



Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

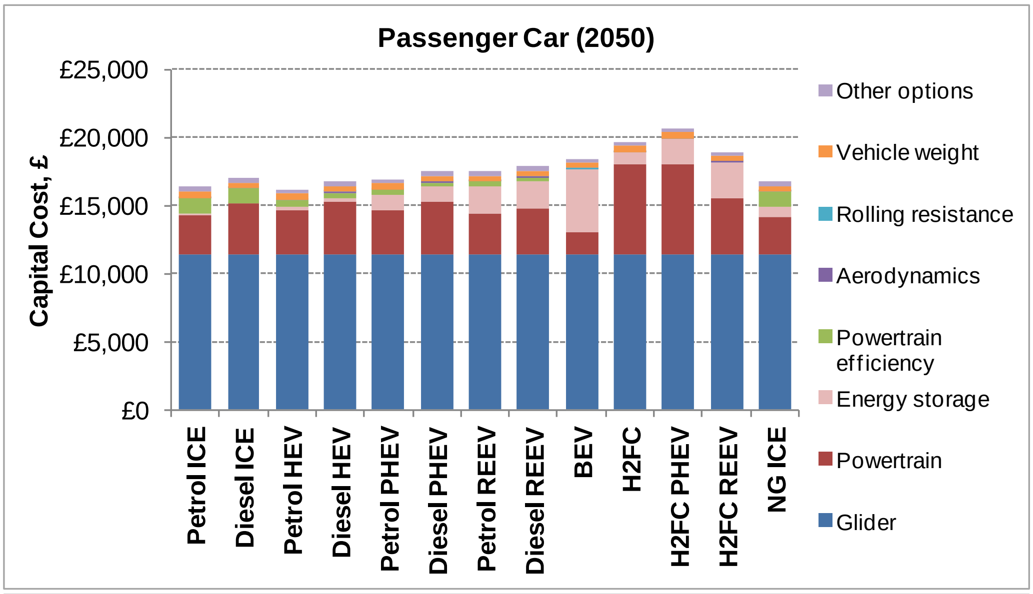
Figure 6.5: Analysis results for Passenger Car Capital Costs for 2020, 2030 and 2050



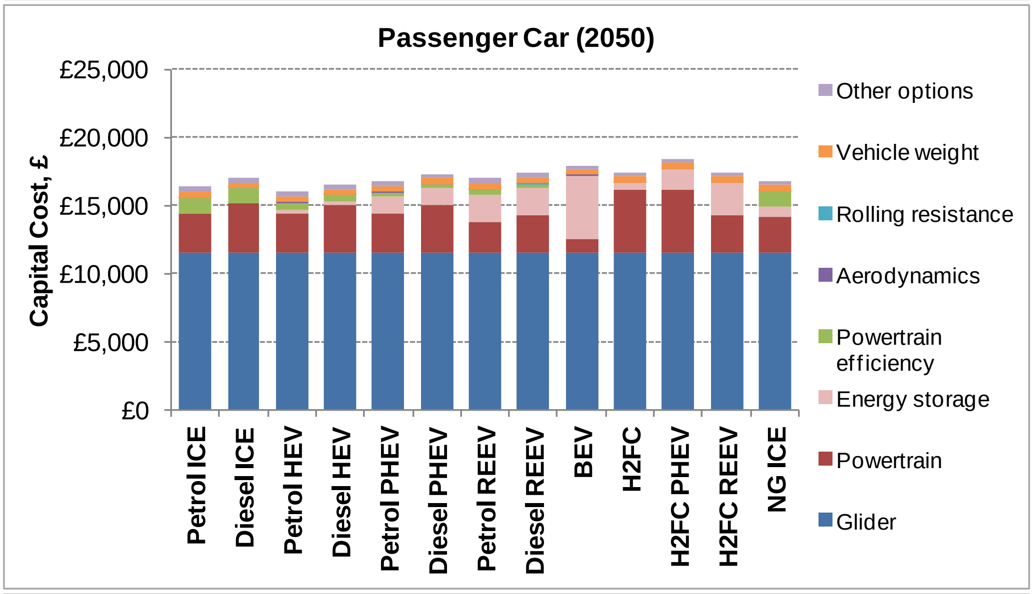
Notes: Coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.6: ***Analysis results for 2050 Passenger Car Capital Costs for Best, Low and High Cost assumptions for key vehicle components***

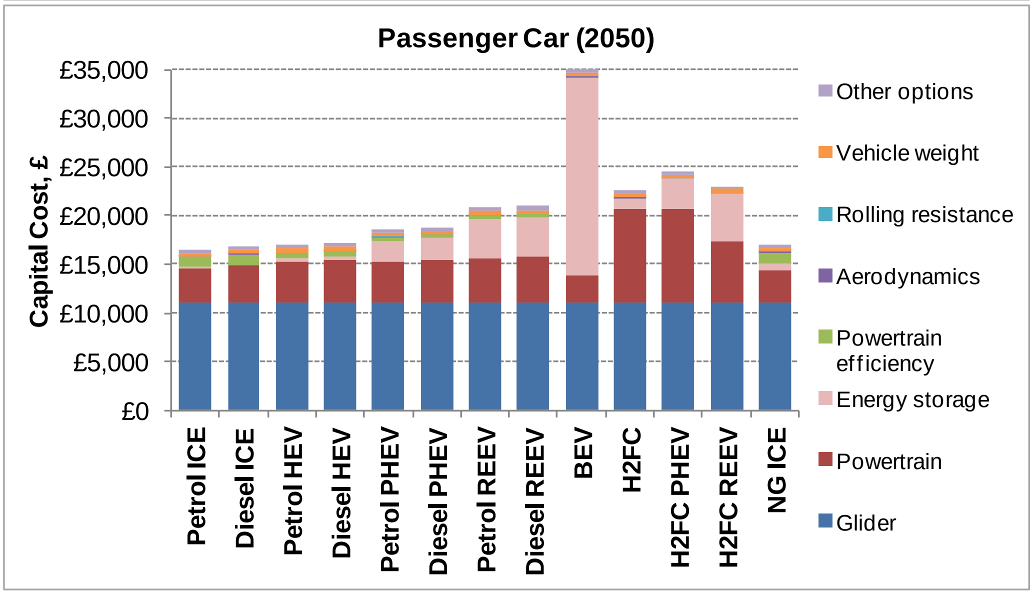
Best Costs



Low Costs



High Costs



Notes: The coloured bars above the ‘Glider’ component represent additional/marginal technology costs.

6.1.2 Vans

Figure 6.7 to Figure 6.10 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to vans on overall vehicle efficiency by powertrain type, direct gCO_2/km (for comparison with regulatory limit values for 2020), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best cost assumptions are:

i. Petrol vans have been characterised based on their average characteristics for the new van fleet, which is significantly skewed towards smaller van categories and are therefore not comparable with diesel van technologies. Natural gas, BEV and H2FC technologies have also been sized to diesel vans, since petrol vans only comprise <2% of the new van fleet.

ii. In general the trends observed for vans are similar to those already discussed for passenger cars in the previous section. The main difference is the slower rate of technological penetration assumed results in lesser reductions in overall vehicle efficiency (23%-41%) when compared to cars (27%-50%).

6.1.3 Motorcycles

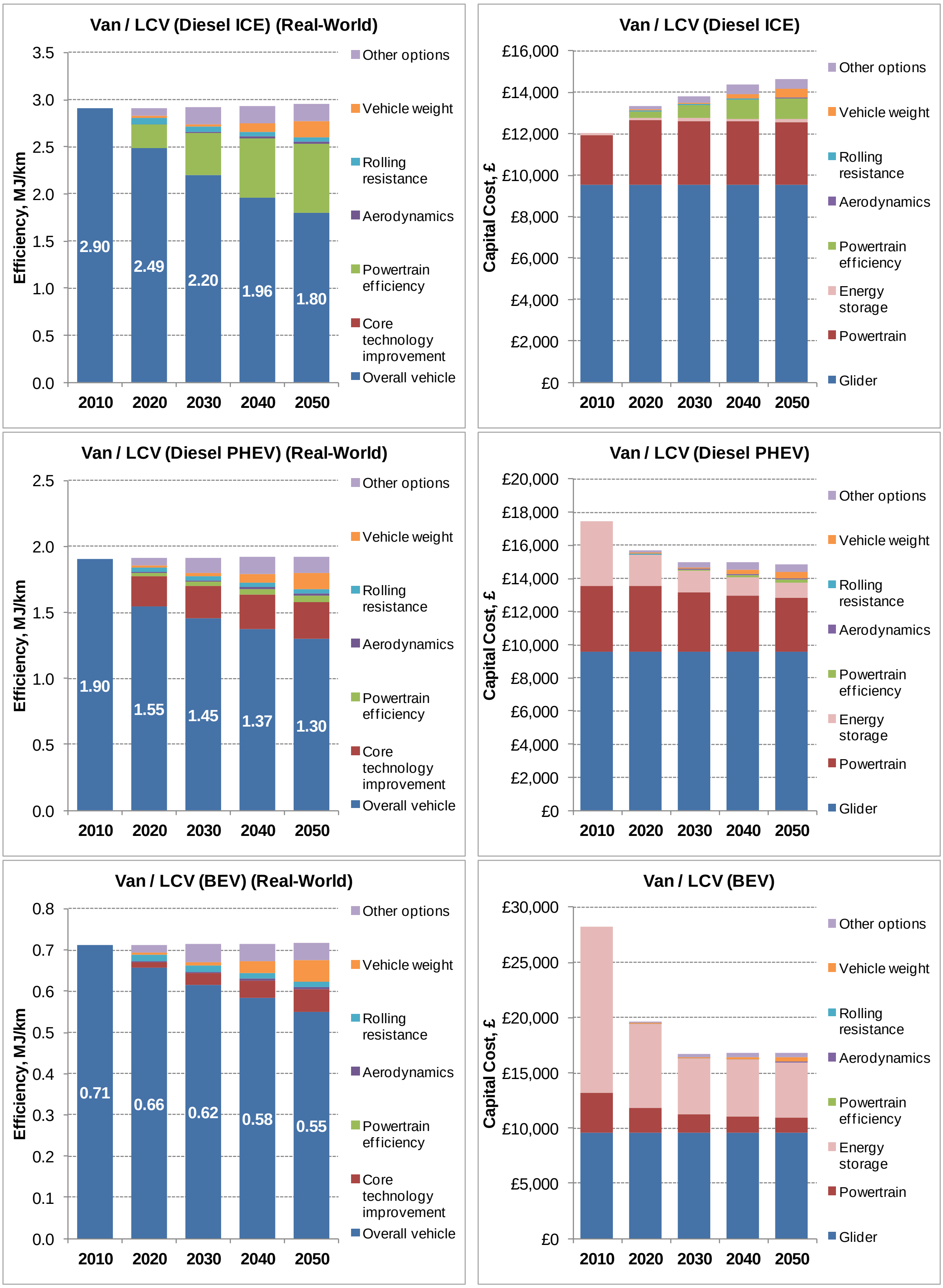
Figure 6.11 to Figure 6.14 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to vans on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best cost assumptions are:

i. The overall efficiency improvements and GHG reduction potential within the different powertrain technologies between 2010 and 2050 are lower than for cars or vans (at 10%-36%). However, this may partly due to the lack of significant information about efficiency improvement technologies for motorcycles in the available literature.

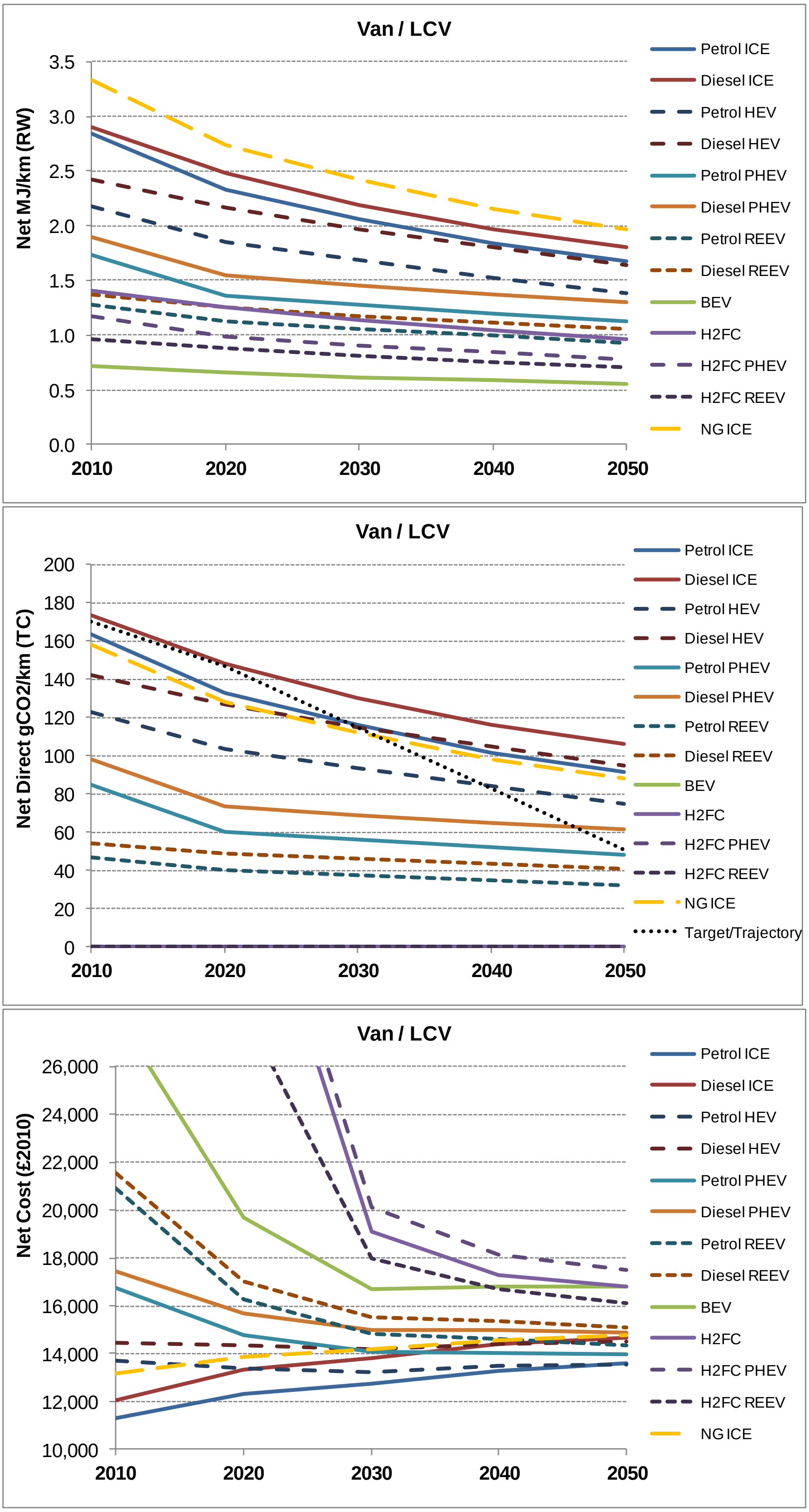
ii. BEV and HEV powertrain technologies appear to become close to cost-competitive with ICE powertrains by 2030. However, H2FC motorcycles still have significantly higher capital costs still by 2050.

Figure 6.7: Trajectory for Van Efficiency and Costs for Diesel ICE, PHEV and BEV



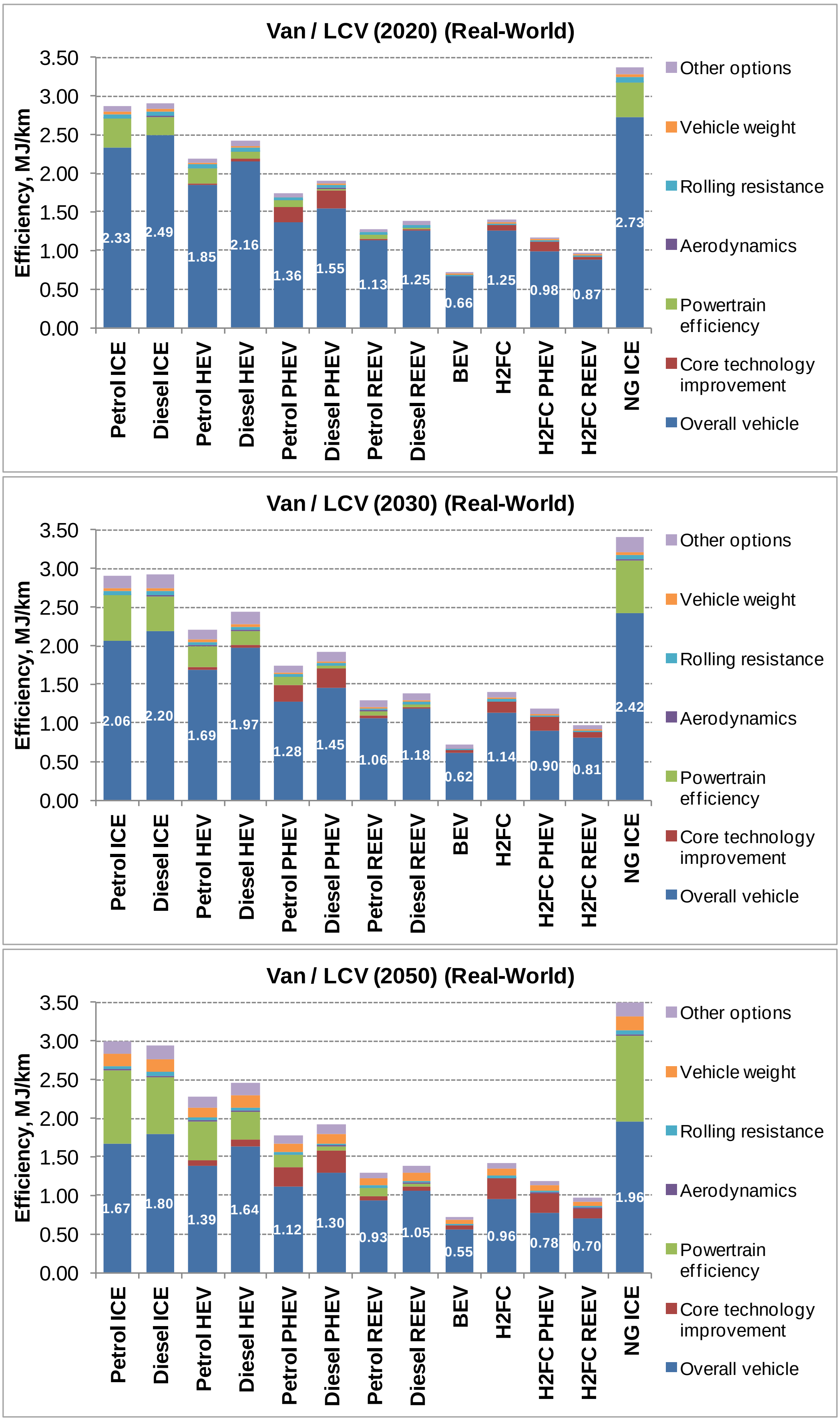
Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.8: Trajectory for Van Efficiency, Direct gCO_2/km and Cost by technology



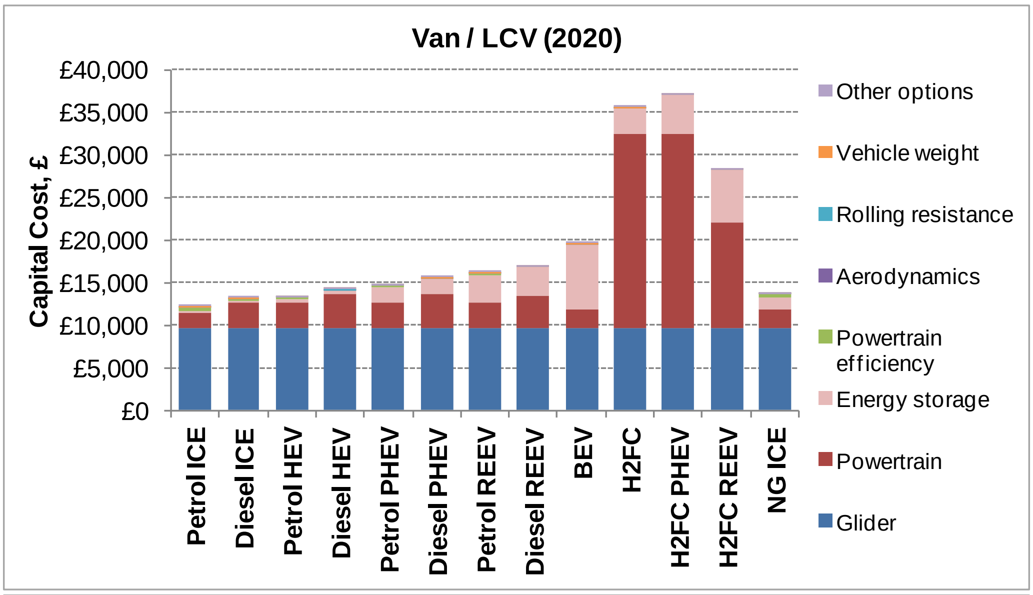
Notes: The 'Target/Trajectory' marks the 2020 gCO_2/km regulatory targets, and a continued indicative trajectory to 70% reduction in direct gCO_2/km by 2050 relative to 2010.

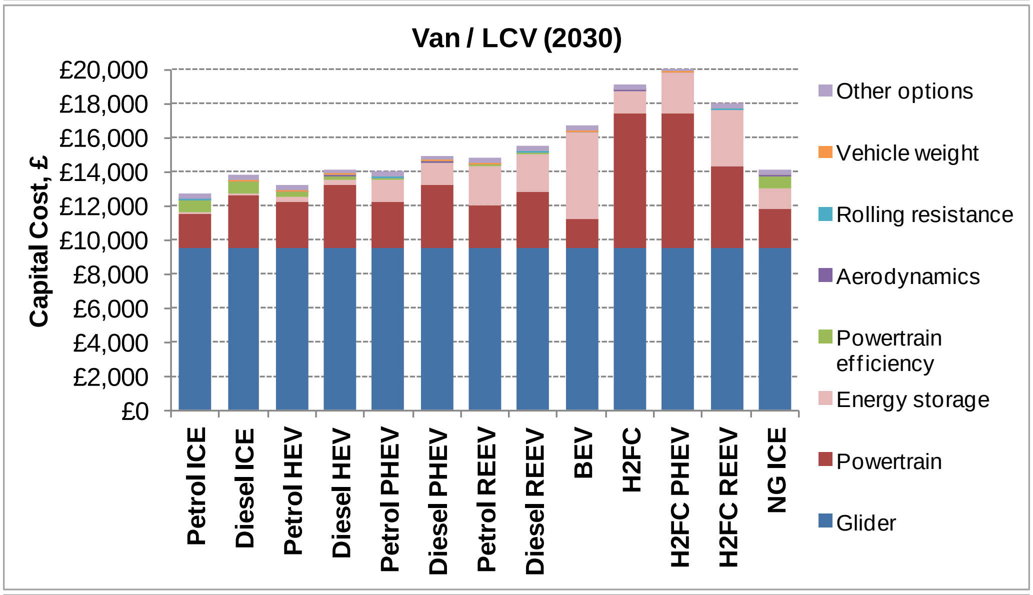
Figure 6.9: Analysis results for Van Efficiency for 2020, 2030 and 2050

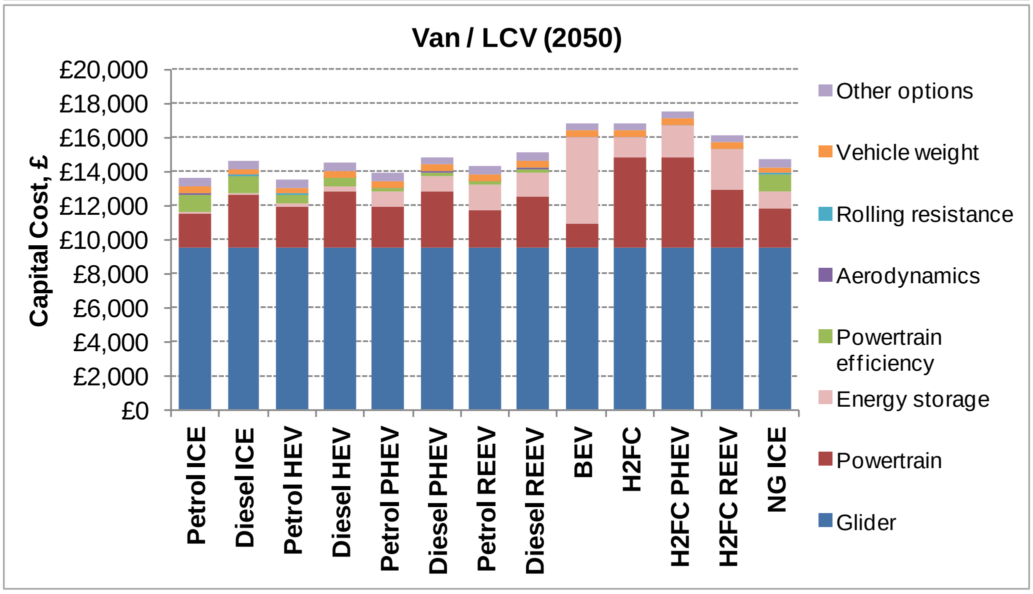


Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.10: Analysis results for Van Capital Costs for 2020, 2030 and 2050

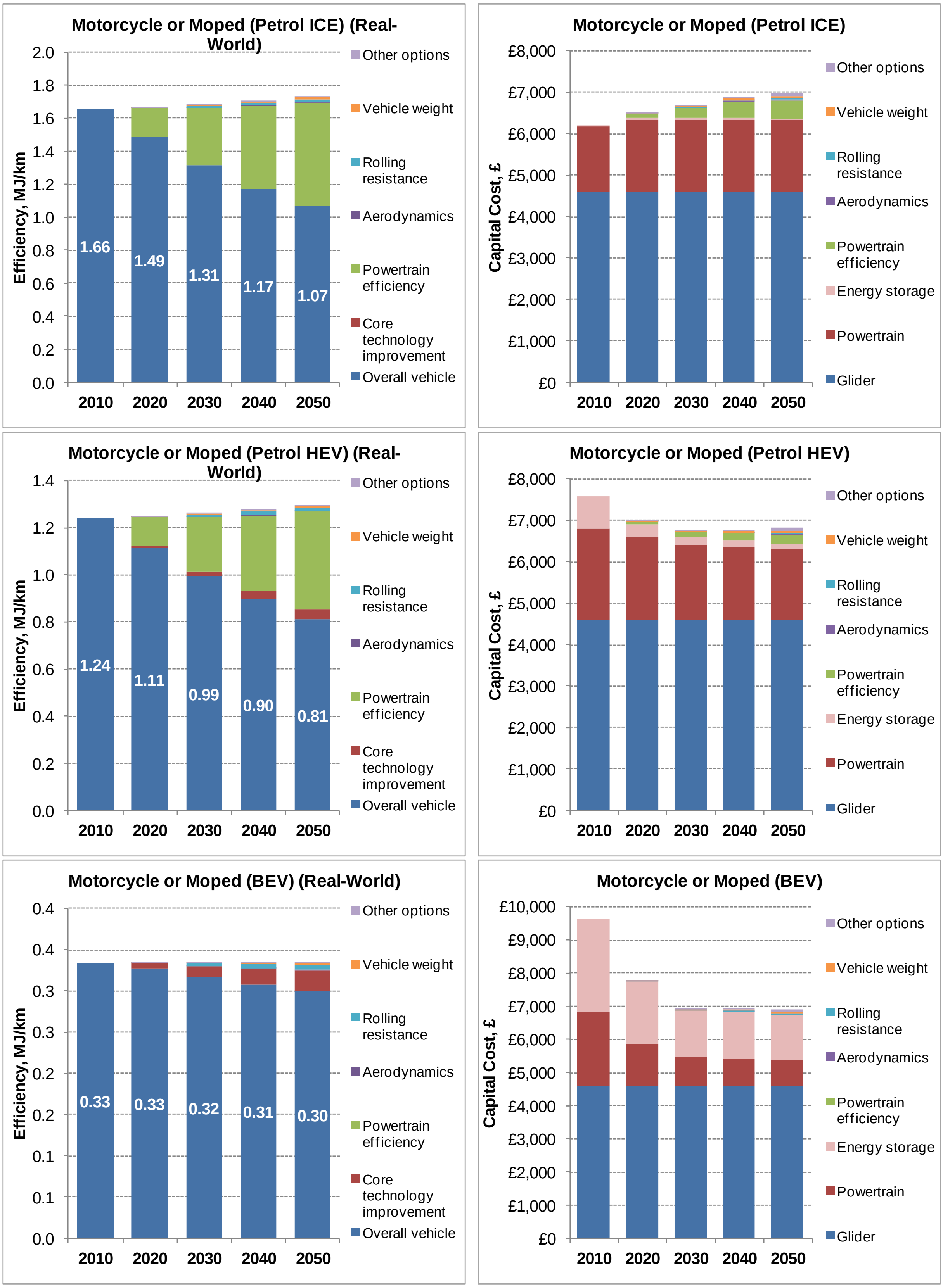






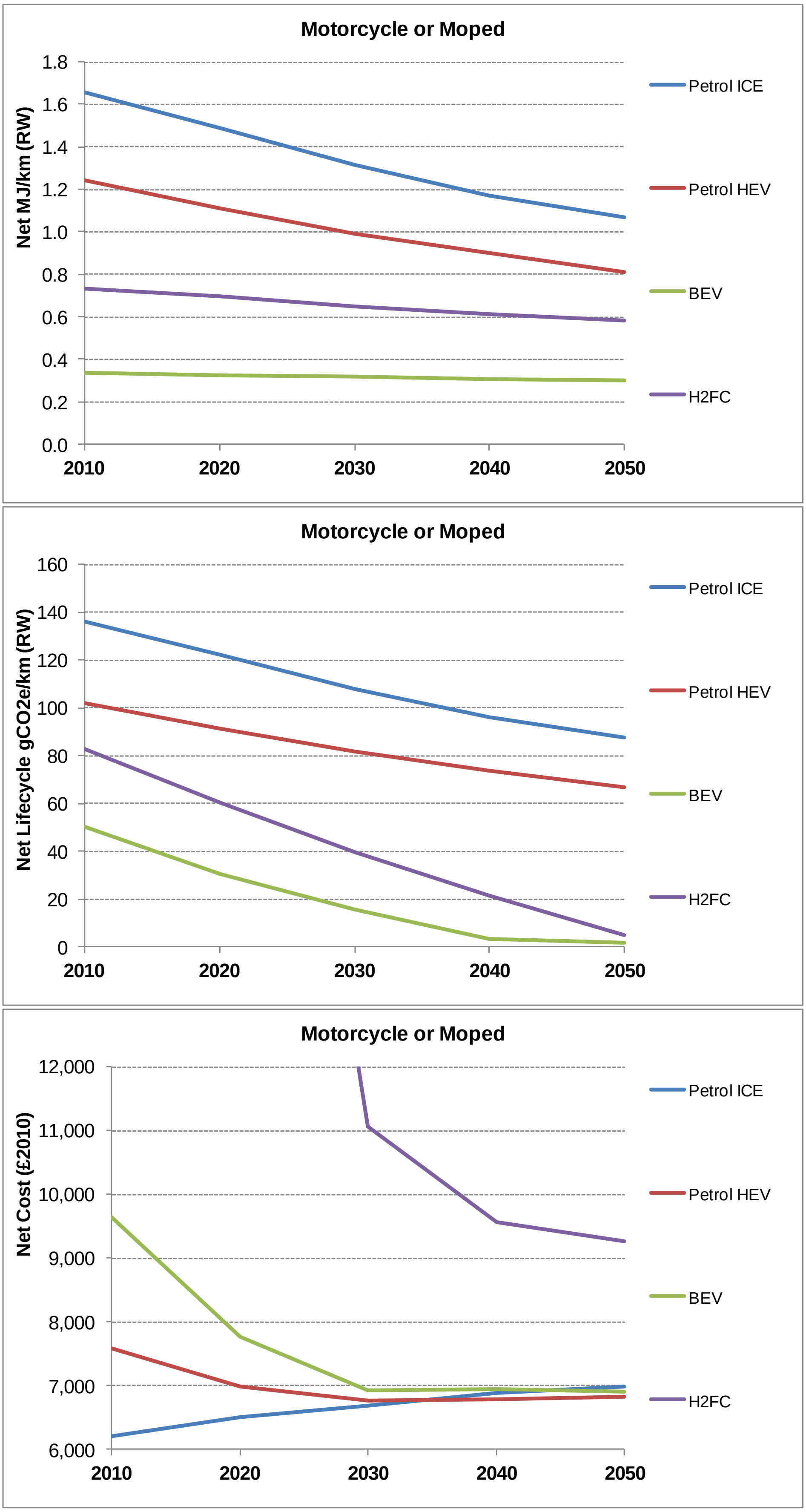
Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.11: Trajectory for Motorcycle Efficiency and Costs for Petrol ICE, HEV and BEV



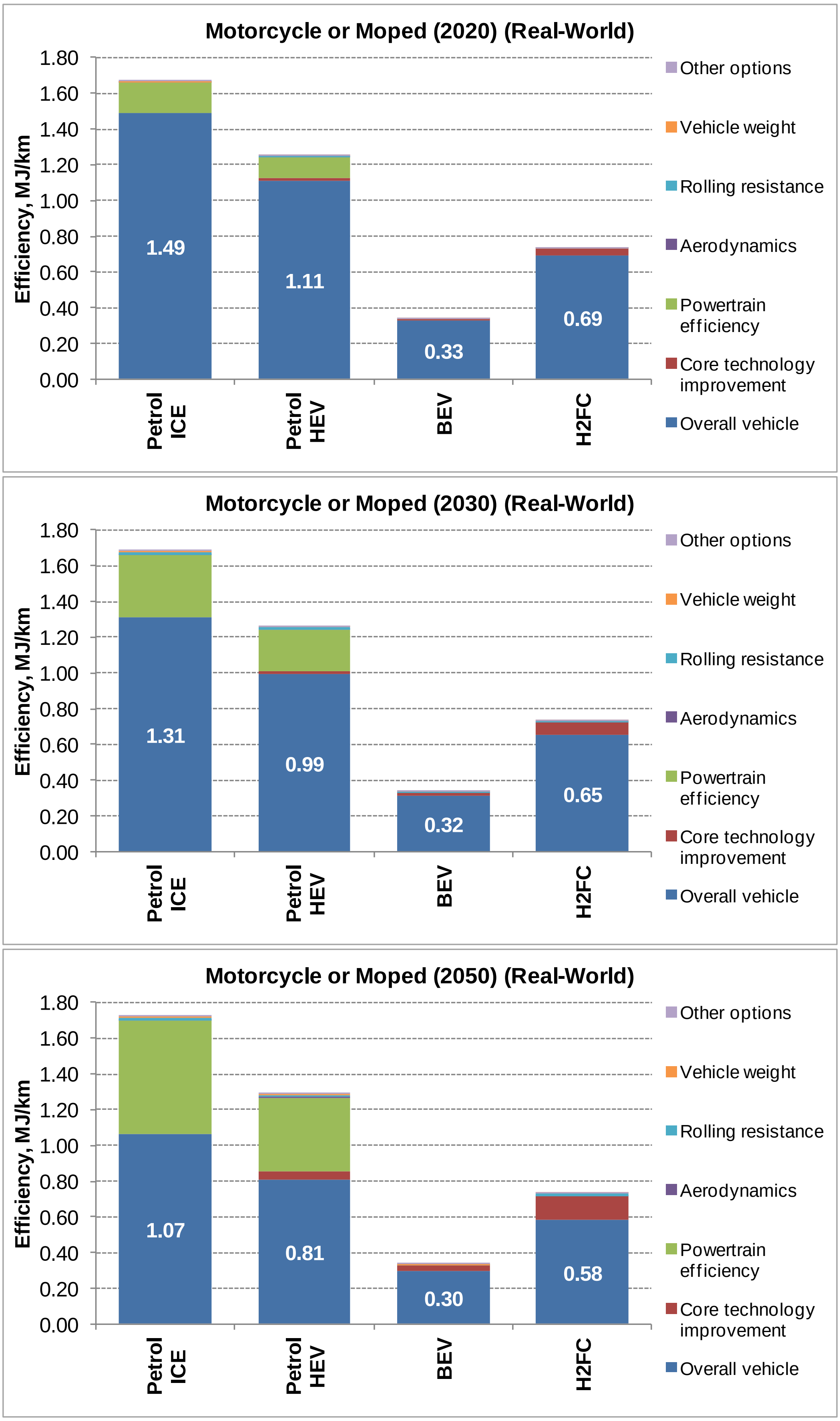
Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.12: Trajectory for Motorcycle Efficiency, Lifecycle gCO_2/km and Cost by technology



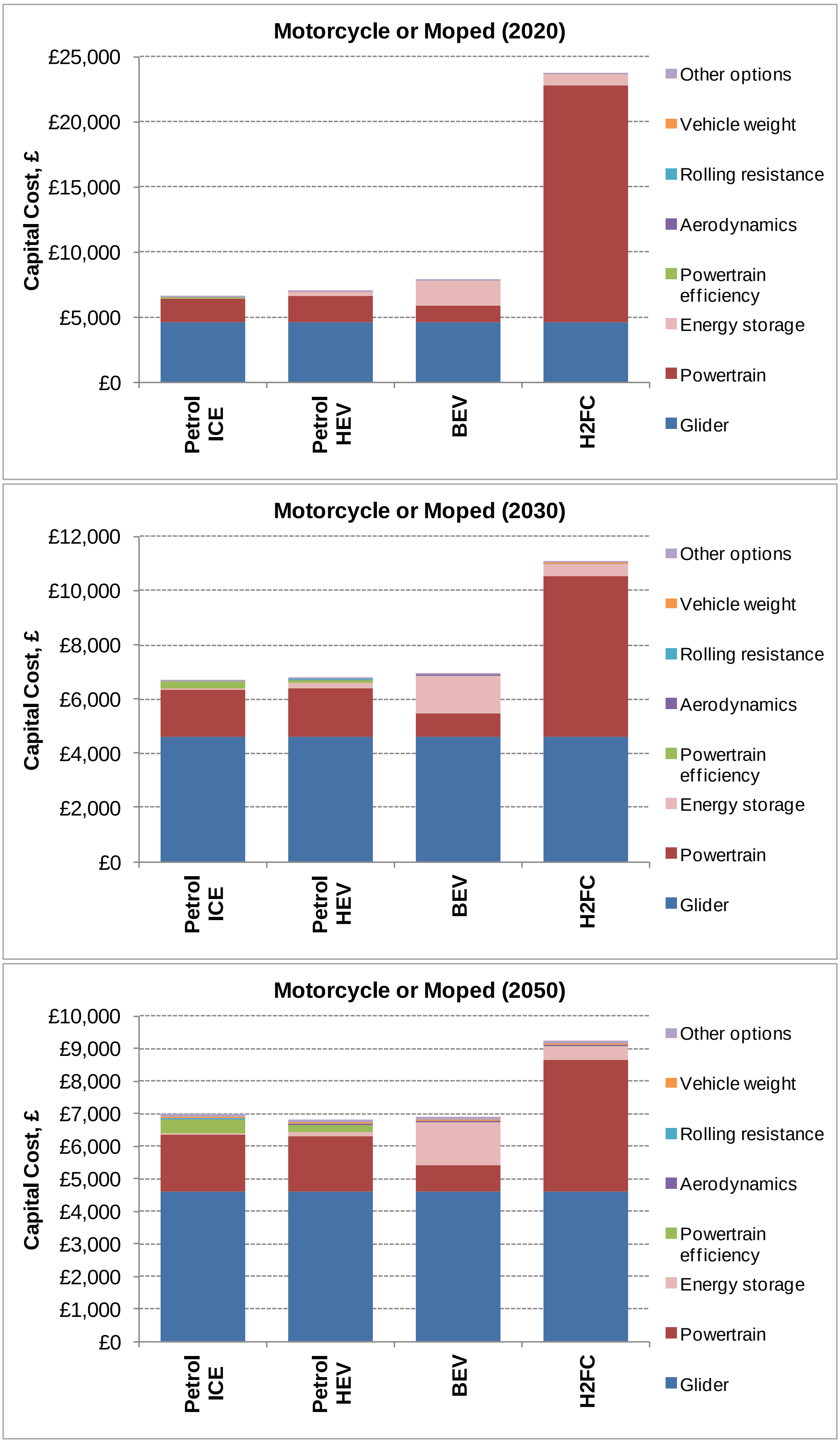
Notes: Lifecycle GHG calculated based on assumptions on the projected GHG intensity of fuels.

Figure 6.13: Analysis results for Motorcycle Efficiency for 2020, 2030 and 2050



Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.14: Analysis results for Motorcycle Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal costs.

6.2 Heavy Duty Vehicles

6.2.1 Small Rigid Trucks

Figure 6.15 to Figure 6.18 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to small rigid trucks on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best case cost assumptions are:

i. The potential combined fuel consumption benefit of all technologies by 2050 is 16% - 28% depending on the powertrain. These benefits are predominantly due to improvements in the powertrain with secondary benefits equally divided among rolling resistance, and lightweighting, with only small contributions from aerodynamics and other technologies. The greatest benefits are therefore achieved through switching from conventional ICE to more efficient alternative powertrains.

ii. In contrast to light duty vehicles, purely in terms of capital costs, H2FC technology appears to be a significantly lower cost ultra-low GHG technology in the longer term than BEV, with capital costs similar to those of alternatives by 2050 (and potentially below those of DNG ICE and NG ICE powertrains). Factoring in likely fuel costs into the equation brings most technologies to overall cost levels similar to, or below those of conventional diesel ICE by 2030. Estimated overall costs of BEVs are also below those of H2FCs, however this assessment critically depends on both the relative prices of hydrogen / electricity and the levels of taxes applied to different fuels in future periods.

iii. DNG ICE trucks may offer a useful short-medium term alternative with similar net GHG savings to hybrid powertrains (and better suited to mission profiles with greater proportions of rural and highway km). However, the total capital costs are expected to remain higher, partly due to the lack of anticipated reductions in natural gas storage costs. Combination of DNG ICE with biomethane would, however, offer substantial further GHG savings beyond those possible with Diesel HEVs. In the long term H2FC offer greater GHG savings at similar capital costs.

6.2.2 Large Rigid Trucks

Figure 6.19 to Figure 6.22 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to large rigid trucks on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best case cost assumptions are:

i. The potential combined fuel consumption benefit of all technologies by 2050 is 33% - 40% depending on the powertrain. The greatest benefits are due to improvements in the powertrain and aerodynamics with lower levels of benefits due to rolling resistance, lightweighting and other technologies.

ii. The capital cost premium of alternative technologies is expected to drop to within a range of 11% by 2050, with savings in fuel consumption likely to outweigh differences in capital costs versus Diesel ICE for all technologies except H2FC by 2020 and all by 2040 (depending on future fuel tax levels).

iii. DNG ICE powertrains appear to offer a cost-effective alternative (under current tax levels) versus alternative powertrains with substantial lifecycle GHG savings in the short-medium term, which could be further improved through the use of biomethane. In the long term H2FC offer greater GHG savings at similar capital costs.

6.2.3 Articulated Trucks

Figure 6.23 to Figure 6.26 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to articulated trucks on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best case cost assumptions are:

i. The potential combined fuel consumption benefit of all technologies by 2050 is 41% - 43% depending on the powertrain. As for rigid trucks, the greatest benefits are due to improvements in the powertrain and aerodynamics, with lower levels of benefits due to rolling resistance, lightweighting and other technologies.

ii. The capital cost premium of alternative technologies is expected to drop to within a range of just over 11% by 2050, with savings in fuel consumption likely to outweigh differences in capital costs versus Diesel ICE for all technologies except H2FC by 2030 (depending on future fuel tax levels). FHV and HHV technologies appear to offer only marginal cost reductions even by 2050, due to the lower level of savings they offer for typical articulated truck mission profiles (i.e. long-haul).

iii. DNG ICE powertrains appear to offer a cost-effective alternative (under current tax levels) versus alternative powertrains with substantial lifecycle GHG savings in the short-medium term, which could be further improved through the use of biomethane. In the long term H2FC offer greater GHG savings at similar capital costs.

6.2.4 Construction Trucks

Figure 6.27 to Figure 6.30 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to construction trucks on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best case cost assumptions are:

i. The potential combined fuel consumption benefit of all technologies by 2050 is 23% - 36% depending on the powertrain. The greatest benefits are from due to improvements in the powertrain, with slightly lower benefits equally divided among rolling resistance, aerodynamics and other technologies. Lightweighting only provides a very small contribution.

ii. Whilst construction trucks have lower potential for aerodynamic improvement benefits versus large rigid and articulated trucks, those with electrified powertrains have a greater additional potential for benefits in dual-mode operation (i.e. supporting non-motive auxiliary loads from tipper mechanisms and other construction specific equipment).

iii. The capital cost premium of alternative technologies is expected to drop to within a range of 14% by 2050, with savings in fuel consumption likely to outweigh differences in capital costs versus Diesel ICE for all technologies by 2030 (depending on future fuel tax levels).

iv. DNG ICE powertrains appear to offer a cost-effective alternative (under current tax levels) versus alternative powertrains with substantial lifecycle GHG savings in the short-medium term, which could be further improved through the use of biomethane. In the long term H2FC offer greater GHG savings at similar capital costs.

6.2.5 Buses

Figure 6.31 to Figure 6.34 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to buses on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

The main key points to draw out of these charts under the best case cost assumptions are:

i. The potential combined fuel consumption benefit of all technologies by 2050 is 17% - 27% depending on the powertrain. These benefits are predominantly due to improvements in the powertrain with lower benefits from weight reduction and from rolling resistance. Aerodynamics and other technical options are not expected to provide very significant contributions. The greatest benefits are therefore achieved through switching from conventional ICE to more efficient alternative powertrains.

ii. The capital cost premium of alternative technologies is expected to drop to within a range of 5% by 2050 for all except BEVs (still 14% higher). Savings in fuel consumption seem likely to outweigh differences in capital costs versus Diesel ICE for all technologies by 2030 (depending on future fuel tax levels).

6.2.6 Coaches

Figure 6.35 to Figure 6.38 provide a summary of the impacts of the assumptions on deployment of efficiency improvements to coaches on overall vehicle efficiency by powertrain type, lifecycle gCO_2/km (for better comparison of net effects in the absence of regulatory targets), and net capital cost increases attributed to the different technology areas.

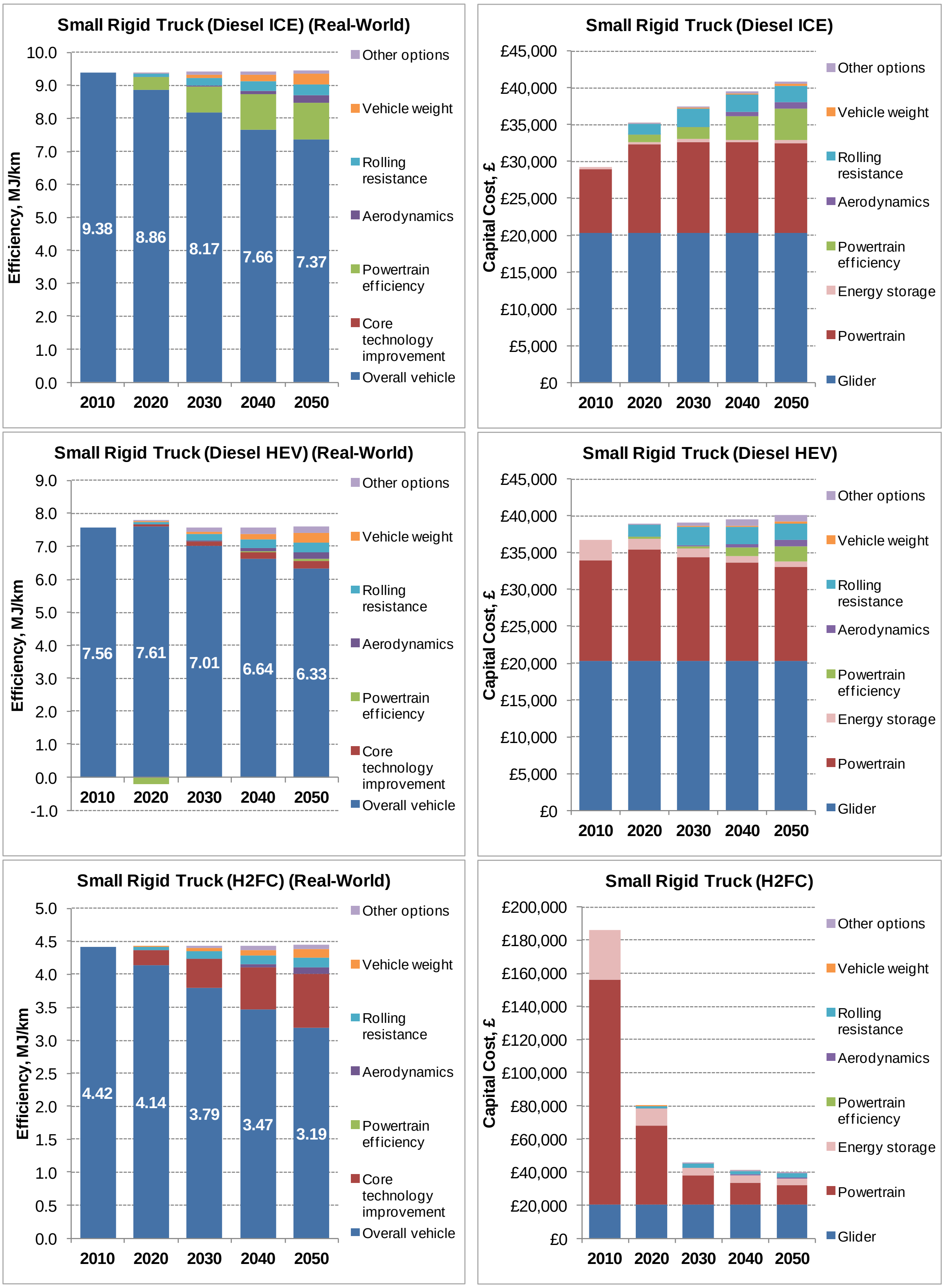
The main key points to draw out of these charts under the best case cost assumptions are:

i. The potential combined fuel consumption benefit of all technologies by 2050 is 30% - 35% depending on the powertrain. The greatest benefits are due to improvements in the powertrain, aerodynamics and rolling resistance, and with lower levels of benefits due to lightweighting and other technologies.

ii. The capital cost premium of alternative technologies is expected to drop to within a range of ~6% by 2050. Savings in fuel consumption seem likely to outweigh differences in capital costs versus Diesel ICE for all technologies by 2030 (depending on future fuel tax levels).

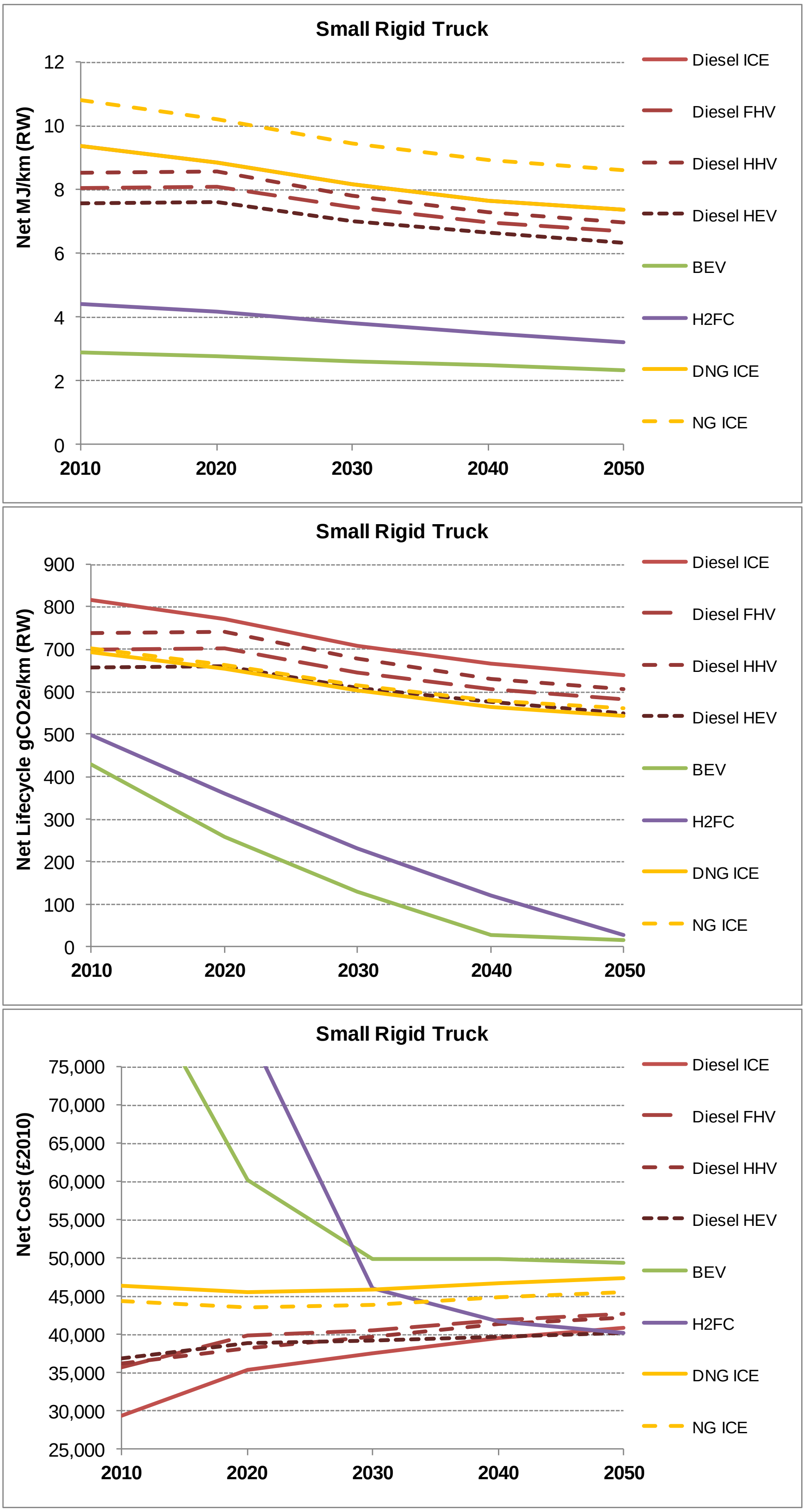
iii. DNG ICE powertrains appear to offer a cost-effective alternative (under current tax levels) versus alternative powertrains with substantial lifecycle GHG savings in the short-medium term, which could be further improved through the use of biomethane. In the long term H2FC offer greater GHG savings at similar capital costs.

Figure 6.15: Trajectory for Small Rigid Truck Efficiency and Costs for Diesel ICE, HEV and H2FC



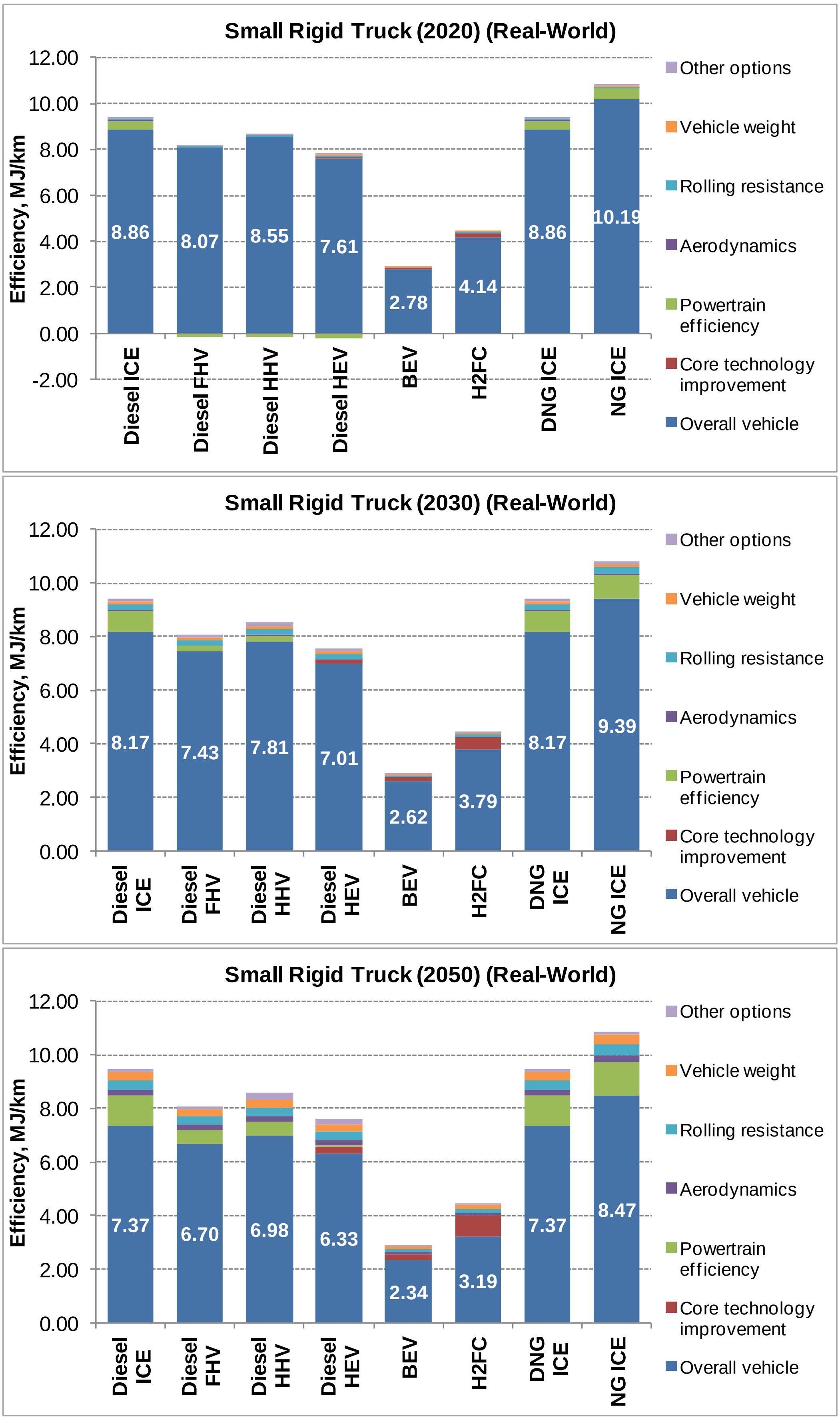
Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.16: Trajectory for Small Rigid Truck Efficiency, Lifecycle gCO$_2$/km and Cost by technology



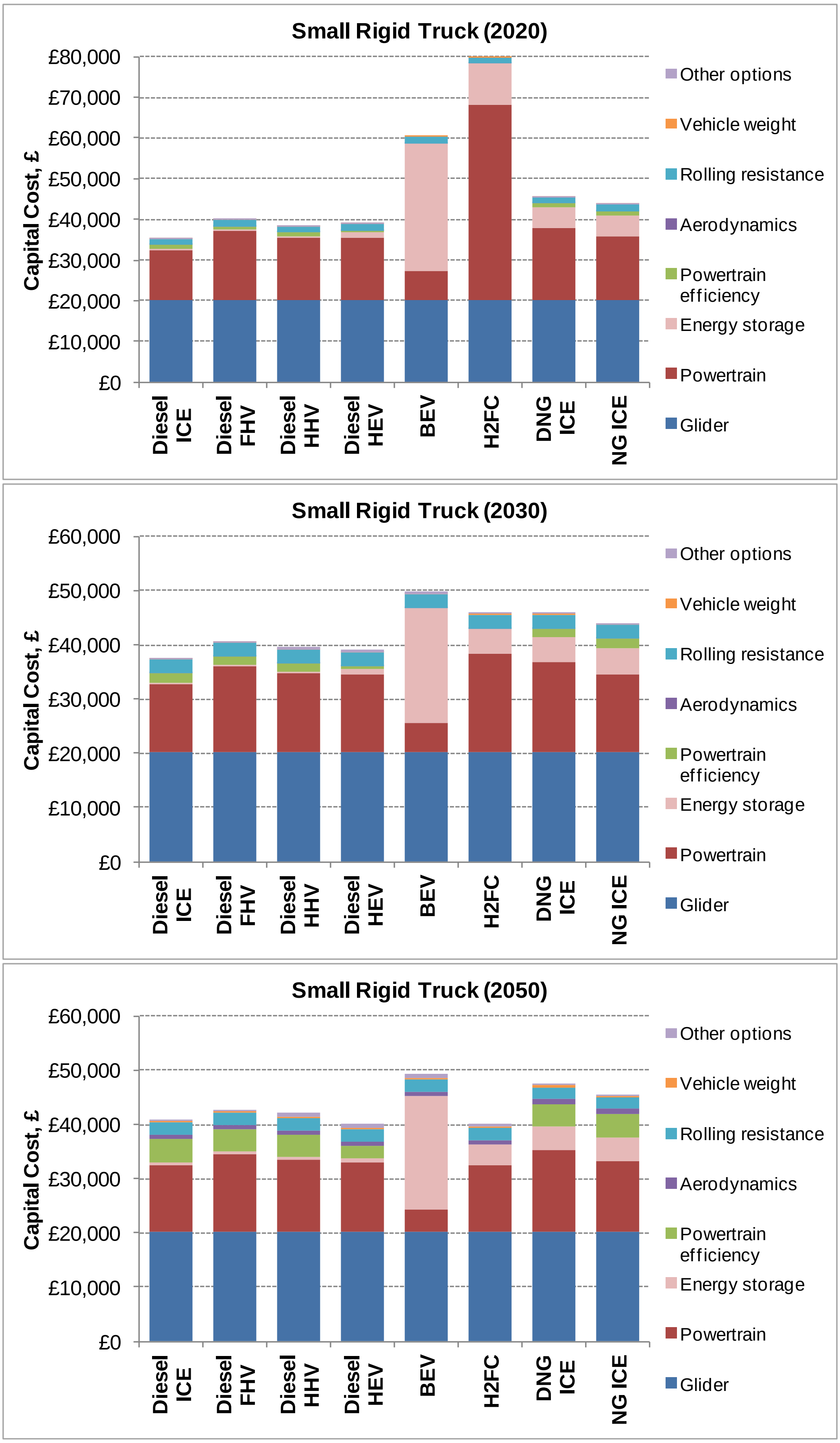
Notes: Lifecycle GHG calculated based on assumptions on the projected GHG intensity of fuels.

Figure 6.17: Analysis results for Small Rigid Truck Efficiency for 2020, 2030 and 2050



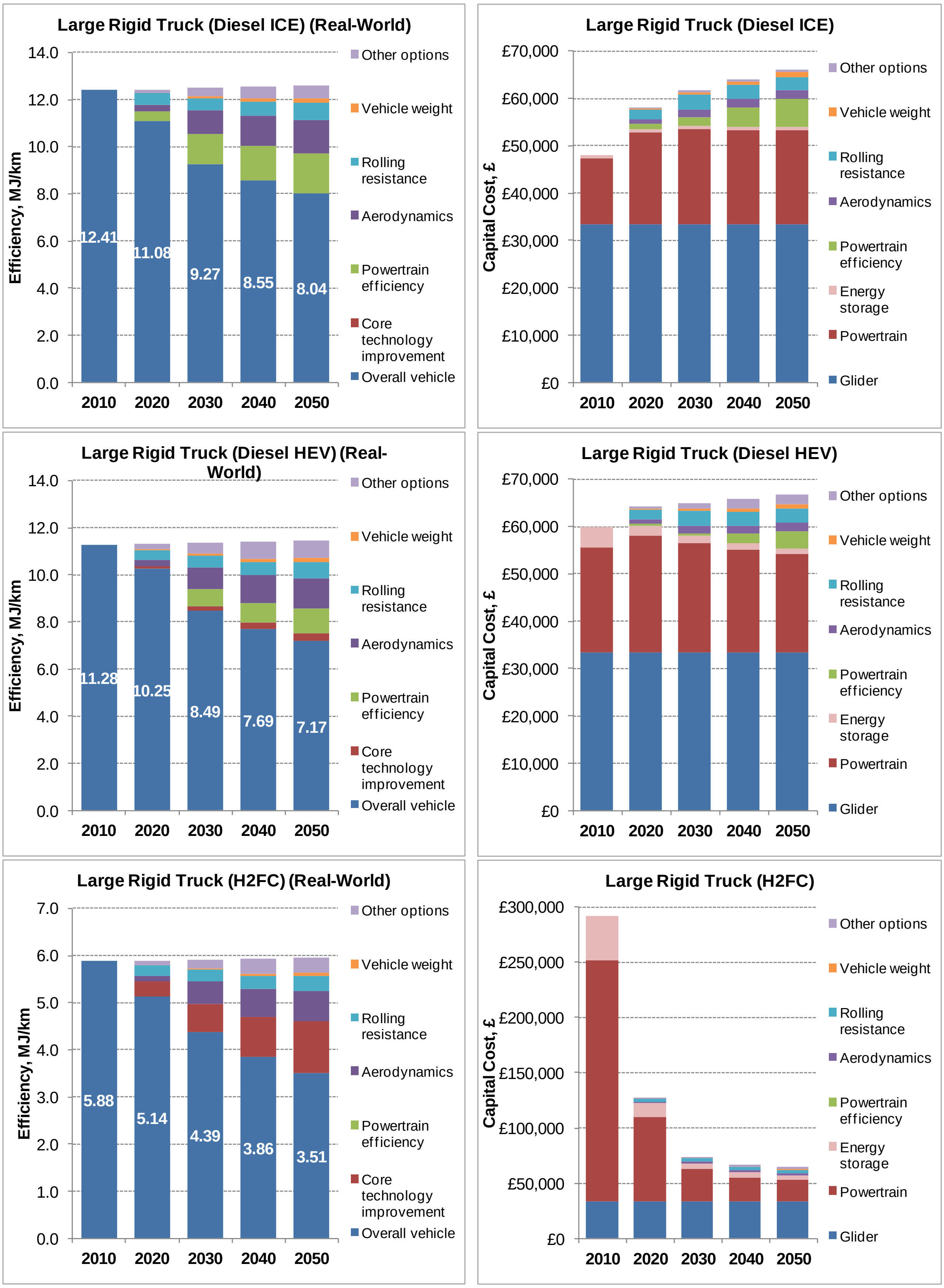
Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.18: Analysis results for Small Rigid Truck Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.19: Trajectory for Large Rigid Truck Efficiency and Costs for Diesel ICE, HEV and H2FC



Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

***Figure 6.20:** Analysis results for Large Rigid Truck Efficiency, Lifecycle gCO_2/km and Cost by technology*

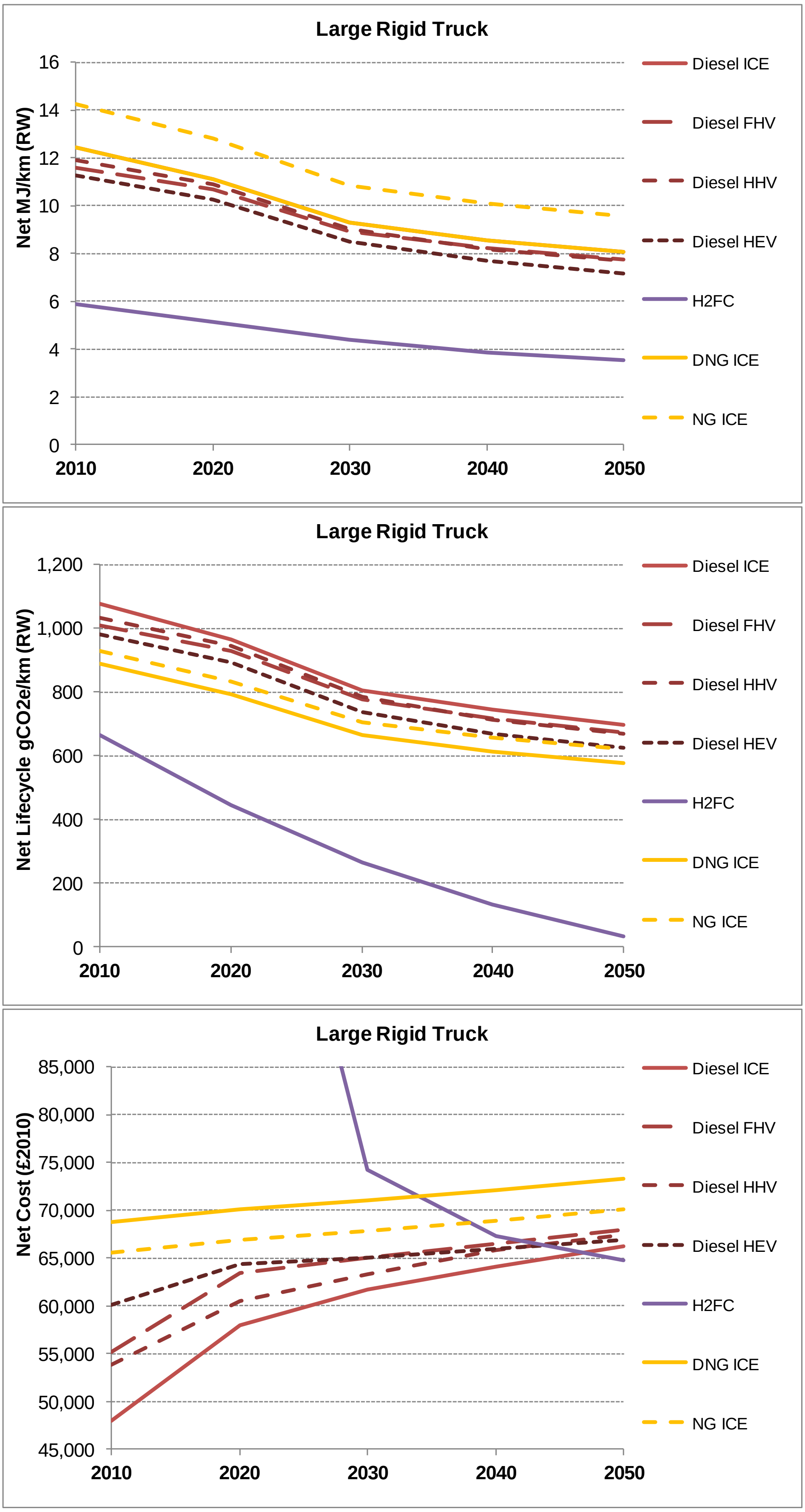
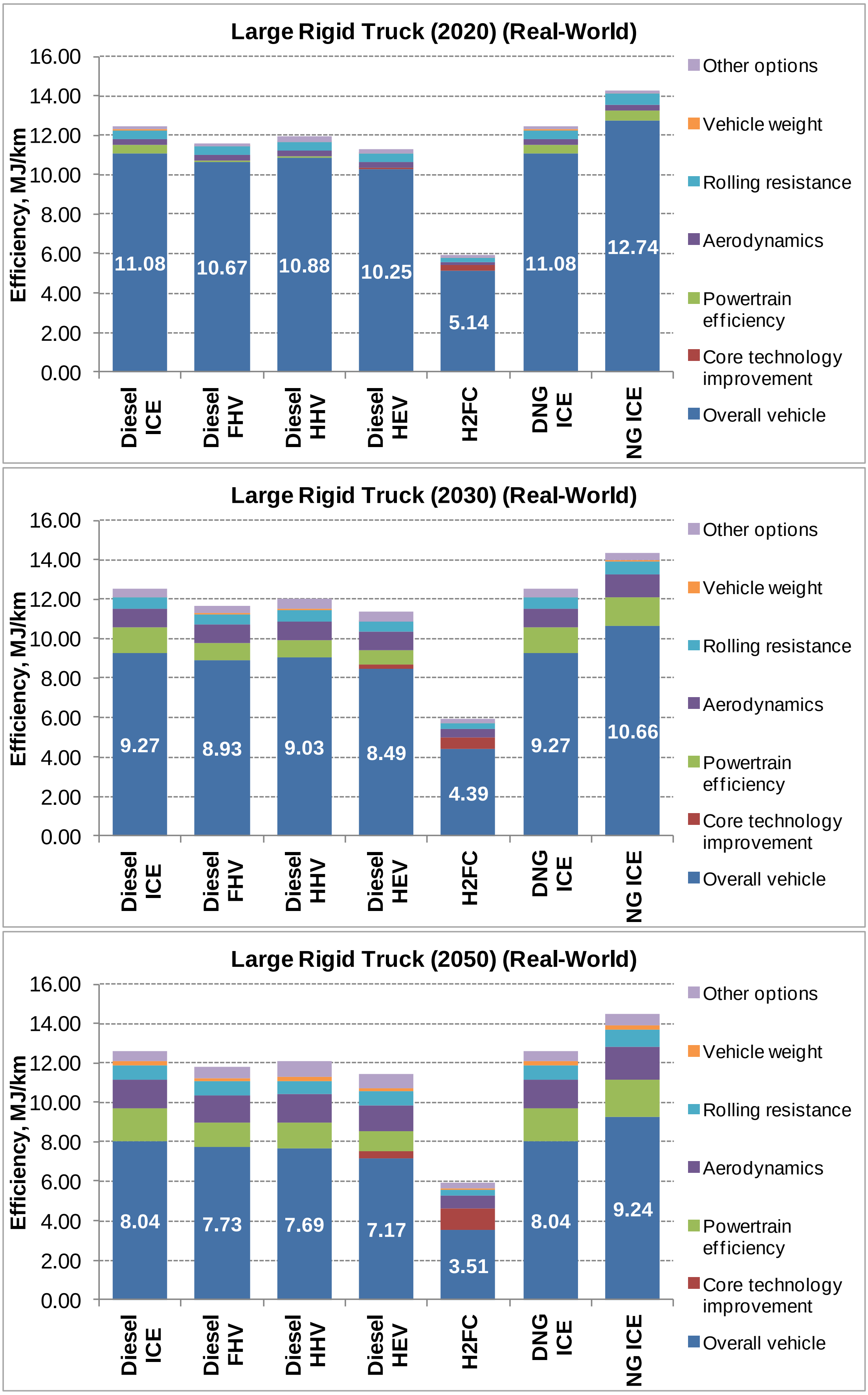
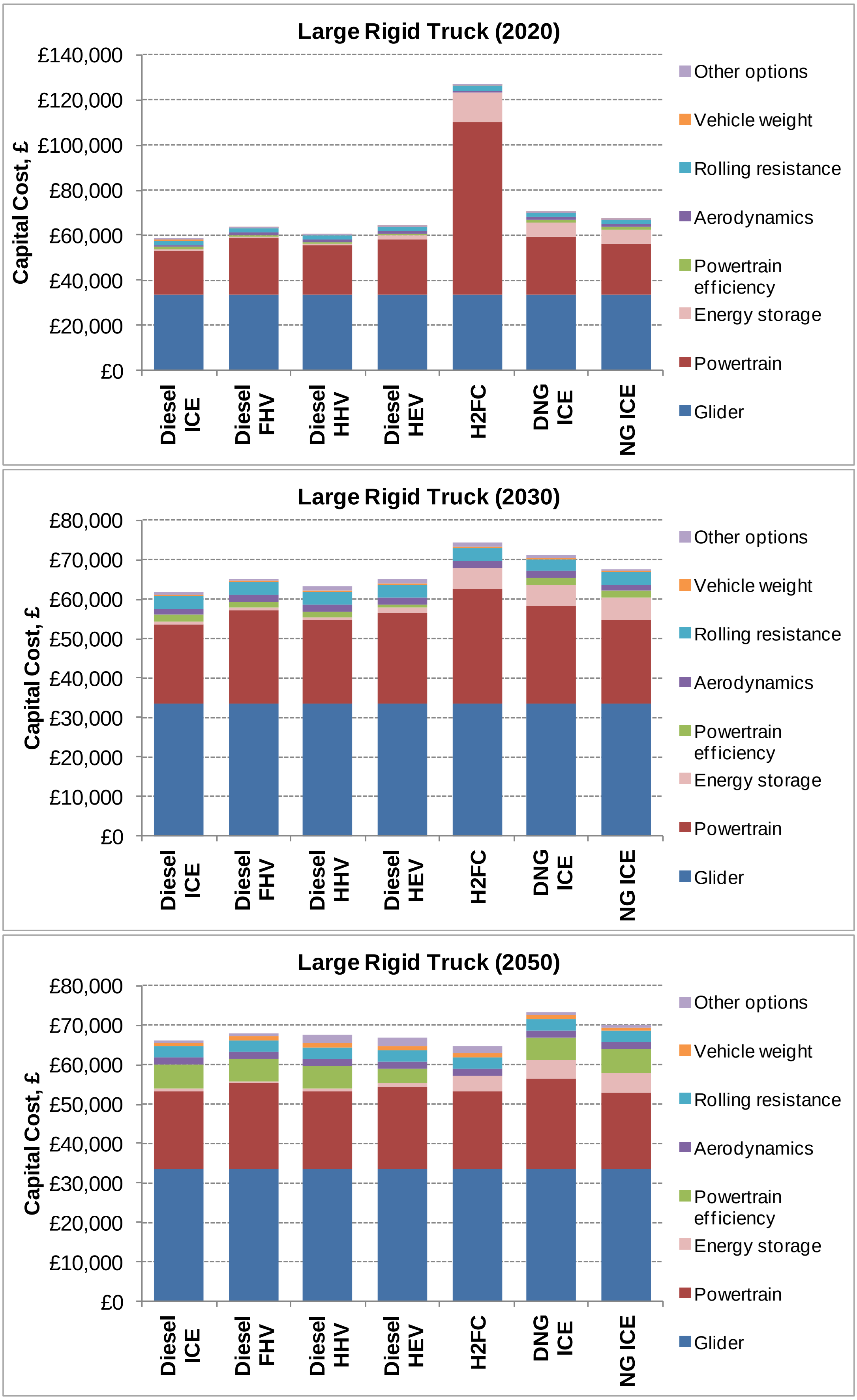


Figure 6.21: Analysis results for Large Rigid Truck Efficiencies for 2020, 2030 and 2050



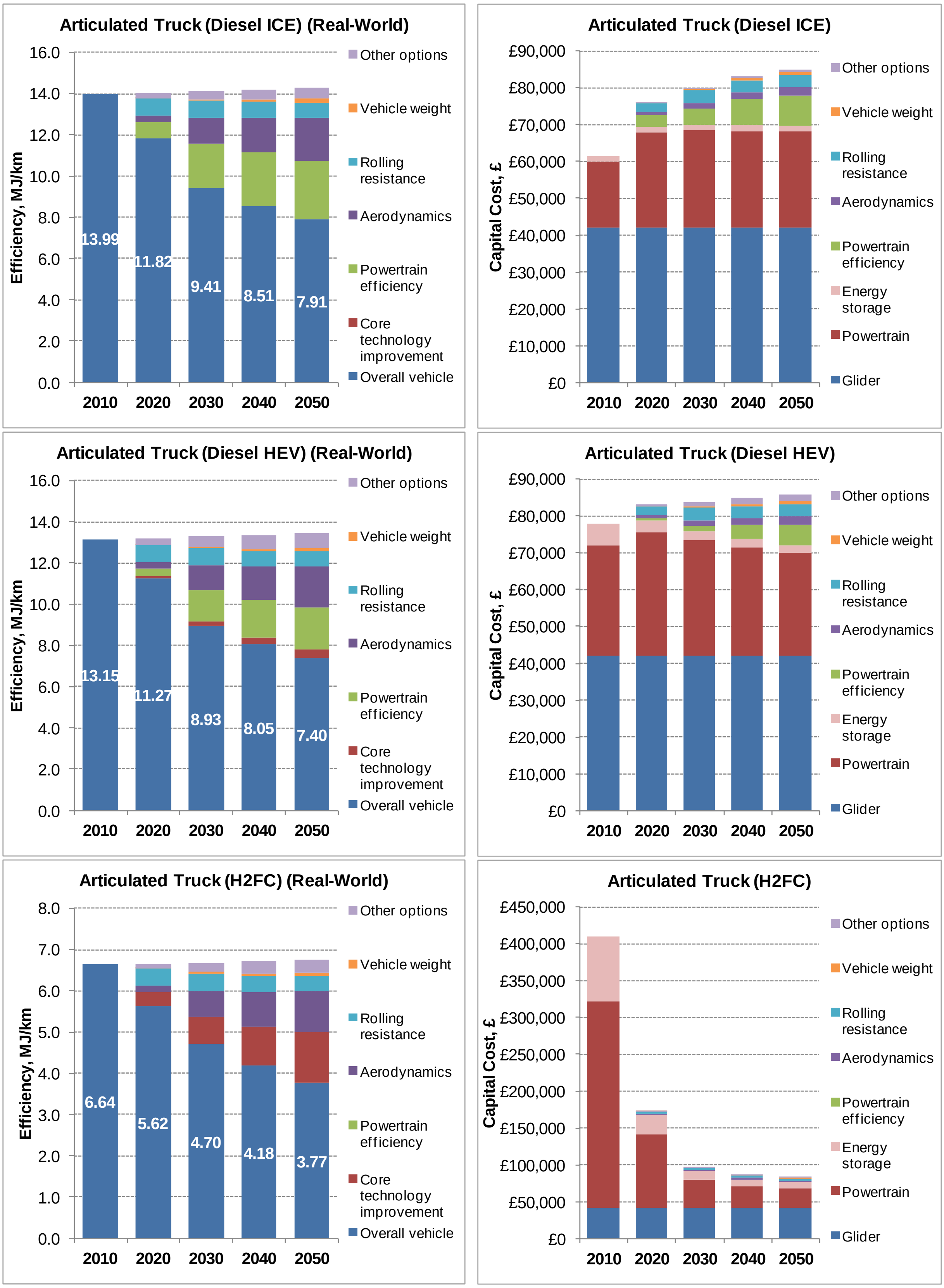
Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.22: Analysis results for Large Rigid Truck Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.23: Trajectory for Articulated Truck Efficiency and Costs for Diesel ICE, HEV and H2FC



Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.24: Analysis results for Articulated Truck Efficiency, Lifecycle gCO_2/km and Cost by technology

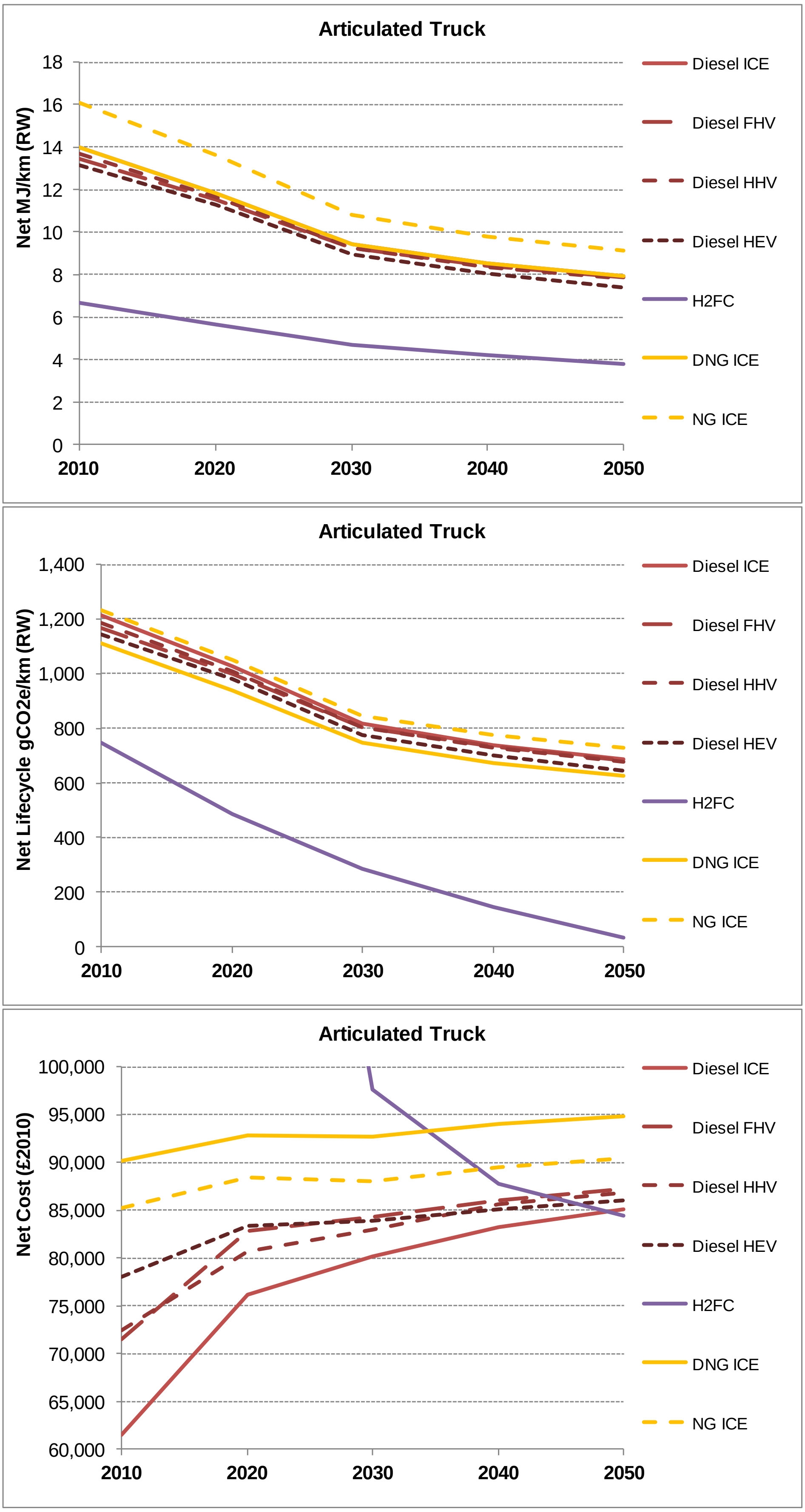
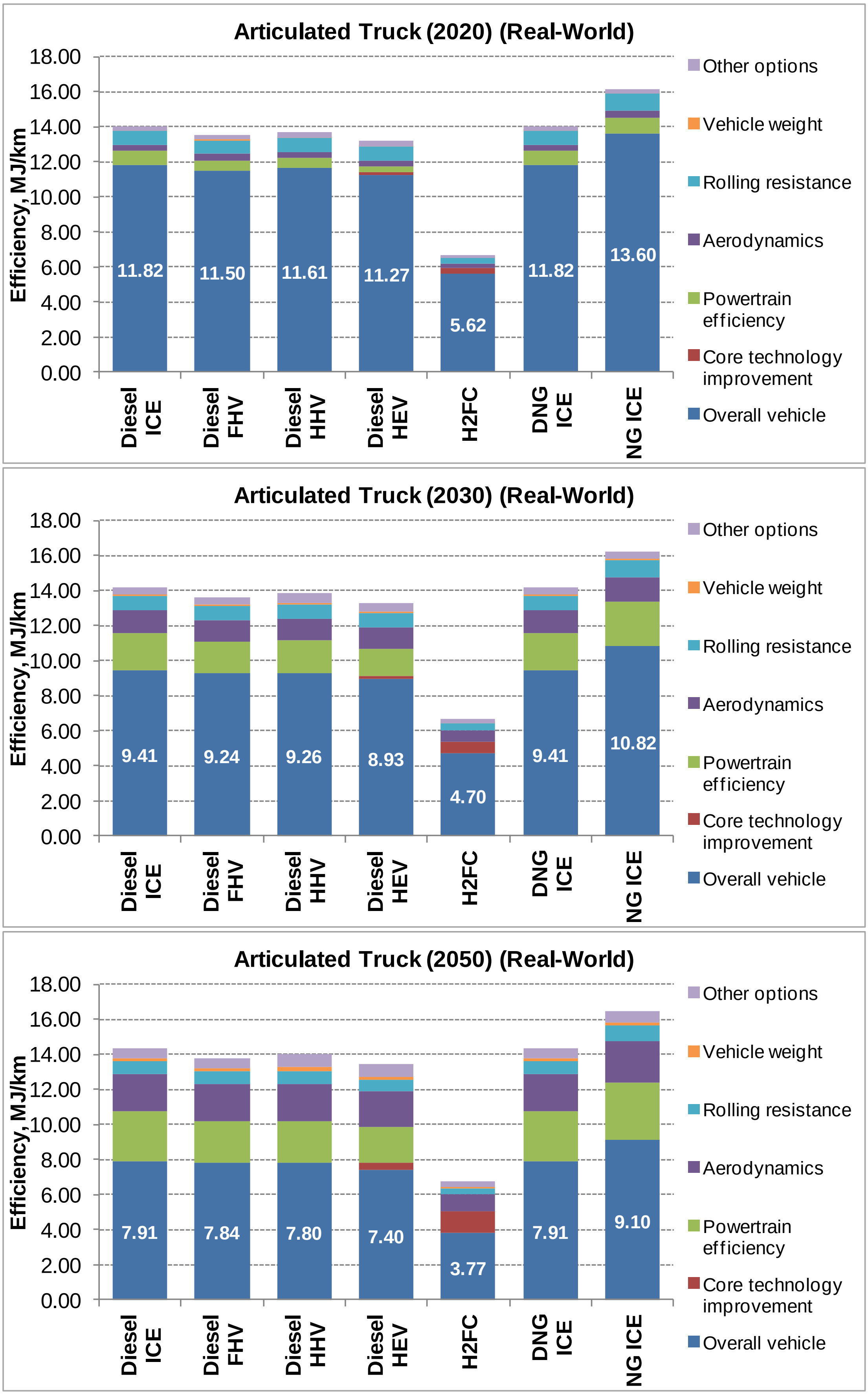
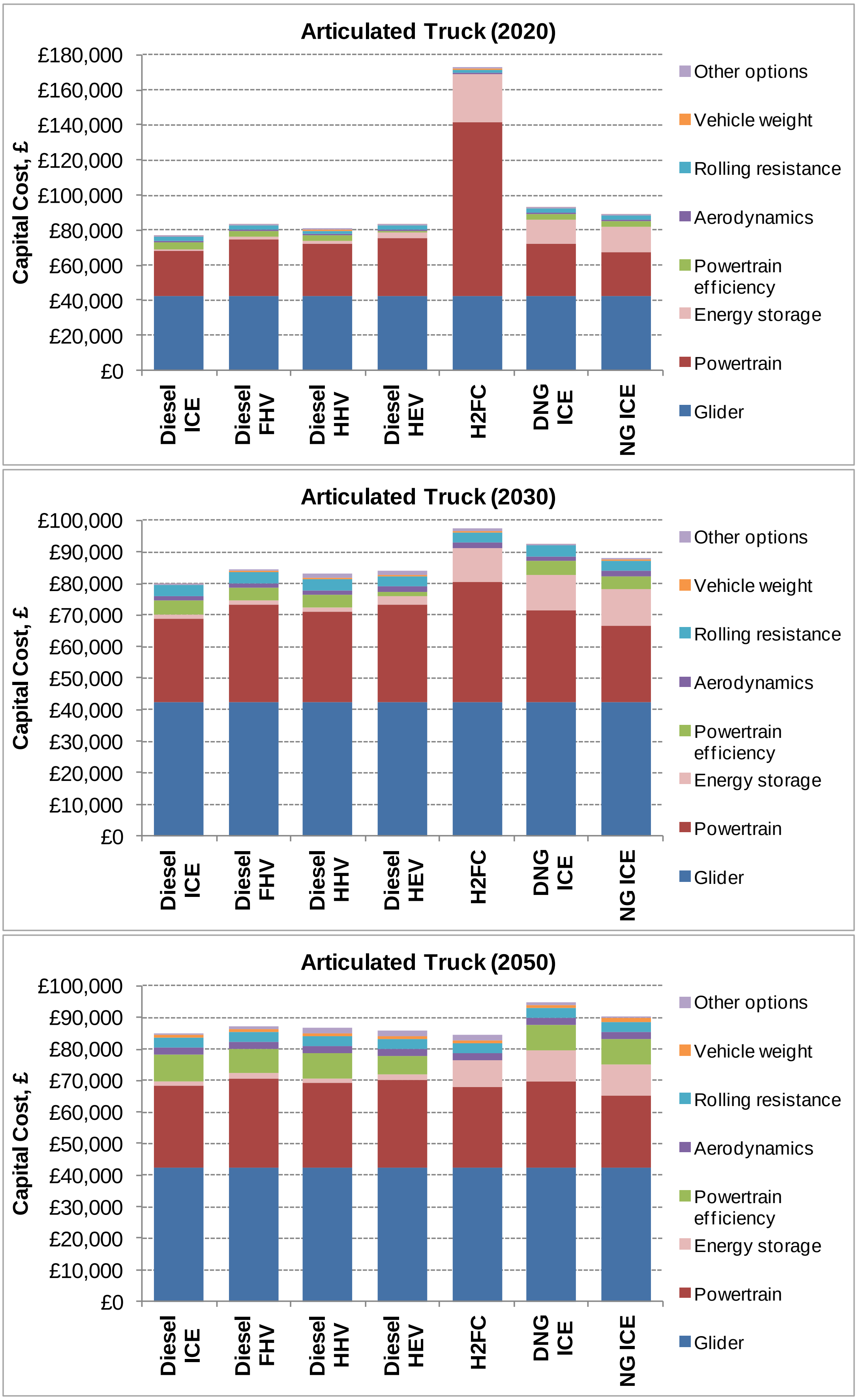


Figure 6.25: Analysis results for Articulated Truck Efficiency for 2020, 2030 and 2050



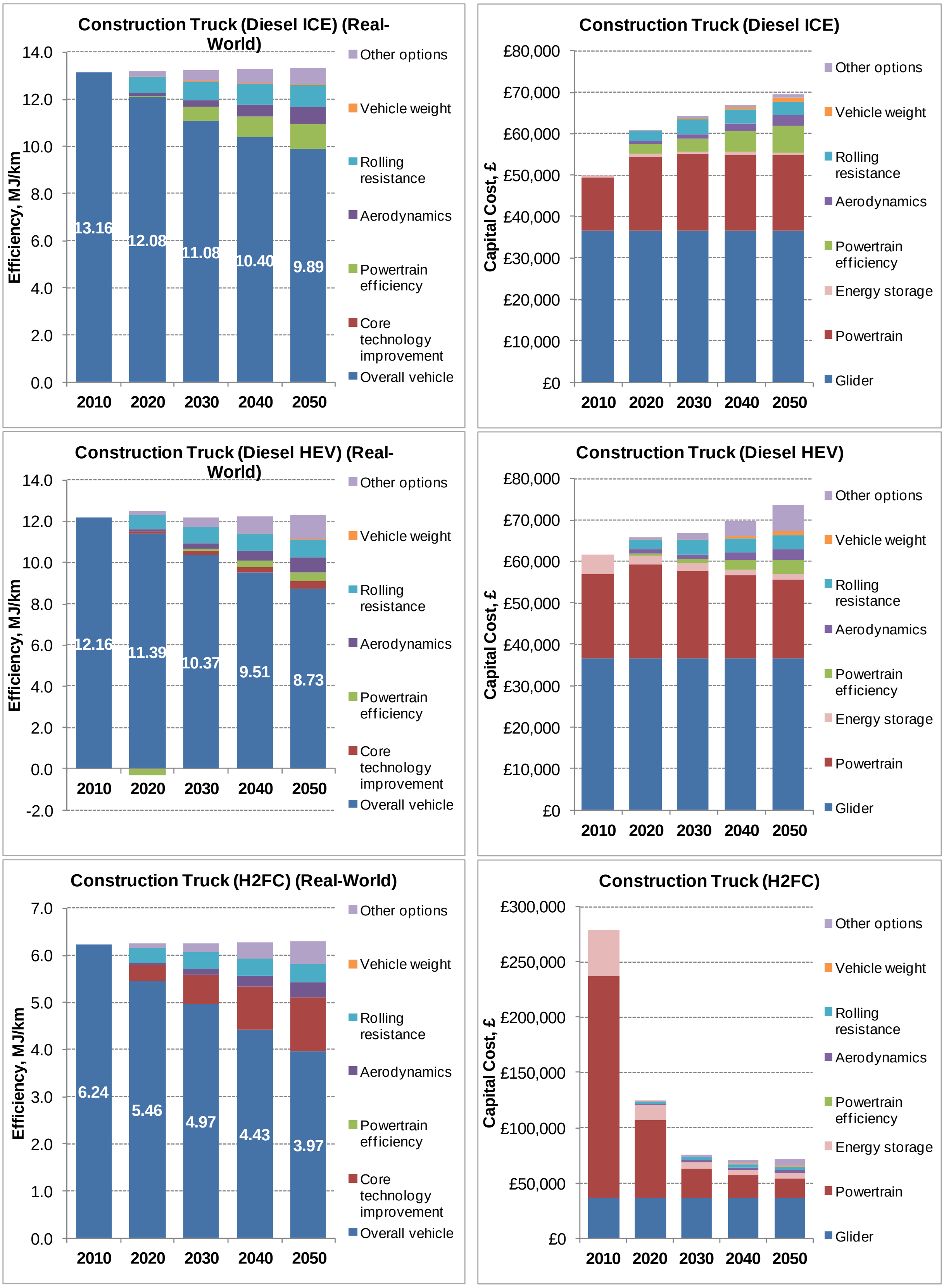
Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.26: Analysis results for Articulated Truck Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.27: Trajectory for Construction Truck Efficiency and Costs for Diesel ICE, HEV and H2FC



Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.28: Analysis results for Construction Truck Efficiency, Lifecycle gCO_2/km and Cost by technology

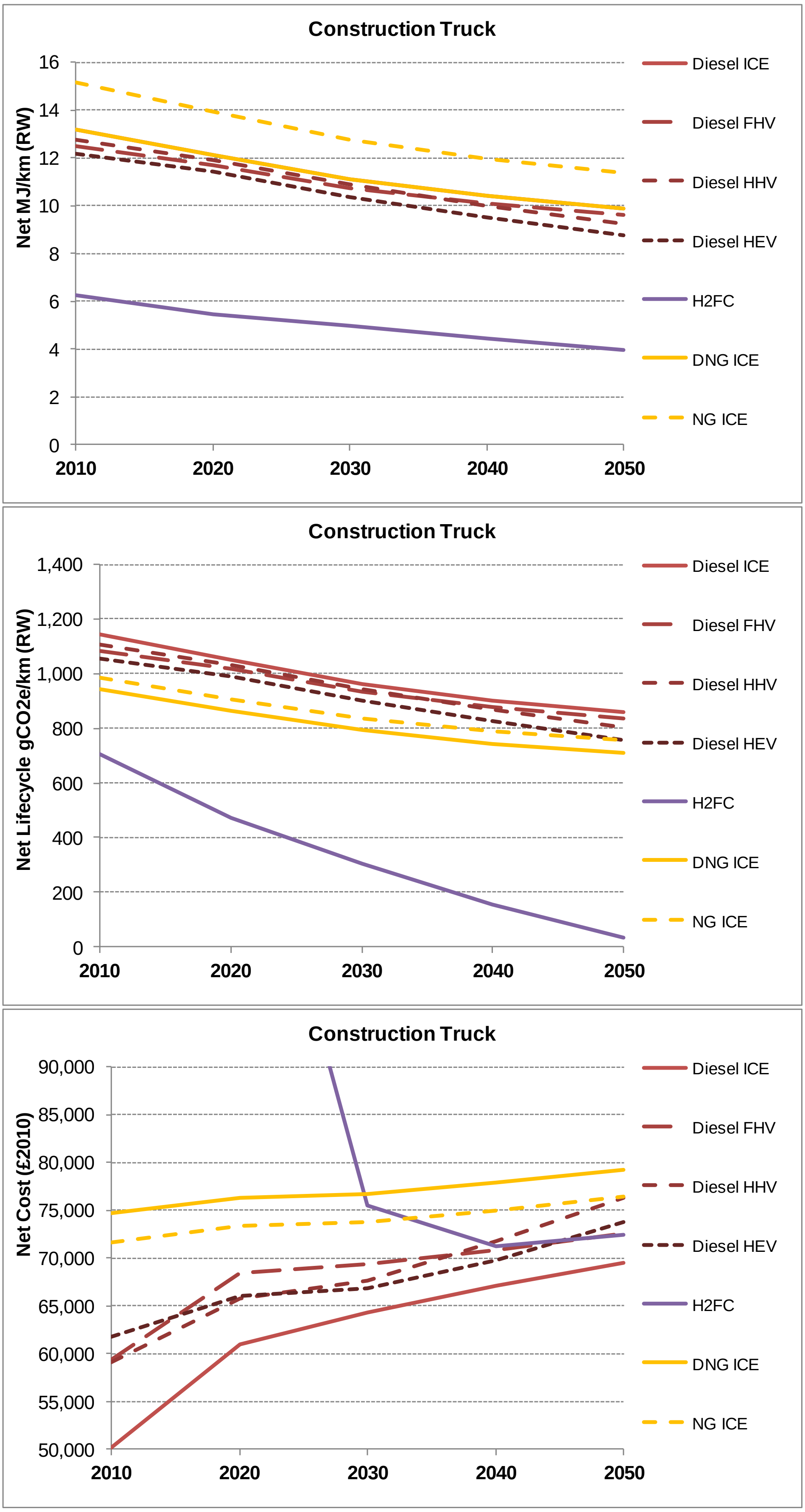
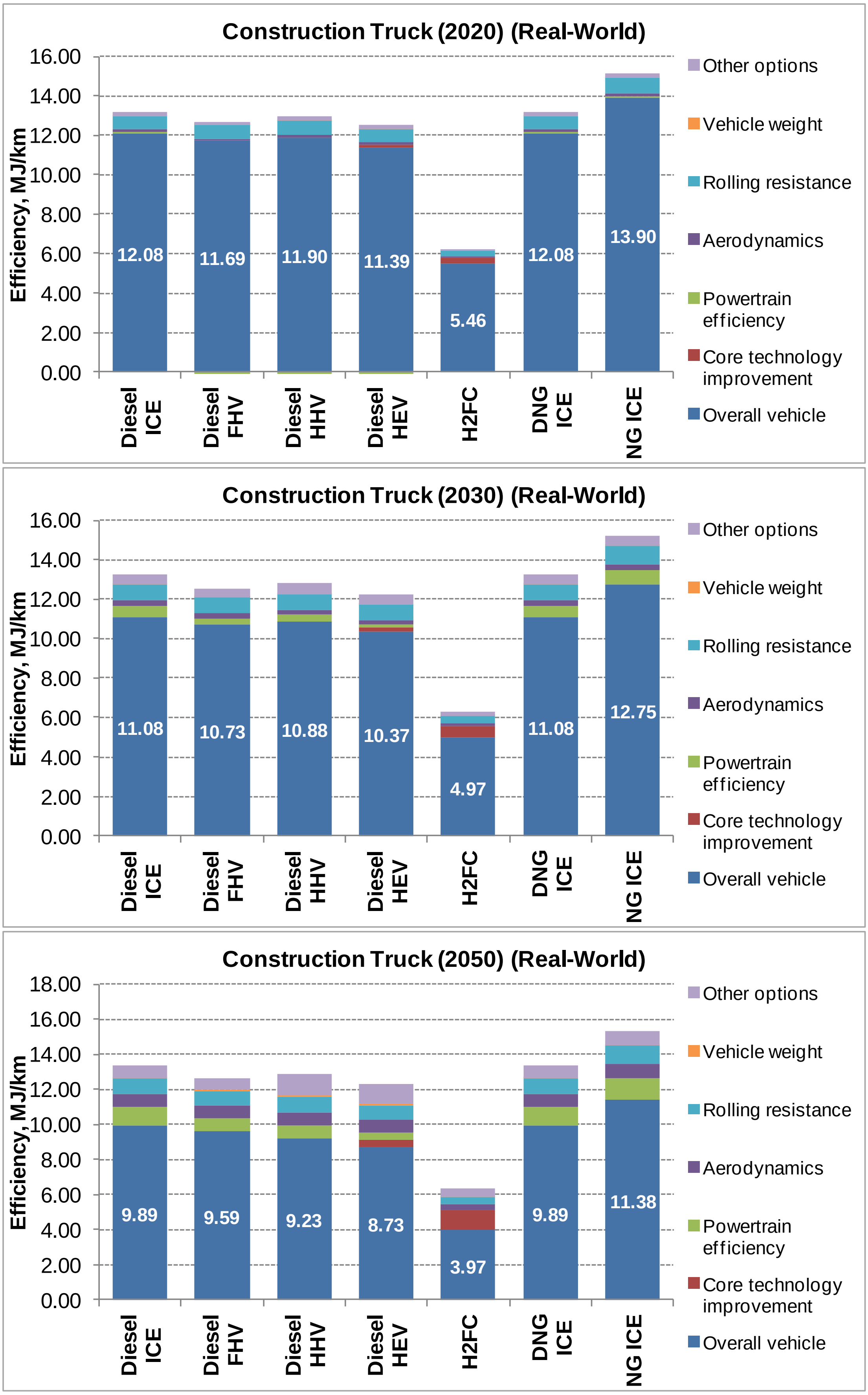
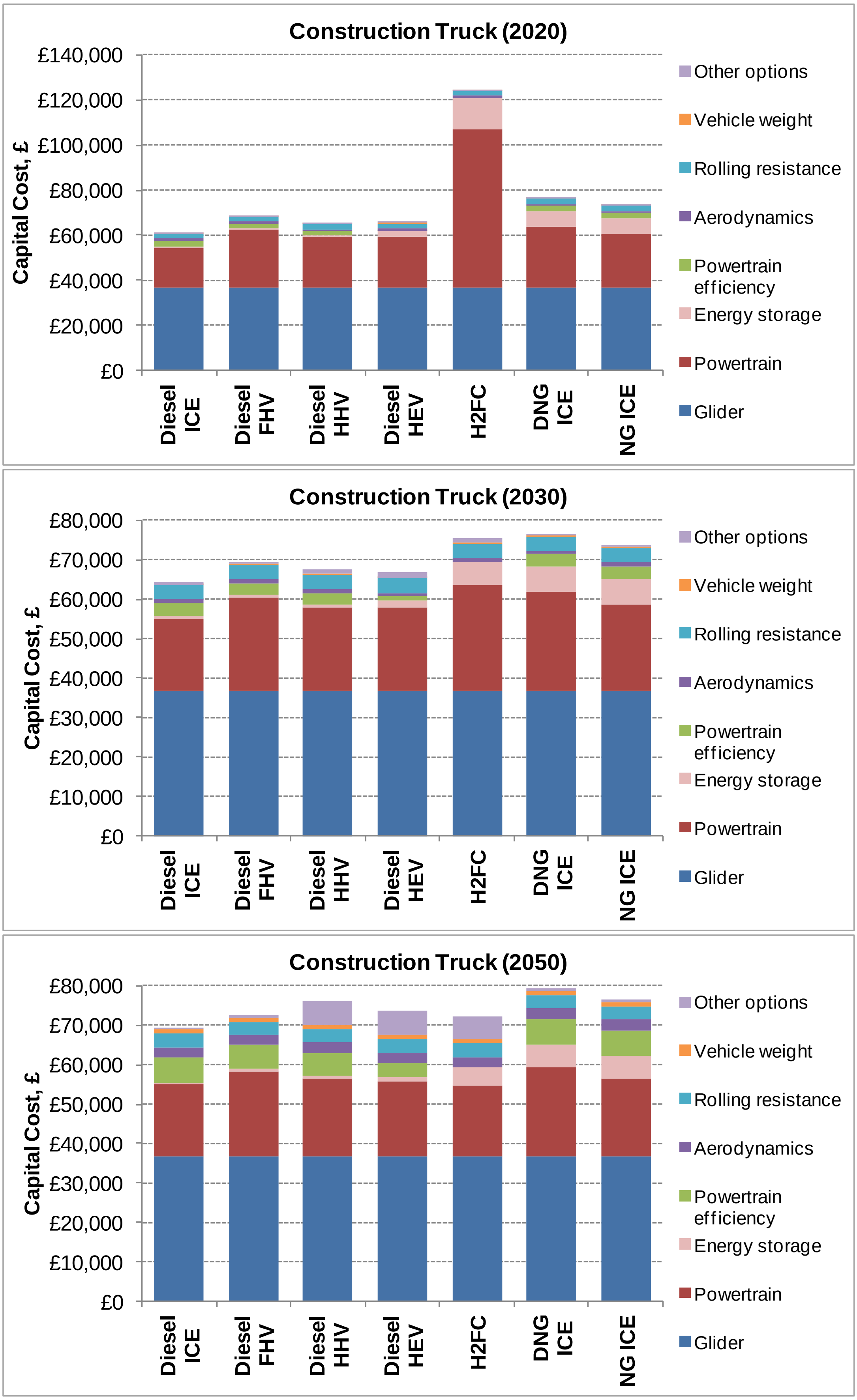


Figure 6.29: Analysis results for Construction Truck Efficiency for 2020, 2030 and 2050



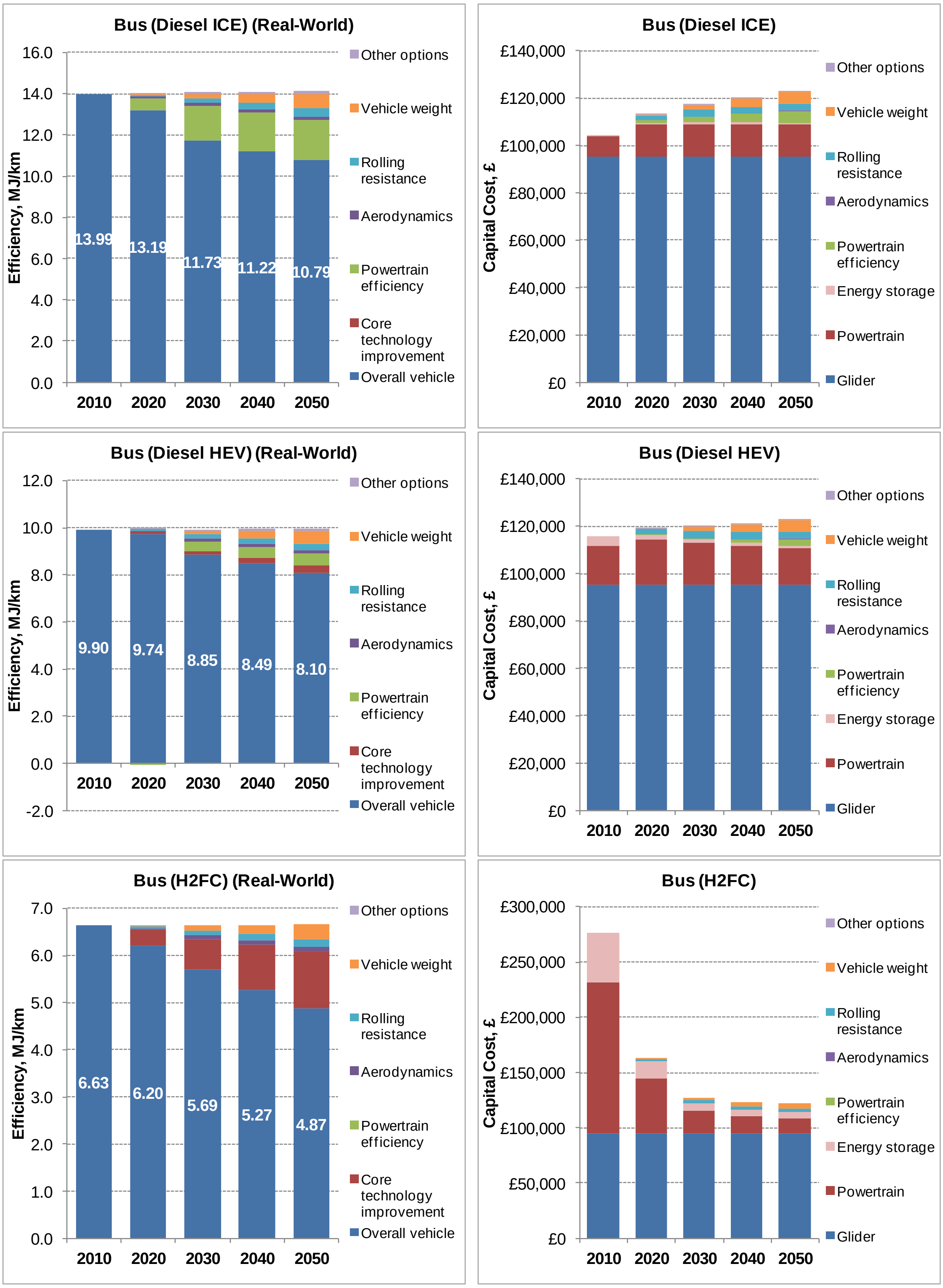
Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.30: Analysis results for Construction Truck Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.31: Trajectory for Bus Efficiency and Costs for Diesel ICE, HEV and H2FC



Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.32: Analysis results for Bus Efficiency, Lifecycle gCO_2/km and Cost by technology

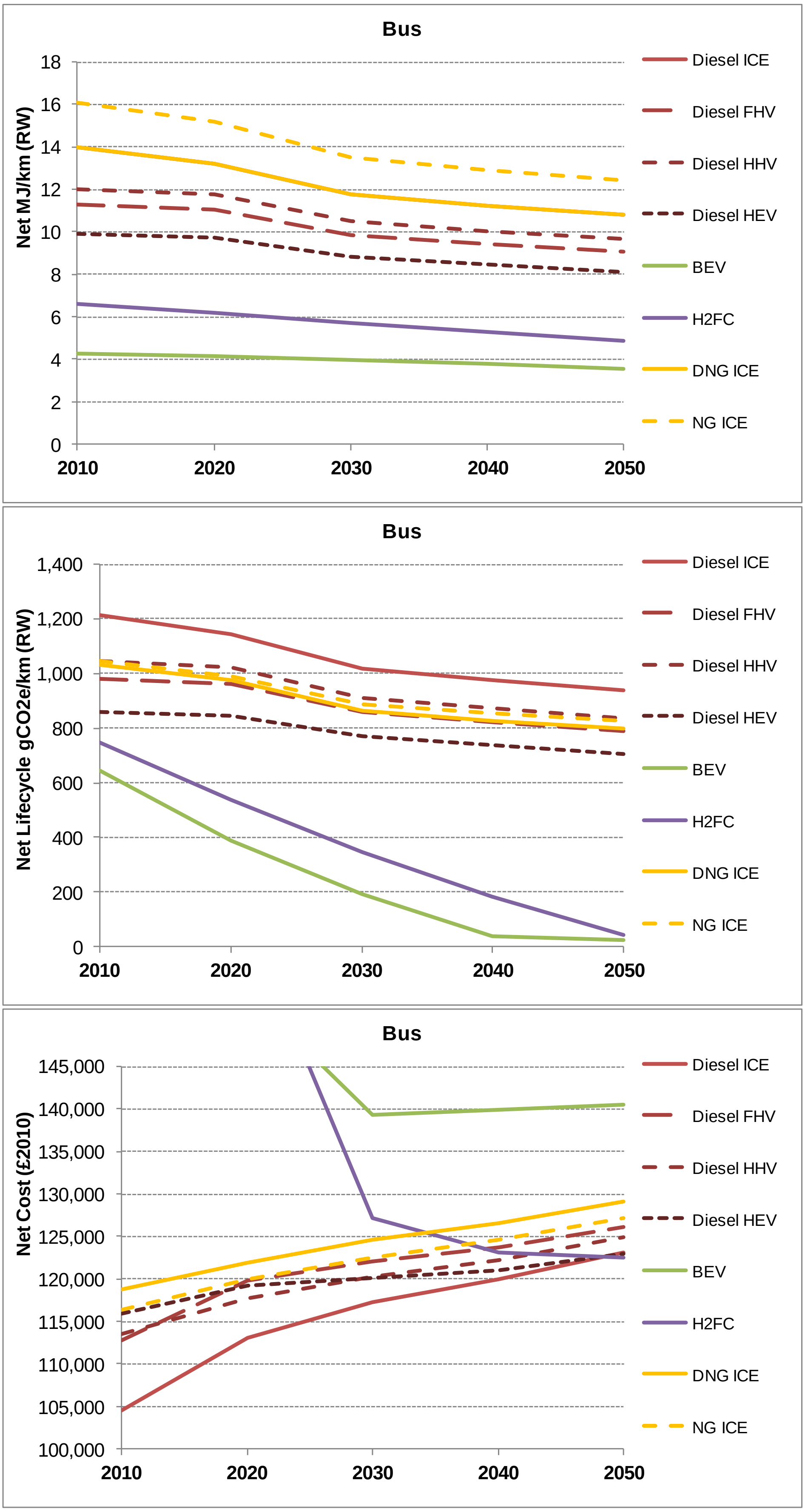
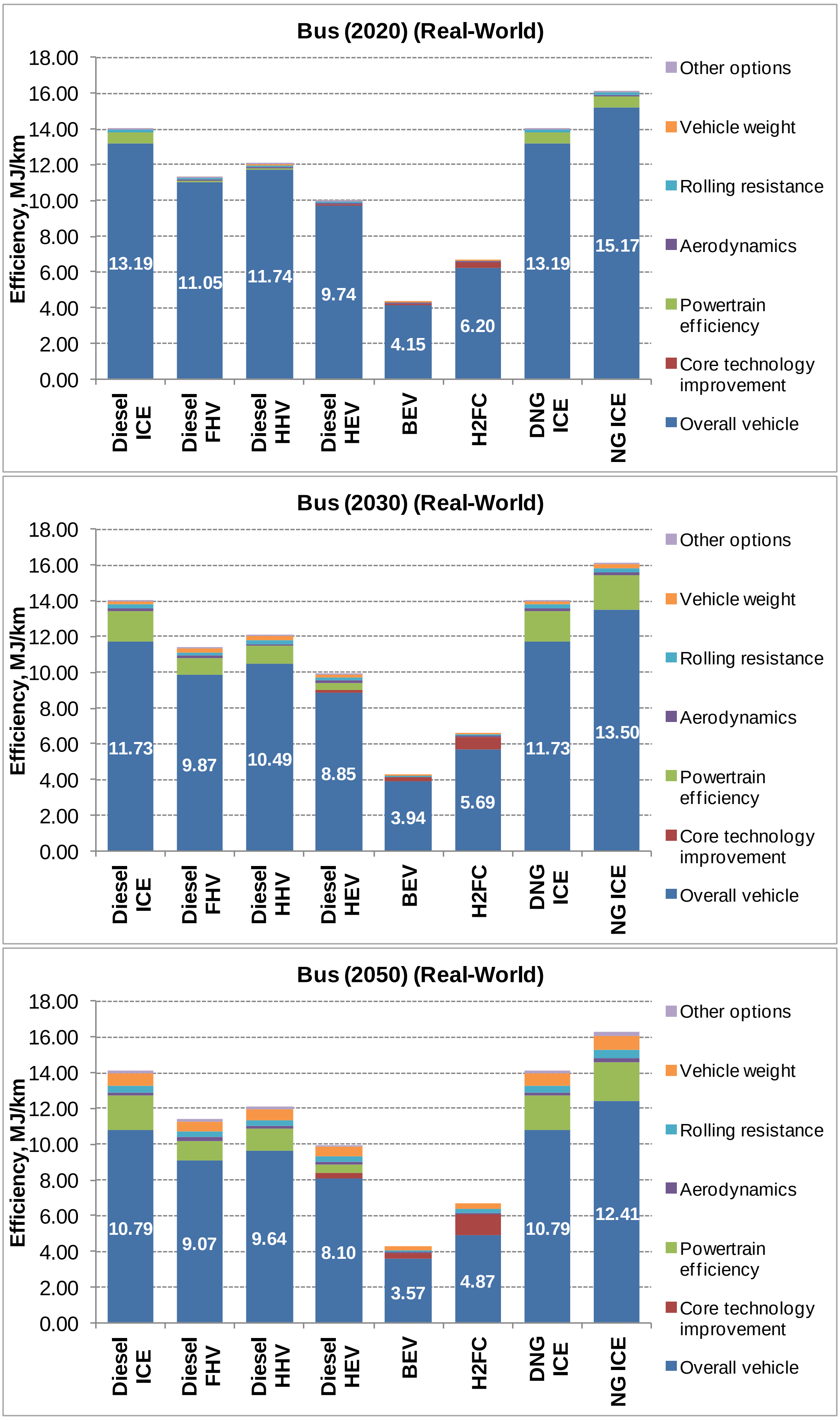
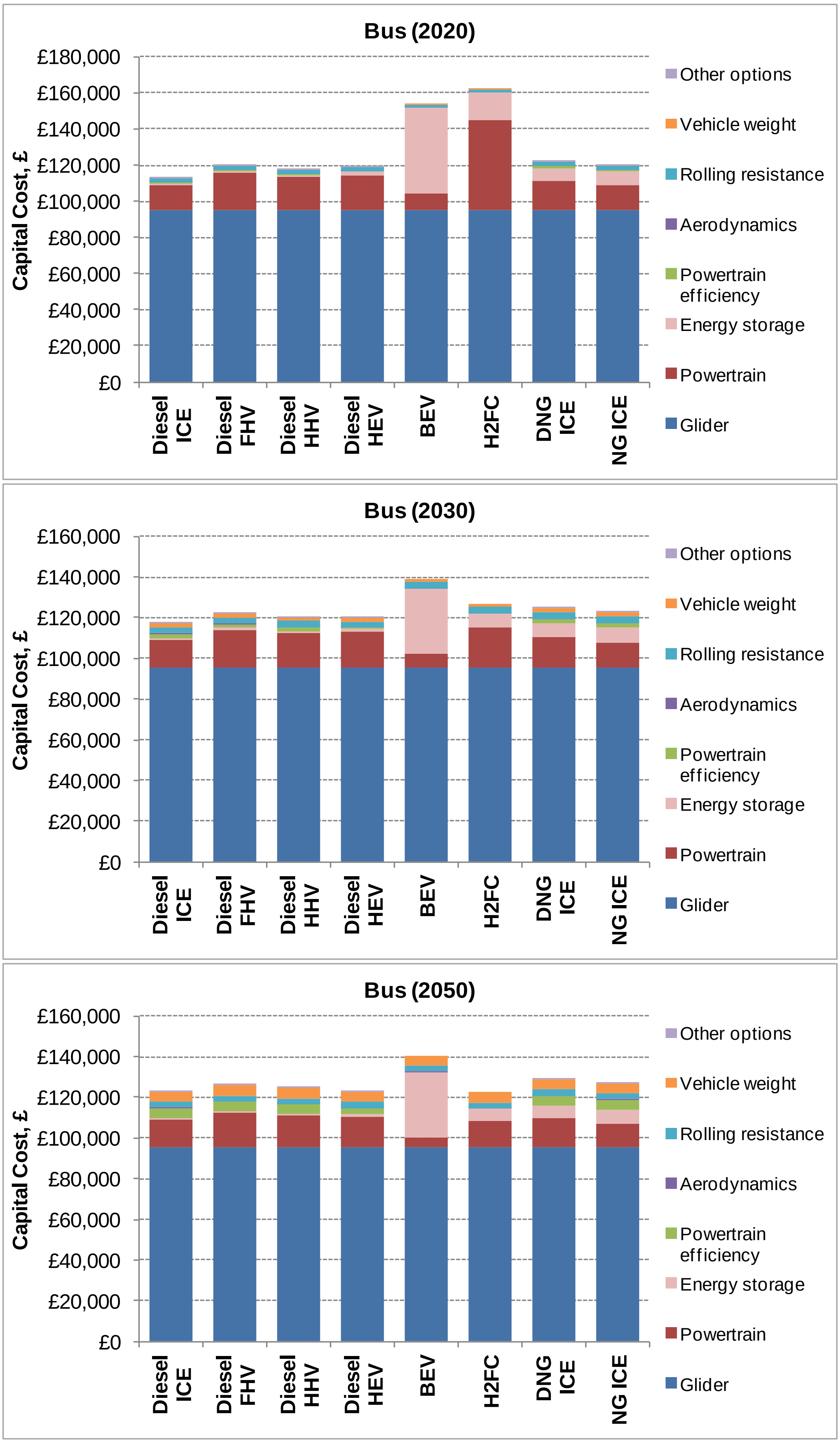


Figure 6.33: Analysis results for Bus Efficiency for 2020, 2030 and 2050



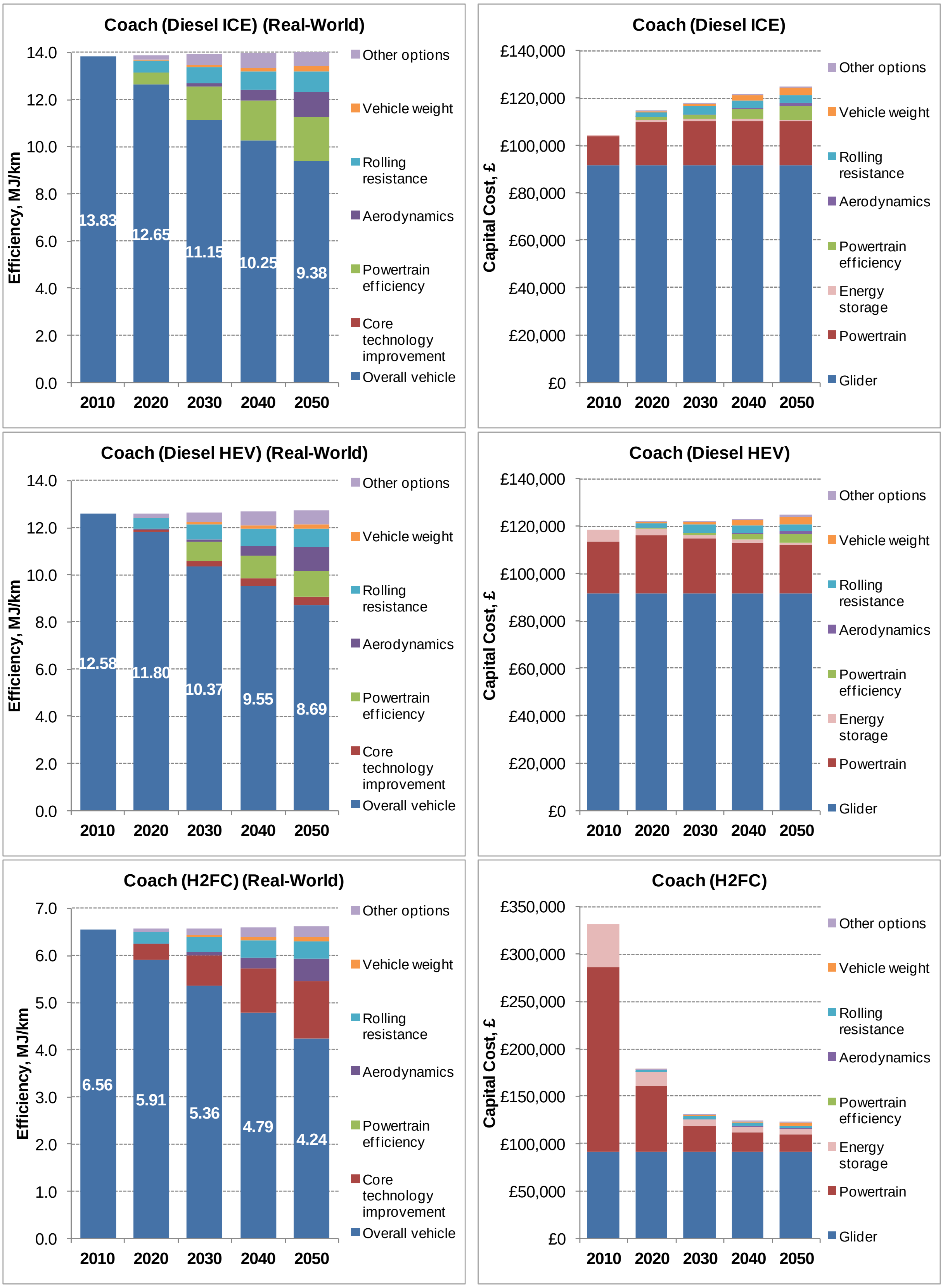
Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.34: Analysis results for Bus Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

Figure 6.35: Trajectory for Coach Efficiency and Costs for Diesel ICE, HEV and H2FC



Notes: **Efficiency:** The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.
Capital Costs: The coloured bars above the 'Glider' component represent additional/marginal costs.

Figure 6.36: Analysis results for Coach Efficiency, Lifecycle gCO_2/km and Cost by technology

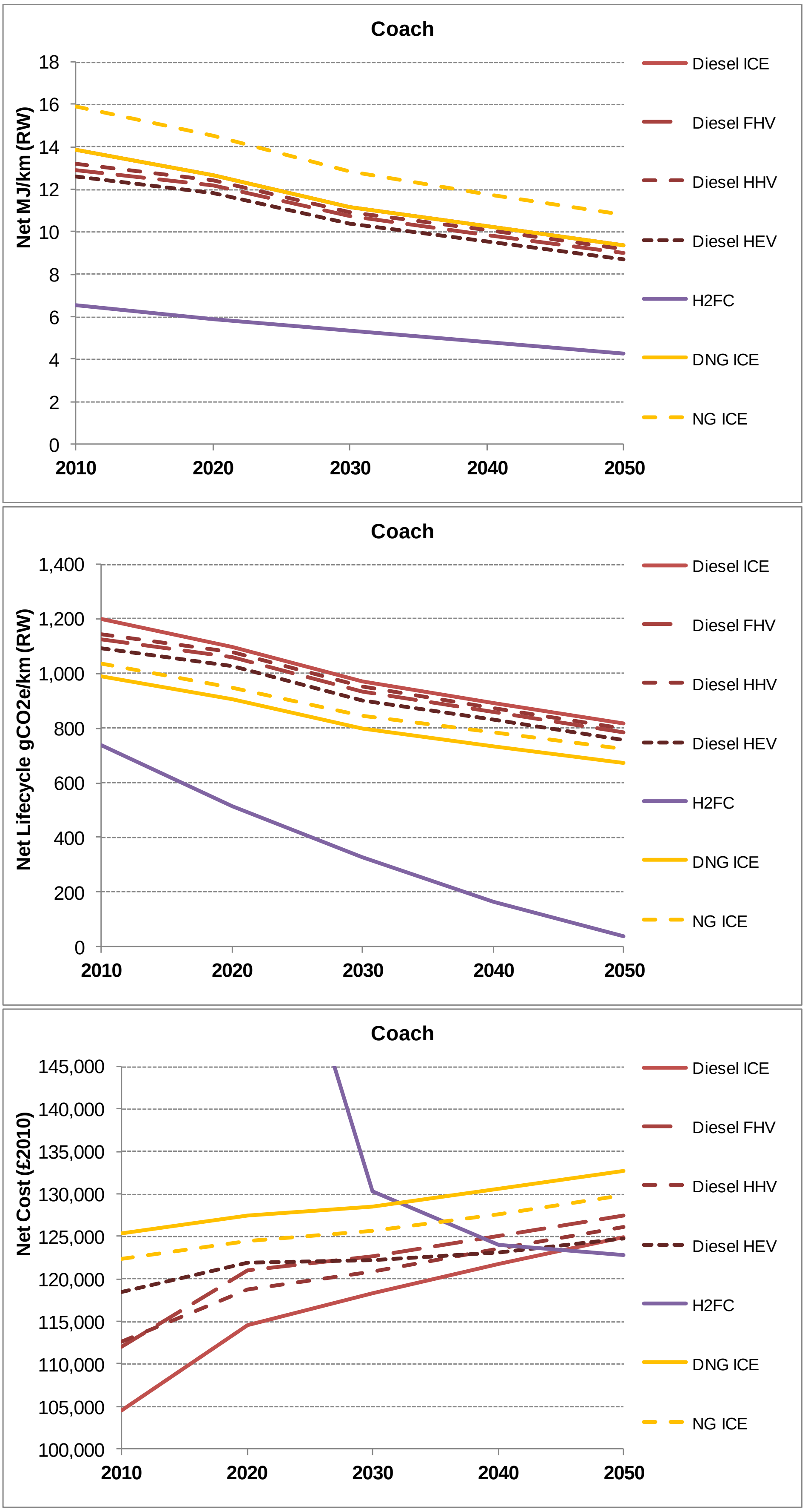
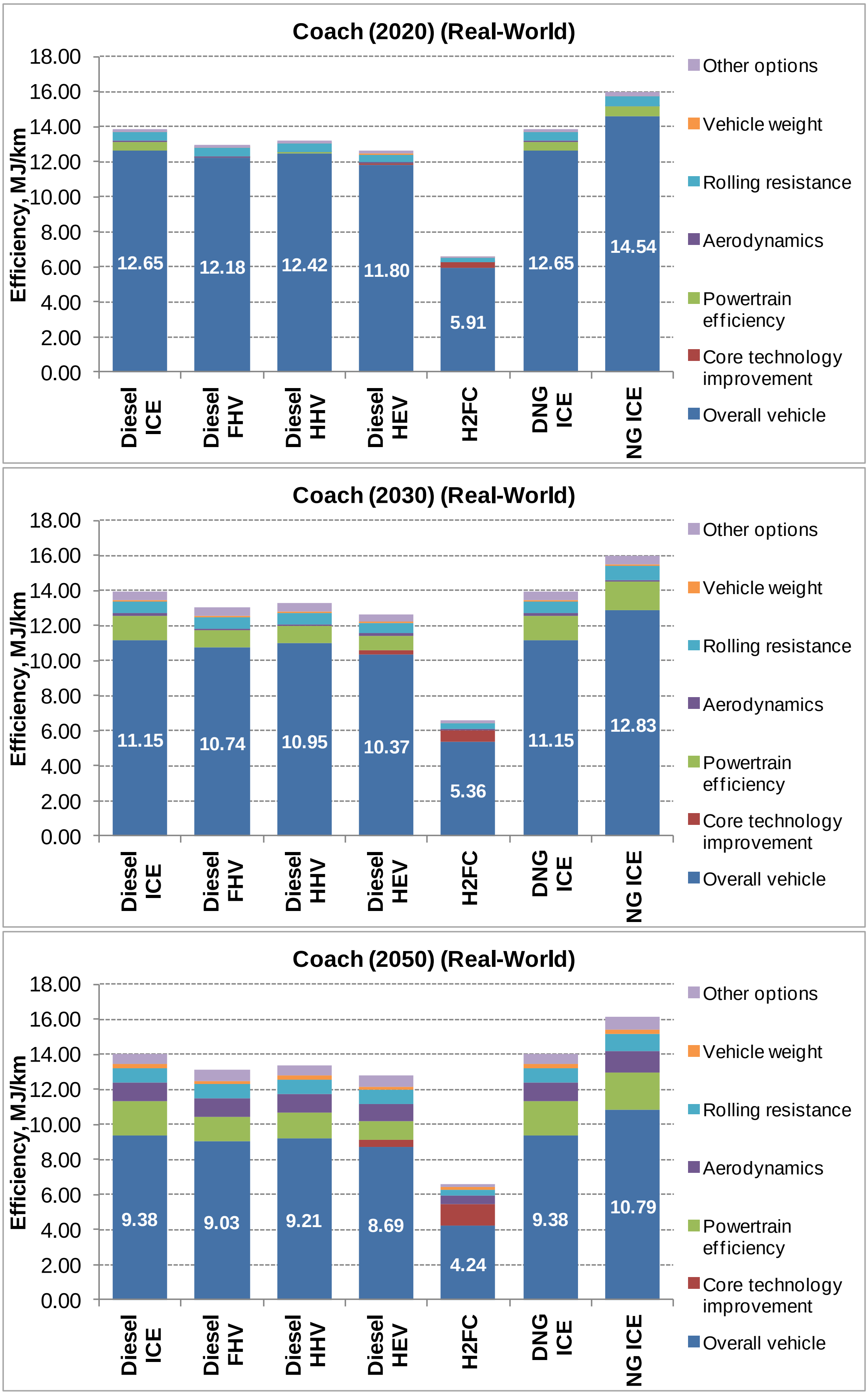
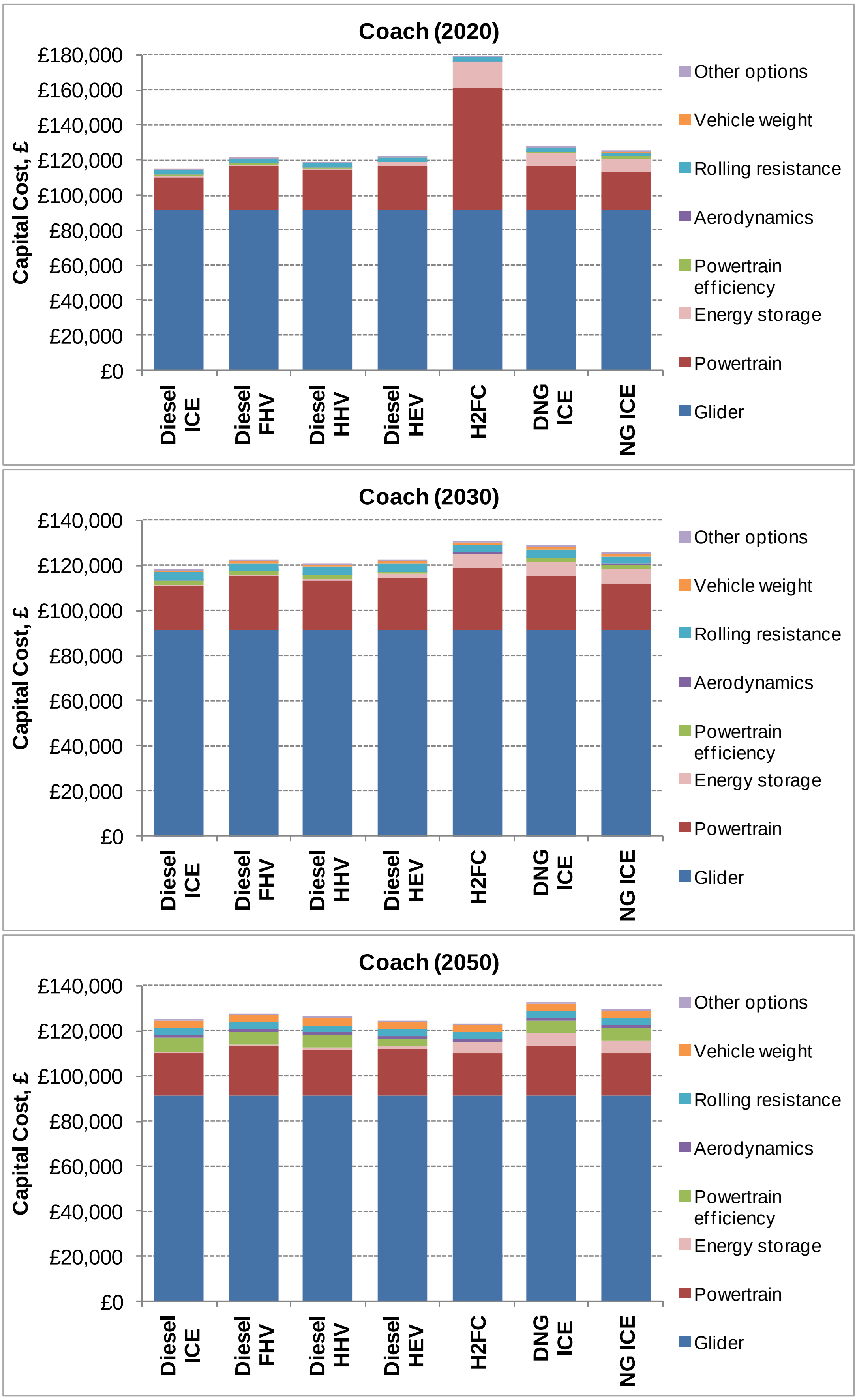


Figure 6.37: Analysis results for Coach Efficiency for 2020, 2030 and 2050



Notes: The coloured bars above the 'Overall vehicle' component represent the reductions in energy consumption vs the base vehicle (chart total) due to technical efficiency improvements.

Figure 6.38: Analysis results for Coach Capital Costs for 2020, 2030 and 2050



Notes: The coloured bars above the 'Glider' component represent additional/marginal technology costs.

7 Evaluation of CCC's Default Trajectory Assumptions

Objectives:

The purpose of Task 4 was to: *"advise on the validity of the CCC's default assumption that in the absence of any government policy to reduce GHG emissions (including existing new vehicle CO_2 regulations), there would be no or minimal change to the fuel efficiency and capital costs of the dominant vehicle technologies within each vehicle category."*

Summary of Main Findings

⇒ For passenger cars there is not sufficiently strong evidence to suggest that the assumption of a flat counterfactual is incorrect and that the CCC should therefore continue to use this assumption in its modelling work.

⇒ For van/light commercial vehicle efficiency there is some evidence to suggest that the assumption of a flat counterfactual is not valid for vans and it may be more appropriate for CCC to revise this assumption in its modelling work to reflect a gradual rate of annual improvement in van efficiency.

⇒ For heavy duty truck efficiency there is good evidence to suggest that the assumption of a flat counterfactual is incorrect for specific sizes of heavy trucks. However, the general trend of increasing vehicle sizing (presumably in a drive to increase operational efficiency on a tonne-km basis) means that the fleet as a whole has a trend to increasing MPG. CCC may therefore wish revise these elements into its modelling work to reflect annual increases in heavy truck efficiency, but factoring in changes in relative vehicle sizing affecting actual energy consumption per km.

⇒ For buses and coaches there some evidence to suggest that the assumption of a flat counterfactual for bus and coach efficiency is incorrect and that the CCC should therefore consider revising this assumption in its modelling work.

⇒ For the capital costs of vans, trucks, busses and coaches, there is not sufficiently strong evidence to suggest that the assumption of a flat counterfactual is incorrect and that the CCC should therefore continue to use this assumption in its modelling work for the capital costs of other vehicles.

⇒ For motorcycles and mopeds, no evidence has been identified to suggest a change in the current assumption.

7.1 Assumptions and scope

The objectives above are focussed on fuel efficiency and the capital costs of vehicles – they do not extend to the GHG emissions from all of road transport. Therefore the following factors are excluded from this analysis:

- The use of (and capability of vehicles to use) biofuels;
- The use of alternative fuels;
- Changes in vehicle km driven and driving style;
- Modal shifts.

The question being addressed is what would happen going forward if GHG policy was removed **today**, regardless of past policy – would new vehicle CO_2 get worse, stay the same, or get better, and by how much.

7.2 Passenger Cars

7.2.1 Context for 'counterfactual' assessment

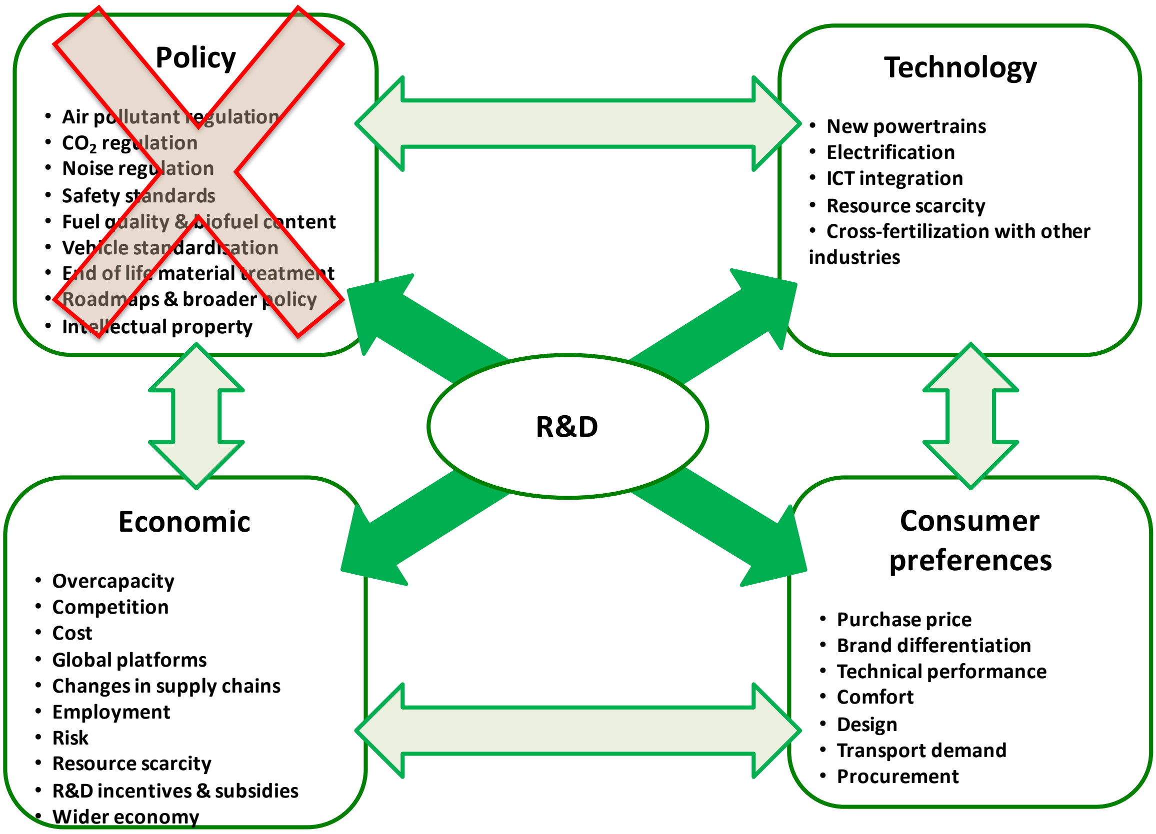
To assess what the 'no policy' counterfactual would be for cars, it is important to understand whether policies are having, or have in the past had, an effect on new car fuel efficiency and capital costs of key vehicle technologies. It is also imperative to know whether other factors - such as market conditions (fuel and resource prices), consumer preference and technology - impact on new car fuel efficiency and capital costs of key vehicle technologies.

A systematic review of recent literature was undertaken to verify the 'counterfactual' case by assessing whether there is any evidence on the:

- Impact of climate change policies on the environmental and energy performance of cars;
- Impact of climate change policies on vehicle costs and end-user prices; and
- Impact of other exogenous factors – oil prices, income levels, technology and consumer preference – on car fuel efficiency.

The key point for testing the above three propositions is that even though a number of technologies, economic signals and consumer behaviours stem from regulation, these exogenous factors can still impact on business and technical strategies of the automotive sector (Figure 7.1). Hence, to separate out the impact of policies, it is also important to look at exogenous factors and the extent to which have they been important in the past, as well as what could happen to them going forward.

Figure 7.1: Number of factors impact on fuel efficiency improvements



This study only considers policies designed with climate change in mind, so it excludes policies such as fuel duty, which have an effect on emissions but are not primarily designed to tackle climate change. The policies that currently affect, or have in the past affected, new car CO_2 emissions in UK are given in Box 7.1.

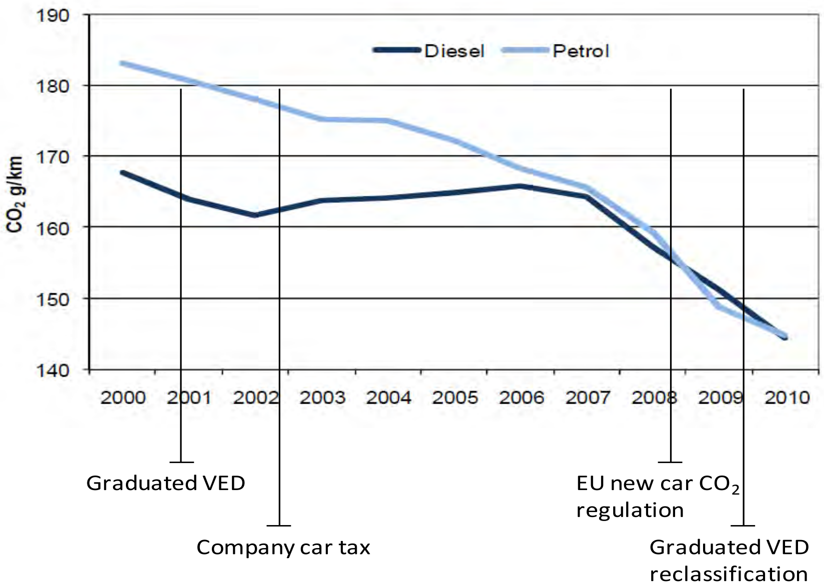
Box 7.1: UK new car CO_2 legislation

- The EU new car CO_2 regulation – agreed late 2008 and sets a target, based on the average mass of the vehicles sold, for manufacturers to reduce their average new car CO_2 emissions for all sales by 2015, such that overall new car CO_2 emissions will fall to 130 g/km. It also suggested an EU wide target of 95 g/km by 2020.
- Graduated VED – introduced in March 2001, with a reclassification in April 2009, with the highest set at £455 per year and the lowest at £0. From 2010, a new first year rate was introduced, ranging from £0 for vehicles in the lower bands, up to £950 for vehicles in the highest band.
- Voluntary Agreements – introduced from 1998/99 and required average new car CO_2 from European, Japanese and Korean manufacturers to be reduced to 140 g/km by 2008 (Europe) and 2009 (Japan and Korea).
- Company car tax - since April 2002 company car tax has been based on a car's list price and official CO_2 emissions figure. Various changes were also made in later budgets, e.g. from 2011 tax rates for company cars that produce more than 129g/km will increase by 1% for every 5g per km increase in CO_2 emissions, to a maximum of 35%. These rules also exempt ultra-low emissions cars and allow businesses 100% first year write-down when purchasing ultra-low emissions cars.

7.2.2 Impact of climate change policies on CO_2 emissions and fuel efficiency of cars

There is evidence to show that climate change legislation has led to improvement in vehicle fuel efficiency or increased the pace of the improvement. Between 2000 and 2010, average new car CO_2 emissions of new cars in the UK fell to ~145 gCO_2/km, 3.5% below 2009 levels and 20% below 2000 levels (Figure 7.2).

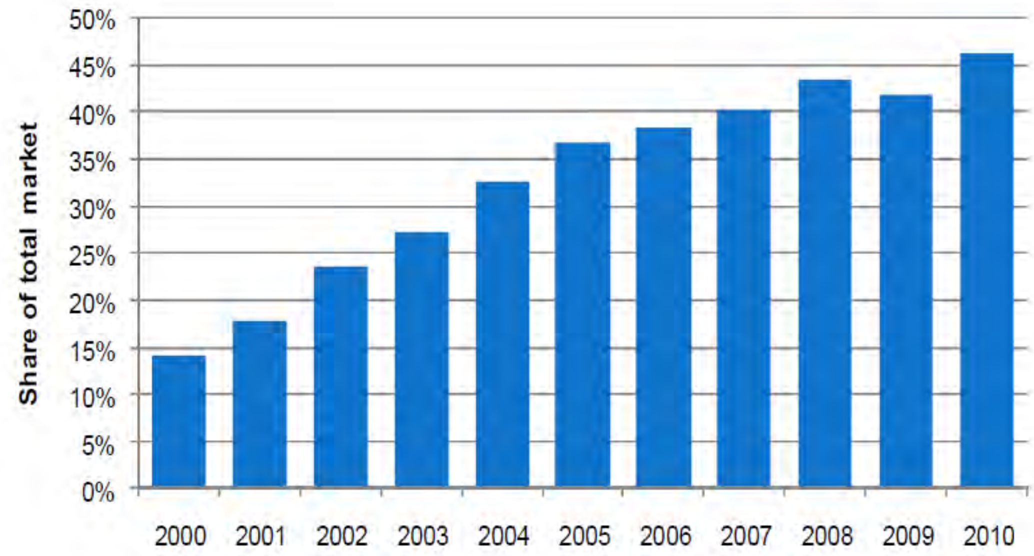
Figure 7.2: Fall in new car CO_2 in the UK since 2000



Source: SMMT new car CO_2 report 2011

Much of this improvement was driven by the increasing market share of diesel cars, which took a record 46% market share in 2010. This is up significantly from 14% in 2000 and 42% in 2009 (Figure 7.3).

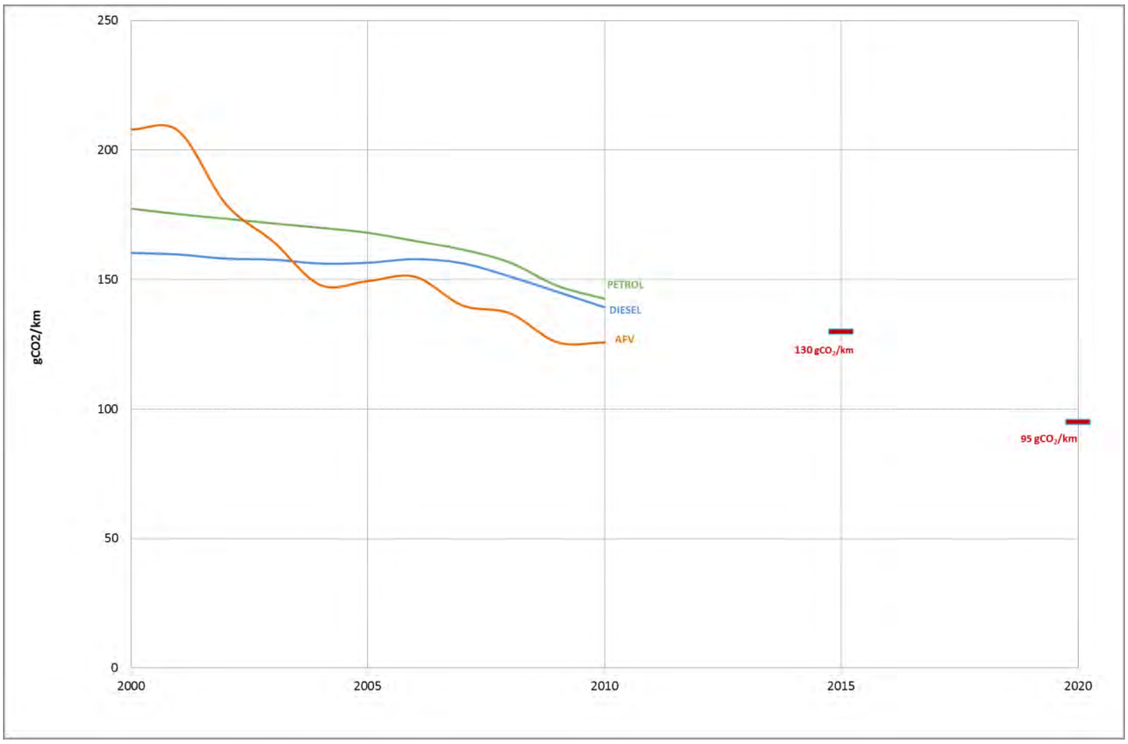
Figure 7.3: Share of diesel in the UK, 2000-2010



Source: SMMT new car CO_2 report 2011

A similar pattern in new car CO_2 can be observed at the EU level, with the European Commission confirming in December 2011 that average CO_2 emissions of new cars across Europe had fallen 3.7% from 2009 levels (Figure 7.4).

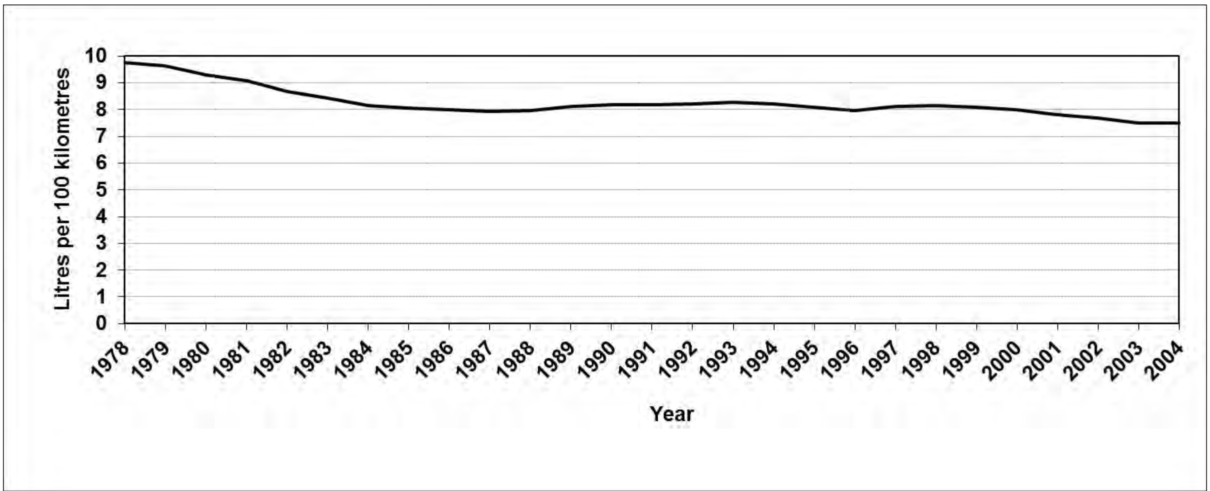
Figure 7.4: New car CO_2 levels in the EU from 2000 to 2010.



Source: EEA 2011

However, in order to assess whether the introduction of the voluntary agreements had a discernible effect on new car fuel efficiency it is important to review trends prior to 2000. Publicly available figures for g/km CO_2 emissions of new cars are not available for before 2000 as it was only at this time that the European Commission brought forward Decision No 1753/2000/EC, establishing a scheme to monitor the average specific CO_2 emissions of new cars. However, data on fuel efficiency going back further than 2000 does show continuing trends in improving fuel efficiency, as shown in Figure 7.5 below, albeit with a period of stagnation in the late 1980s and early 1990s. Note that this plot only shows figures for petrol vehicles. The period 1987 to 2000, saw the introduction of mass market turbo-diesel engines and direct injection turbo diesel technology. These new advances resulted in diesel car's market share growing to almost 15 % by 2000. Given the significantly lower fuel consumption of these new diesel technologies, this would be likely to have resulted in a slight overall downward trend in average new car CO_2 emissions.

Figure 7.5: Average new car fuel consumption (petrol two wheel drive vehicles only) in Litres/km, from 1978 to 2004



Source: DfT (2005)

The trends in Figure 7.2 and Figure 7.4 above shows a clear acceleration in fuel efficiency improvements around the time of the introduction of the new car CO_2 regulation (late 2008), suggesting that the regulation had more of an impact on fuel efficiency of new cars than the voluntary agreements that preceded it. Indeed the UK-level data in Figure 7.2 suggests that the acceleration started in 2007. This could be an anticipatory effect of the EU new car CO_2 regulation, with manufacturers ramping up efforts in the knowledge that a regulation was being negotiated. However, it is also important to consider the exogenous factors that could have played a part (see section 7.2.4). The sharp rise in fuel price around the same time (see section 7.2.4.1) may have driven purchasing patterns, as well as the general squeeze on incomes from the economic downturn (e.g. see "*Recession has driven interest in greener cars*" - Sytner, 2011).

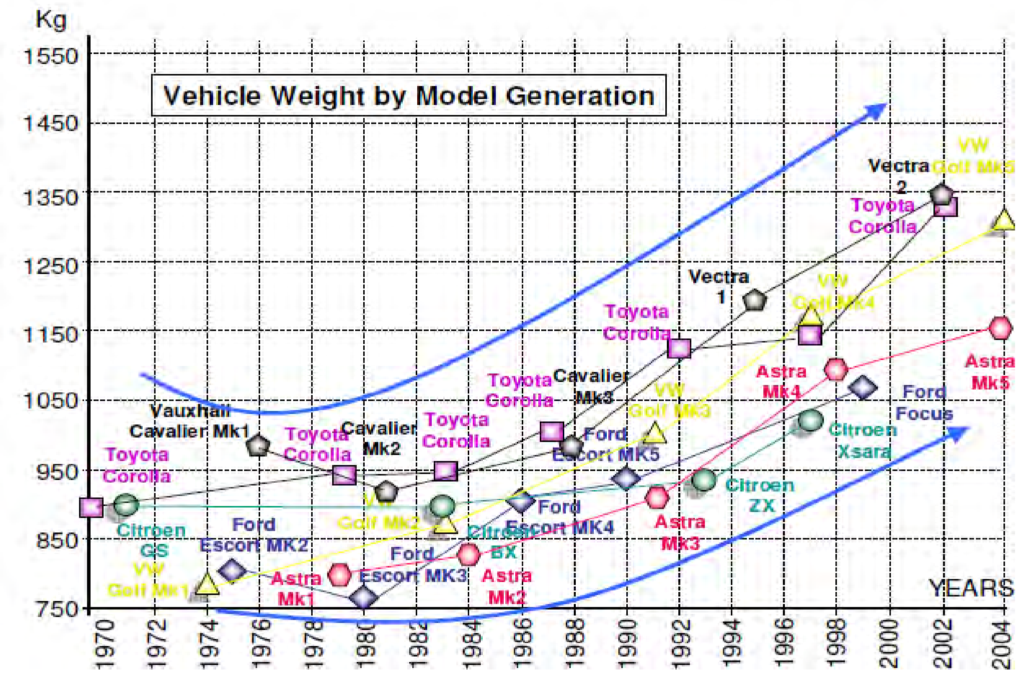
Before the introduction of the new car CO_2 regulation, charts Figure 7.2, Figure 7.4 and Figure 7.5 also show that fuel efficiency was improving, albeit at a slower rate. It is difficult to isolate the specific drivers behind this trend, however two important factors have played a part:

1. **Company car tax -** According to the Energy Savings Trust, of all the policies to reduce new car CO_2 emissions up to 2008, the revision of the company car tax system in 2002 had the strongest effect (EST, 2008). The HMRC evaluation in 2006 of the company car tax system suggested that average CO_2 emissions from company cars were around 15 g/km lower in 2004 than would otherwise have been the case if the reforms to the tax had not taken place.

2. **Voluntary Agreements -** It is reasonable to assume that the voluntary agreements had some impact, not least because Figure 7.5 shows that the rate of improvement in fuel efficiency accelerated around the time of the introduction of the agreements (1998/9), following around 10 years of no improvements. Figure 7.3 shows that much of the improvements from 1998/9 will have come from increasing dieselisation of the fleet. It would be reasonable to assume that between them, the voluntary agreements and the reform of the company car tax played a significant role in the dieselisation of the car fleet and consequent improvement in new car fuel efficiency.

Vehicle weight is a key factor that has impact on the level of CO_2 emissions and fuel efficiency. Figure 7.6 below shows how C-segment cars have got heavier since the 1980s.

Figure 7.6: Vehicle weight, 1970-2004



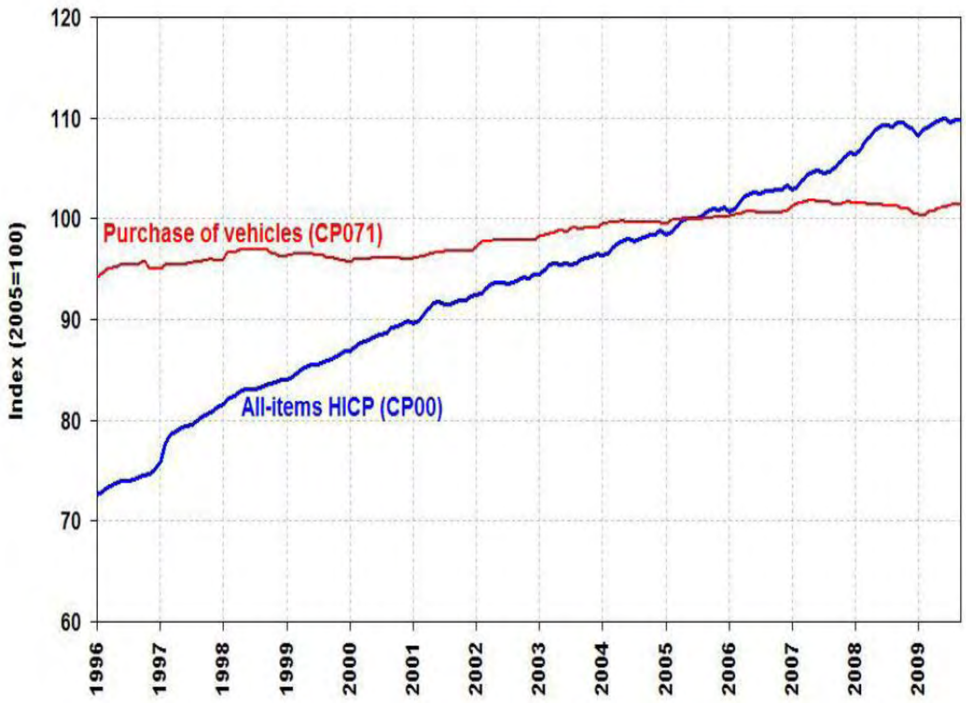
Source: Incerti et al (2005)

However in more recent years, the trend of increasing weight has slowed and started to reverse, and in their 2011 report for the Low Carbon Vehicle Partnership (LowCVP), Element Energy assume that weight will continue to fall. However they make this assumption on the basis of the expected response by manufacturers to the existing EU new car CO_2 regulation (and on the assumption that a mass-based utility parameter will not encourage manufacturers to increase the weight of their vehicles to receive easier targets). This therefore does not give us compelling evidence for the likely trend of weight in cars in the absence of any policies. But historically, the larger end of the car market has been particularly profitable for manufacturers and it is possible that in the absence of policy, manufacturers would explore whether even bigger vehicles are profitable.

7.2.3 Impact of climate change policies on vehicle costs and end-user prices

The last fifteen to twenty years has seen a significant increase in regulation to reduce the environmental and health impacts of car emissions. One would assume that these more stringent requirements will lead to higher production costs and consequently, higher vehicle prices for consumers. However, in practice it is difficult to find real-world evidence that such price increases have actually occurred (Figure 7.7), especially given that over the last two decades there has been a significant amount of new EU-level legislation focused on road vehicles.

Figure 7.7: EU-27 Harmonized indices of consumer prices indicate that vehicle prices have remained constant



Source: Eurostat (2010)

Studies conducted ten and five years ago predicted that reducing CO_2 emissions from new cars to an average level of 140g CO_2/km would make cars €2,400 and €1,200 more expensive, from 1995 and 2002 baselines respectively (T&E, 2011). This implies that these studies estimated the marginal costs of one percent of CO_2 emissions reductions towards 140 g/km at around or likely above €100, which is about 0.5% of a car's retail price.

Overall cars have become 12% to 22% cheaper – after inflation – in the eight years from late 2002 to late 2010 (AEA, 2011). For example, new cars have become 13% cheaper on average in real terms over the past eight years, which means a €20,000 car in 2003 would sell for €17,400 today. Before the CO_2 regulation started to have an impact on the CO_2 emissions from cars, the annual average reduction of car prices was slower compared to the period after the CO_2 regulation was announced in 2007. The average annual reduction in CO_2 emissions was 0.7% and 2.5% in 2002-2006 and 2002-2010 respectively.

Growth in environmental, safety and product regulation has led to a wide range of strategies and practices by manufacturers to balance production costs and regulatory compliance. Manufacturers have had to balance production costs while ensuring that they comply with environmental regulation and meet the high standards of quality and performance that the market demands. This has led to the growth of practices such as platform sharing, parts 'commonisation' and sharing of powertrains, all of which have been key to cost reductions in the industry. Manufacturers have also shifted production of vehicles away from Western Europe to Eastern Europe and Asia, in a bid not only to drive down costs through lower labour rates, but also to satisfy rapidly growing new markets.

Essentially it has become extremely difficult to isolate the impact of vehicle attributes on prices. This is mainly due to the complexity of vehicle production technology, pricing strategies, numerous car segments and compliance with regulations. The findings of our literature review show that it has now become more difficult to isolate the impact of various car attributes - such as performance, environmental and safety features - on car prices compared to ten to fifteen years ago. The temporal dimension of cost and profit is separate. The cost of compliance, for example R&D investment or factor development, could be spread over anything between 5 to 20 years. Pricing, servicing and finance plans are also designed to spread the cost of ownership over a number of years.

Hence, climate change regulation is a sub-set of all the factors that affect costs and which, potentially indirectly, influence car prices. The net impact of all these factors in balance will determine how these costs translate into prices. While, additional features introduced as a result of regulatory requirements increase costs, the inclusion of additional features that improve performance levels and comfort can lead to improved margins (and higher prices), where these bring added value to the consumer. For example, the introduction of catalysts, the fitting of which was effectively required to meet EU air pollutant emissions legislation, forced changes that have enabled improved performance of cars, (e.g. direct injection).

In summary, climate change legislation would always lead to increased costs, although the requirements of some pieces of legislation did not necessarily increase costs. Where such increased costs did not subsequently lead to increased prices, it was argued that this was due to competition in the markets concerned. Reduced costs resulting from, for example, economies of scale or improved productivity (for the reasons identified above), could offset the increased costs of regulation. However, where net cost increases could not be passed on to consumers, then the margins of manufacturers and/or their suppliers would be reduced. More generally, if climate change legislation had not increased costs, car prices would be lower than current levels. The extent to which increased costs can be passed on to consumers depends on competition and market conditions. The ability to pass on costs would vary by brand and the type of vehicle being sold (as well as the market) and exposure to foreign brands.

7.2.4 Impact of other exogenous factors – oil prices, income levels, technology and consumer preference – on car fuel efficiency

Car manufacturers function in an extremely complex and competitive market. Manufacturers engage heavily in R&D to improve their service and product offering. In many cases performance, safety and comfort related technologies and improvements have been introduced while at the same time meeting more stringent environmental regulations. Improvements in safety and comfort have tended to result in increased vehicle size and weight. As a result, in order to maintain performance, engine power outputs have increased. Despite this, test cycle fuel consumption figures were improving prior to the introduction of tailpipe CO_2 emissions regulations, although improvement has accelerated since regulations were introduced. The impacts of rising fuel and commodity prices might also be expected to provide a constant incentive to improve vehicle fuel consumption.

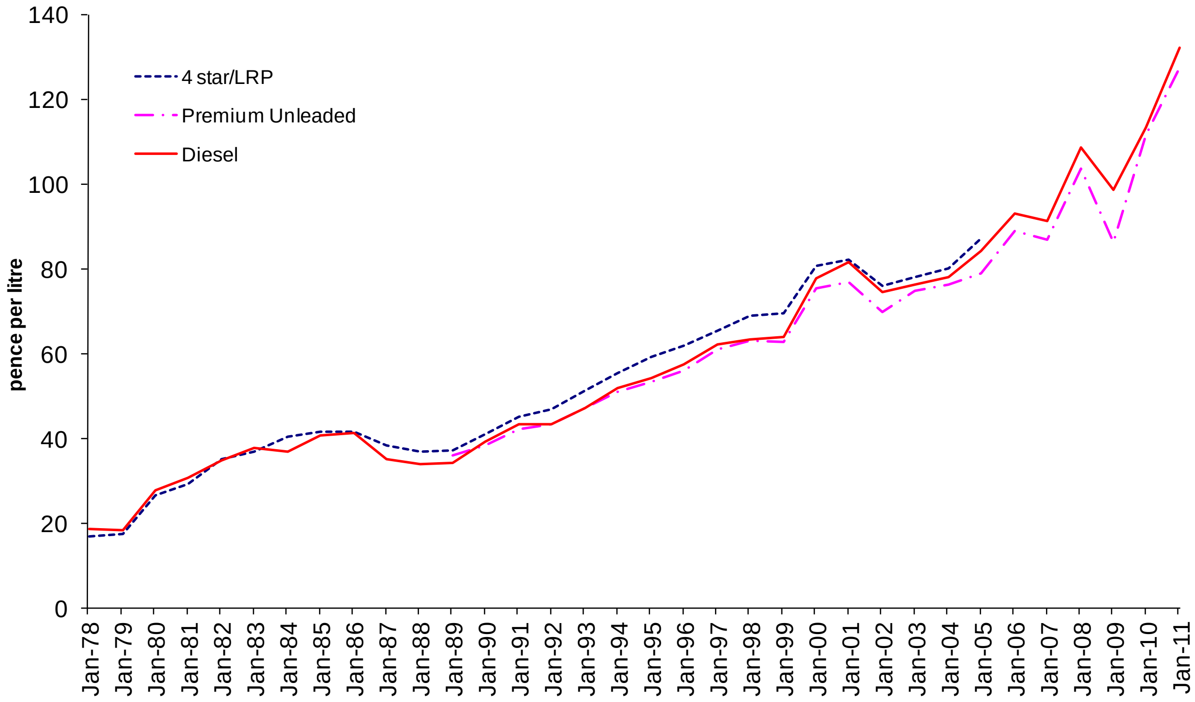
Car manufacturers are forced to maximise profits under whatever policy framework they all operate in. They would thus only make efforts to improve fuel efficiency if it appeared this would act to maximise profits. Much can also depend on consumer preferences – and these can be influenced by a variety of external factors.

Hence, business strategy factors, direct cost factors (e.g. Resource Prices (raw materials, energy), component and labour costs, exchange rates and shipping costs), indirect cost factors (e.g. Research & Development, plant maintenance and depreciation, marketing), market and consumer factors can all impact on fuel efficiency directly or indirectly. Some of these factors are discussed in more detail below.

7.2.4.1 Fuel prices

In terms of exogenous factors affecting fuel efficiency of new cars, the principle factor is fuel price, which in turn is driven by the oil price and taxation policy. Figure 7.8 below shows a trend of increasing fuel price since 1991, with only some minor falls around 2001, 2006 and 2008.

Figure 7.8: Chart of Motor Spirit Prices in January from 1991 to 2011

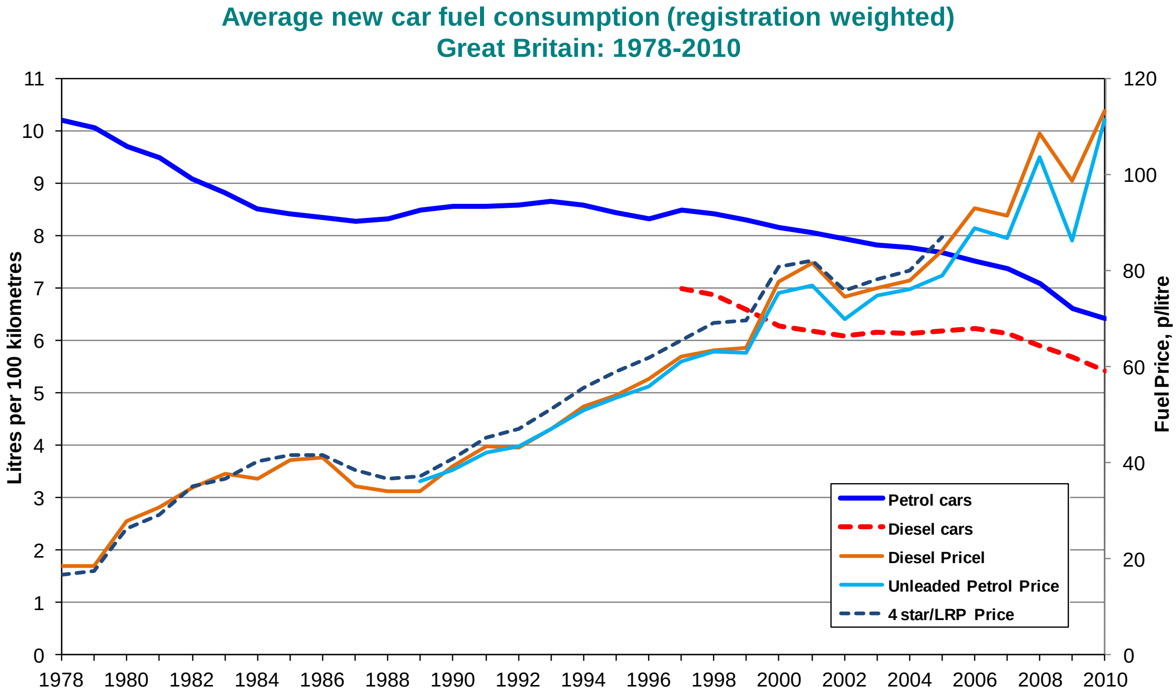


Source: DECC (2012)

Figure 7.5 showed that fuel efficiency improved from 9.8 l/100km in 1978 to about 8 l/100km in 1987. As mentioned above, it remained fairly static at around 8 l/100km to 2000 and has fallen again (i.e. improved fuel efficiency) since then to 7.5 l/100km in 2004. This pattern can be compared against the trend in rising fuel price shown in Figure 7.8. Figure 7.9 below combines these two trends.

This suggests that there may not always be a direct link between rising fuel price and new car fuel efficiency, which can be a useful caveat when looking at future trends of fuel price. Looking at the period from 1997 onwards, there would seem to be a reasonable correlation between the progressive introduction of car CO_2 policies, and new car fuel efficiency. This would suggest going forward that the absence of policies could lead to little or no improvements in new car fuel efficiency. However the above trends are not conclusive as Figure 7.9 also shows that improvements in fuel efficiency took place from 1978 to 1987 in the absence of any Government policy.

Figure 7.9: Average new car fuel consumption (registration weighted) Great Britain: 1978-2010

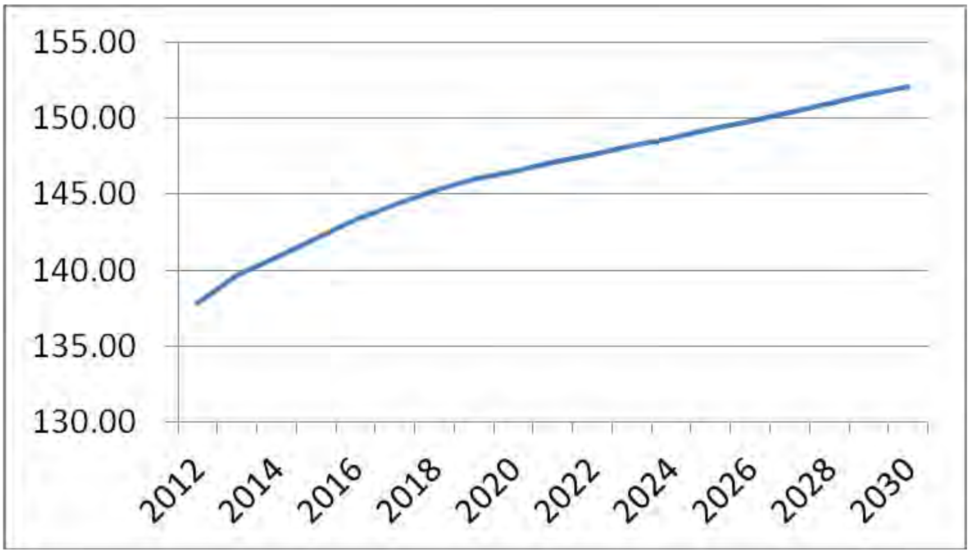


Source: DfT 2011, DECC (2012)

7.2.4.2 Elasticity of fuel consumption with respect to price

As noted by the World Energy Council in 2008, many studies have demonstrated a link between the fuel consumption of cars and the price. Their results are consistent, and converge towards a long-run elasticity of fuel efficiency to fuel price of +0.4 meaning that in the long run, a 10% increase in the price of motor fuel leads to a total improvement in fuel efficiency of 4% (WEC, 2008). This would suggest that a rising fuel price could lead to some improvements in fuel efficiency (although this might include some changes to driving styles rather than just from changes to new car purchasing habits). Figure 7.10 below suggests a 10% increase in fuel price by 2030, thus suggesting (that with all other factors equal) fuel efficiency might improve by 4% over the same period. This would equate to a rate of around 0.3 g/km a year. This would represent a significantly lower rate of progress than historic trends (for example, a 26% reduction in new car fuel efficiency over the 18 years from 1992 to 2010). Hanley et al (2002) suggest a lower elasticity of fuel price with respect to car ownership, being 0.25 in the long term, suggesting that lower levels of fuel efficiency improvements than those suggested above might result from the kind of fuel price increases seen in Figure 7.10. Similarly, Graham and Glaister (2002) suggest a long run fuel price elasticity with regard to car ownership of -0.1 to -0.24.

Figure 7.10: ***Forecast retail petrol price 2012-30, pence per litre***



Source: DfT 2011

Finally, some studies (JTRC, 2007) suggest that fuel price elasticities are likely to fall in the future as incomes increase and with increasing urbanisation. All of this suggests that the relatively limited fuel price forecasts foreseen in Figure 7.10 could lead to yet lower levels of fuel efficiency improvements in the absence of policies to drive such changes. Thus the evidence in relation to fuel price forecasts and fuel price elasticities suggests that very low levels of fuel efficiency improvements, if any, are to be expected from fuel price alone.

This view is supported by work done by Element Energy for the Low CVP which concluded that low carbon cars are likely to require continuing financial support, in the form of differential taxation (e.g. through company car tax or Vehicle Excise Duty) if they are to be widely adopted in future (EE, 2011).

7.2.4.3 Business strategies and manufacturer choices

The car manufacturing business has seen huge changes over the past three decades. The car markets these days feature a far greater range of models, variants and options. Most studies (and interview respondents) indicate that manufacturers operate in several different markets and determine optimal business and technological strategies on the basis and nature of the car segment and competition in each market. If fuel prices remained constant in real terms (and perhaps the distances that people felt they had to drive did too) then there is little evidence that manufacturers would voluntarily improve fuel economy. Most likely there would be an equilibrium in which manufacturers would provide a range of products some with good fuel economy some with poor, to cater to the majority of customer tastes, but that overall fleet average economy would remain constant over time.

Other factors can influence this equilibrium. For instance safety was never viewed by OEMs as something which helped maximise profits – unless your brand was built on it like Volvo. Euro NCAP changed all that as now OEMs pour money into getting the best possible rating. Consumer preferences were shifted by some vivid press reporting of the Austin Metro’s vulnerability in combination with nice clear metrics helping them to choose safer options. Potentially the same thing could happen with fuel efficiency.

7.2.4.4 Technologies

Work done by AEA (2011) for the European Commission suggests that whilst car purchase prices have fallen despite the introduction of car fuel efficiency policies, regulations and standards have generally increased costs for manufacturers (although the extent of this is dependent on the extent to which the manufacturer can offset the costs through economies of scale or improved productivity, e.g. platform sharing). Flexible manufacturing techniques allow manufacturers to more closely match supply to demand, while quality improvements have reduced costs and contributed to profitability. Improved computing power coupled with techniques such as simultaneous engineering has helped to reduce research and development costs and product development times. This being the case, one would expect manufacturers to avoid these costs in the absence of policy so as to maximise their profit margins. Generally speaking, manufacturers are likely to continue to produce a range of vehicles to suit different customers with a focus on optimising profits and if there were improvements in overall fleet average fuel economy it would only be as a by-product of that process.

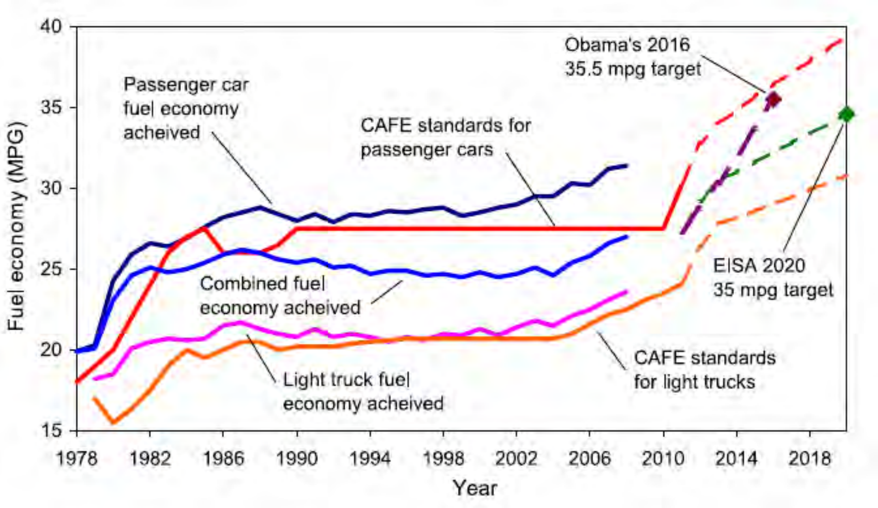
7.2.4.5 Consumer demand and preferences

Consumer demands have evolved substantially over this period, with the emphasis shifting from a desire simply to own a vehicle, to the desire to own a characterful and distinctive vehicle of high quality and specification. Rising fuel prices, and to some extent environmental concerns, are driving a shift in consumer preference towards relatively more economical models; a sector which has traditionally generated thinner margins for the manufacturers. It might also be reasonable to expect a continuing trend in consumer awareness of fuel efficiency and climate change. However, there is no evidence that this consumer demand will be a sufficiently strong signal in the absence of either a rapidly increasing fuel price or policies to drive demand (e.g. graduated vehicle excise duty, fuel efficiency labelling etc). If fuel prices remained constant in real terms then only a small percentage of the population will make purchase decisions based on altruistic/environmental motives, the vast majority primarily respond to price signals.

7.2.5 Historical trends in fuel efficiency in other countries

Some useful insight can be gained from the US, where the evolution of the Corporate Average Fuel Economy (CAFE) standards gives an insight into potential ‘no policy’ counterfactuals. Figure 7.11 below shows that the introduction of CAFE coincided with sharp improvements in fuel efficiency in the early to mid-1980s. When the CAFE standard was flat-lined from 1990, improvements in fuel efficiency slowed and made little progress between 1990 and 2000.

Figure 7.11: Evolution of CAFE standards and change in fuel economy, from 1978 to 2019



Source: Shiau et. al (2009)

However, some improvements, albeit at a slower rate, are in evidence from 2000, which could be taken as evidence to challenge the assumption that fuel efficiency would not improve in the absence of policy. The improvements in this case could be due to rising fuel prices, especially from 2006 onwards. However there could also have been an expectation factor – having a flat-lined standard could be viewed quite differently by manufacturers to having no standard. There may be an expectation that a flat-lined standard could be tightened in future, so some improvements may come from a desire to manage this risk, whereas manufacturers could in theory behave quite differently if they knew that there would be no policy mechanism in place with which to regulate them. It is also important to bear in mind that manufacturers became increasingly global organisations over this period, with many products and technologies being developed to cater for markets where standards have been introduced over this time. The US saw increasing levels of imports – e.g. rising imports of Japanese cars – which may also have explained the rising fuel efficiency. This trend from 2000 onwards cannot therefore be seen as conclusive proof for a rising fuel efficiency counterfactual, and indeed the sharp slowdown seen in fuel efficiency improvements around 1990 suggest a sizeable policy impact.

7.2.6 Likely future trajectories for fuel efficiency

Whilst historical trends can give us some insights into what the effect has been previously of the introduction of policies, or the impact of exogenous factors such as oil price, it is also important to consider the extent to which future improvements may mirror the historical trends. For example, even if historical trends suggested that fuel efficiency improved in the absence of policies in the past, this does not mean that such a trend will be likely in the future, as there may be technological and physical constraints to further improvements.

The CCC's work on fuel efficiency of new cars out to 2050 takes fuel price assumptions from DfT, see Figure 7.10. This clearly shows a trend of increasing fuel price. However it is worth noting that the rate of increase in the future is much lower than that seen historically in Figure 7.8 (0.4 ppl a year between 2012 and 2030, compared to 3 ppl a year from 1992 to 1999, 4.5 ppl a year from 2002 to 2006 and a huge 16.5 ppl a year from 2009 to 2011). Some commentators have suggested that 'peak oil' will result in severe fluctuations and instability in oil prices as demand exceeds supply. Sudden price spikes might provide an increased focus on fuel economy amongst consumers (as happened as a result of the 1973 oil crisis).

What this means for the future evolution of new car fuel efficiency will depend on various factors, including on the demand side (e.g. elasticity of fuel consumption in response to fuel price) and on the supply side (e.g. available cost effective technologies for manufacturer to install).

7.2.7 Conclusion

Overall, the following conclusions can be drawn for passenger cars:

I. **An analysis of past trends does indicate a noticeable impact from climate change policy.**
   - Before the introduction of the voluntary agreements in 1998 new car fuel efficiency had remained static for around ten years and started to improve after their introduction.
   - The rate of fuel efficiency improvements increased further around 2007/8, coinciding with the introduction of the more binding new car CO_2 regulation.

II. **However this evidence in itself is not conclusive and proving causality is always difficult.**
   - For example, there is some evidence that new car purchasing habits had been influenced by the economic downturn from 2008, which could have helped contribute to the acceleration of fuel efficiency improvements.

- Furthermore, evidence on fuel efficiency from the late 70s and early 80s showed rapidly improving fuel efficiency even in the absence of government policies.

III. **Evidence from other countries gives a similar picture**, namely that policies seem to have had a noticeable impact on fuel efficiency, but the evidence is not clear cut.
  - Fuel efficiency improvements did stall noticeably when the CAFE standards in the US were flat-lined from 1990, however improvements did start again in 1990 whilst the standards still remained flat.
  - That said, a standard that is in place but not getting progressively harder, is not the same as not having any policy in place, and some of the improvements from 1999 may have resulted from manufacturers' expectation that the standards would be tightened in the future, and therefore may not be expected in a no-policy counterfactual.

IV. **Whether the increased costs of complying with change policies lead to increases in prices depends on inter alia the extent to which these costs are offset by cost reductions resulting from economies of scale and improved productivity and whether any cost increases can be passed on to consumers.**
  - The extent to which increased costs can be passed on to consumers depends on competition and market conditions. The ability to pass on costs can vary by brand and the type of vehicle being sold (as well as the market) and exposure to foreign brands.
  - Where net cost increases could not be passed on to consumers, then the margins of manufacturers and/or their suppliers would be reduced. More generally, if environmental and safety legislation had not increased costs, car prices would be lower than current levels as manufacturers might relax fuel efficiency improvements, so as to maximise their profit margins.

V. **Looking ahead there is little evidence to suggest that fuel efficiency would continue to improve in the absence of policies.**
  - It is likely that fuel prices will continue to rise, and that this could lead to some fuel efficiency improvements, but these improvements from fuel prices alone are likely to be negligible and definitely much lower than historic rates.
  - We do not expect weight to continue to increase (weight can be a comparatively low cost way of improving fuel consumption) and analysis of vehicle technologies suggests there are few low cost options that can be implemented by manufacturers.

In summary, we believe that there is not sufficiently strong evidence to suggest that the assumption of a flat counterfactual is incorrect and that the CCC should therefore continue to use this assumption in its modelling work.

7.3 Vans/LCVs

Vans occupy an interesting position between passenger cars and the larger commercial vehicles. In this section we are defining vans as commercial vehicles < 3.5 tonnes GVW, i.e. those vehicles subject to EC Regulation 510/2011 Van CO_2 regulations.

In preparation for the introduction of this regulation, the UK DfT was required to prepare a Regulatory Impact Assessment. As part of this RIA AEA undertook a study of the counterfactual CO_2 emissions of new vans, working with TNO who undertook the generation of revised cost curves (AEA, 2010a). This study considered the issues to be considered over the 2008 – 2020 timeframe. These are the same issues that are relevant to this portion of the study.

7.3.1 Diesel – petrol vehicle ratio

In 2001 DfT statistics indicated 95.3% of the around 275,000 LCV sold were diesel fuelled. By 2010 this figure was 98.2% (DfT, 2011). However, closer examination of the detailed database indicates that it contains a small number of vehicles registered as “light commercial vehicles” which many would regard 4x4 private vehicles. These increase the non-diesel proportion of the sales. Consequently, a 98.2% diesel proportion is likely to be an underestimate, with very few non-diesel vans are sold. The corollary to this is that there is negligible scope for improving the efficiency of the van fleet through increased dieselisation of the fleet.

The principal driver for the existing diesel-petrol vehicle ratio is the economics of operating vans. It is independent of GHG policy.

7.3.2 Trends in increasing vehicle efficiency

The study undertaken for the DfT noted that “vans” were not optimally considered as a single homogenous group. For pollutant emission compliance they are grouped by their reference mass (linked to kerb weight) with Class I vans having < 1265 kg, and Class III being >1,705 kg reference mass. Many class I vans can be viewed as being derived from cars, i.e. are passenger cars from which the rear seats and windows have been replaced with a panel body. These vehicles often use the chassis and powertrain platform of passenger cars, and their CO_2 emissions efficiency follows that of the passenger cars.

In contrast, the heavier light commercial vehicles have no car counterpart. Their CO_2 emissions efficiency is independent from that of passenger cars, but is influenced by commercial pressures, where the importance of fuel costs in the overall cost of ownership ensures manufacturers promote fuel efficiency at the van design stage of the vehicles’ lifecycle.

Consequently, the increases in van efficiency differed for the fuel-weight range classes, as illustrated below in Table 7.1.

Table 7.1: Increases in van efficiency and reported in the DfT new van counterfactual study

	Diesel			Petrol		
	Class I	Class II	Class III	Class I	Class II	Class III
Change 2008 – 2020	-47.2%	-29.5%	-12%	-34.7%	-23.8%	-12.0%
Change per year	-3.9%	-2.5%	-1.0%	-2.9%	-2.0%	-1.0%

From this analysis, which assumes the absence of GHG van regulations, if GHG car regulations were removed **today**, the fuel efficiency of smaller vans would continue to improve slightly more than heavier duty vans because of technology transferring from cars to these small vans. The counterfactual study concluded that in the absence of any vehicle CO_2 regulations a natural improvement rate of 1% p.a. would occur between 2008 and 2010 (**all other factors remaining unaltered**). However, as will be seen, there are other factors reducing this improvement.

7.3.3 Trends in increasing weight

A trend leading to poorer fuel efficiency, i.e. in the opposite direction to either technology crossover from passenger cars, or intrinsic efficiency improvements, arises from the trend for vehicles to get heavier. The analysis undertaken for the DfT quantified this trend as leading to a +0.65% change in CO_2 emissions per year, i.e. a 7.8% increase over the 12 year period 2008 – 2020.

7.3.4 The impact of environmental and safety regulations

The counterfactual van study also considered the impact of changes in the regulations concerning vans. These included:

- The introduction of diesel particulate filters (increasing CO_2 emissions for diesel vehicles);
- The introduction of selective catalytic reduction for NOx abatement (increasing CO_2 emissions for diesel vehicles);
- The introduction of daytime running lights (increasing CO_2 emissions for all vehicles).

Tyre pressure monitoring systems (TPMS) and gear shift indicators (GSI) were also considered. In the DfT study it was anticipated these would not change CO_2 emissions over the regulatory test cycle (because at homologation vehicles are tested with correctly inflated tyres and gear changes occur at specified points). However, for on-the-road driving, these are anticipated to lead to modest CO_2 emissions reductions.

7.3.5 Summary of data on vans

The DfT counterfactual new van CO_2 study provides an evidence based baseline for vans. Over the period 2008 to 2020 it concludes that in the absence of CO_2 regulations the CO_2 emissions (and by inference the fuel consumption) of Class III vans will decrease by 2.7% for diesel vans(and by 5.2% for petrol vans though these only comprise around 2% of new van sales). The difference is caused by other regulations on vehicle emissions and safety leading to step increases in CO_2 emissions from diesel vehicles at the date of their introduction.

If the diesel trend were to apply consistently between 2020 and 2050 this would lead to the following average van CO_2 emission values:

Table 7.2: Increases in van efficiency as reported in the DfT new van counterfactual study, projected from 2020 to 2050

	Average van CO_2 emissions	Change relative to 2008
2008	202.9 g/km	
2020	197.5 g/km	-2.7%
2050	182.0 g/km	-10.3%

Consequently this analysis predicts that in the absence of CO_2 regulations by 2050 “natural improvements” would not lead vans to meet the 175 g/km 2016 target.

It is also noted that this is a more modest rate of improvement than was reported for passenger cars over the period 1978 – 2004 in DfT Statistics (a 23% improvement in this 26 year period). However, this figure includes contributions from:

- the changing ratio of petrol to diesel fuelled vehicles, and
- the replacement of carburettors for petrol vehicles to fuel injection systems, computer engine management systems etc, and similar changes from mechanical systems to electronically controlled fuel injection systems for diesel vehicles.

The former factor does not apply to vans, and the latter factor can be viewed as a one off step change in technology that will not be repeated. When these factors are removed the trends given in Table 7.2 appear well aligned with those seen in the past.

In summary, we believe that there is some evidence to suggest that the assumption of a flat counterfactual is not valid for vans and it may be more appropriate for CCC to revise this assumption in its modelling work to reflect a gradual rate of improvement in van efficiency.

7.4 Heavy Trucks

Heavy trucks are defined as commercial vehicles whose gross vehicle weight (GVW) is greater than 3.5 tonnes. They are used for the movement of goods, and have a range of sizes and configurations from small (for example 5 tonne rigid trucks) used for local deliveries, to large tractor units that are hitched to trailers and form a 44 tonne articulated vehicle.

The EC has introduced regulations on the average CO_2 emissions from cars and light commercial vehicles (in 2010 and 2011) and is considering the options for heavy duty vehicles. They commissioned two studies on the “reduction and testing of greenhouse gas emissions from heavy duty vehicles;

- Lot 1, Strategy, led by AEA, and
- Lot 2, Test methodology, led by TU Graz

The Strategy study involved laying the foundations for all the work, and involved collecting information on the European heavy duty vehicle market. Whilst this was from a European, rather than only UK perspective, this study most probably provides the best contemporary, authoritative information pertinent to this study for the CCC.

Some other noteworthy differences between heavy goods vehicles, passenger cars and vans are:

- Heavy goods vehicles are operated virtually exclusively for business, commercial, purposes
- The cost of fuel when operating a heavy goods vehicles is a markedly higher proportion of the overall operational costs than for lighter vehicles.

These two factors mean that the operators of trucks are very aware of fuel consumption (through its cost) and there is a much higher demand for improved fuel efficiency than for light duty vehicles. However, there are some fundamental physical constraints, involved with the energy requirements for moving a tonne of freight a set distance. These factors mean that heavy duty trucks have been subject to reductions in fuel consumption in the absence of GHG regulations, but there are higher barriers to further large reductions relative to light duty vehicles.

Heavy duty vehicle fleet segmentation:

For this study heavy duty trucks are sub-divided into the following groups:

- Rigid trucks up to 15 tonnes gross vehicle weight
- Rigid trucks above 15 tonnes gross vehicle weight
- All articulated trucks (those there are very few of these less than up to 15 tonnes gross vehicle weight
- Construction trucks (a mixture of the above 3 categories, with specialist body types and duty cycles).

7.4.1 Diesel – petrol vehicle ratio

For heavy duty vehicles this is not a variable because the quantity of petrol used in HDVs, relative to diesel fuel, is extremely small.

7.4.2 Trends in increasing vehicle efficiency

This is challenging to quantify because:

- Unlike cars trucks are not homologated over a road drive cycle leading to mass of emissions /km driven, but rather **their engines** are homologated using an engine dynamometer, and emissions are characterised in units of mass /kWh output at the driveshaft.
- The fuel consumption achieved by trucks on the road is markedly affected by the load it carries. This is rarely well characterised.
- Commercial pressures on trucks mean that fleet managers focus their attention on the fuel bill. Whilst vehicle km data are often gathered, attention is paid to aspects like:
    - Routing, i.e. avoiding unnecessary vehicle km;
    - Load factors, particularly trying to carry a load for the return journey
    - Driving style, e.g. promoting safe and fuel efficient driving.

All the above factors combine with the intrinsic fuel efficiency of the vehicle to affect the fuel bill. Key questions for this study are:

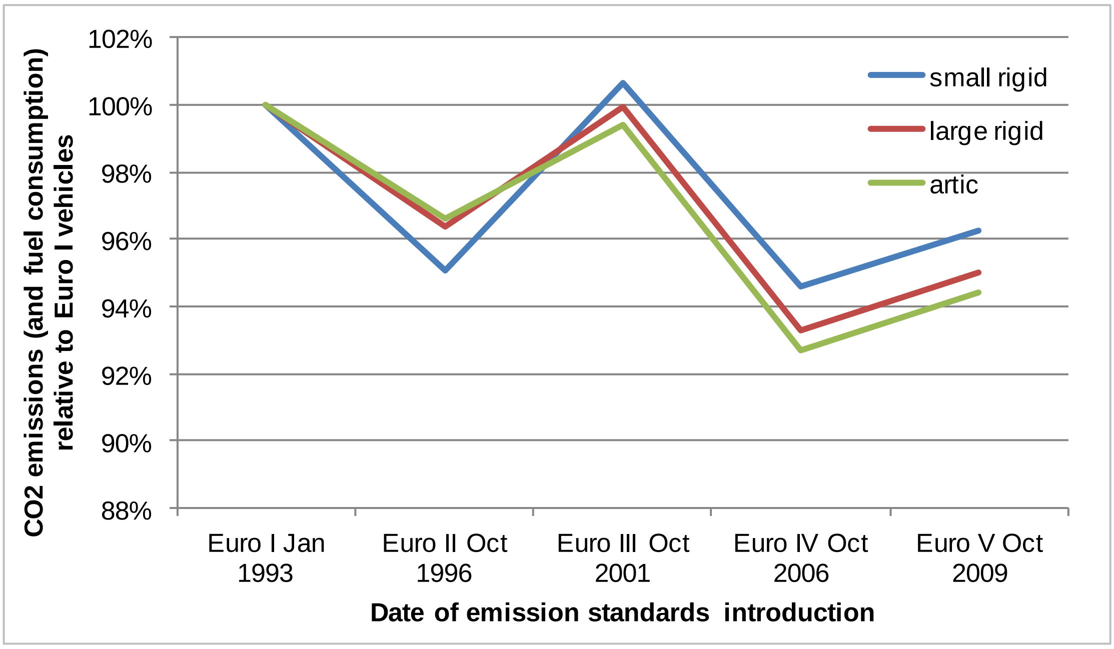
- How has fuel economy changed over time;
- Is this different for the three categories of trucks; and
- How might this change in the future.

A quantification as to how fuel efficiency has changed over time comes from the data within road transport inventory compilation tools. This was quantified using the most recent DfT sponsored review into the speed related emission functions for u-CO_2 DfT (2009). The CO_2 emissions (per km travelled for vehicles on flat roads with 50% payload) were taken for the following heavy duty vehicle types:

• Rigid truck 3.5 to 7.5 tonnes GVW	Small (< 15 t) rigid truck
• Rigid truck 12 to 14 tonnes GVW	Small (<15 t) rigid truck
• Rigid truck 20 to 26 tonnes GVW	Large (>15 t) rigid truck
• Rigid truck >32 tonnes GVW	Large (>15 t) rigid truck
• Articulated truck 20 to 28 tonnes GVW	Articulated truck
• Articulated truck 40 to 50 tonnes GVW	Articulated truck

The data were referenced relative to Euro I (which applied to all vehicles sold from January 1993), and then pairs of truck weigh range data were averaged to give relative fuel efficiency and CO_2 emission factors for the three categories of trucks. This is plotted in Figure 7.12.

Figure 7.12: The CO_2 emissions, and fuel efficiency, as a function of time for three different sized trucks deduced from inventory emission factors.



Factors influencing the fuel efficiency for mainstream technology options include engine size and their power rating. Changes that have occurred within the 1993 to 2011 timeframe include:

- Engine changes including from IDI to DI, the addition of turbochargers and the addition of intercoolers;
- Fundamental changes in fuelling systems, from mechanical pumps and metering to very high pressure, computer controlled unit injectors, to very high pressure common rail systems;
- Improvements in vehicle aerodynamics;
- The addition of speed limiters, mandated by Directive 2002/85/EC for all new vehicles sold after 1st January 2005;
- Changes in emissions abatement technology;
- Increases in mass caused by changes in comfort levels, cab sizes, fittings (MAC, fridges etc) (Issue of demographic profile of truck drivers and need to make the profession attractive).

An estimation as to how fuel efficiency might change in the future has been given in the EC Lot 1 report, where a baseline for future fuel use and GHG emissions was developed (AEA-Ricardo, 2011)[9]. The tabulated conclusions from this are given in Table 7.3. Three different components are considered:

- Changes in fuel consumption caused by improvements in the powertrain for new vehicles;
- Changes in fuel consumption caused by changes in the rest of the vehicle (e.g. light weighting, or aerodynamics and changes is weight and safety equipment) for new vehicles;
- Changes in fuel consumption caused by emissions legislation (negative numbers indicate an increase in fuel consumption, or a fuel consumption penalty).

[9] Section 4.4 (page 177) of final report

Table 7.3: BAU estimates on evolution of fuel consumption benefit (penalty) for base conventional diesel vehicles - figures indicate benefit/penalty compared to previous year

		2010	2013	2015	2018	2020	2025	2030
New Vehicle % powertrain natural improvement [(a)]	Truck	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
	Bus / Coach	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
New Vehicle % vehicle FC improvement	Long Haul Truck [(b)]	0.0%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
	Coach [(c)]	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
	Bus [(d)]	0.0%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
% FC penalty from emissions legislation [(e)]	All	0.0%	-3.0%	0.0%	-3.0%	0.0%	0.0%	0.0%

Source: Estimates by Ricardo (2010)

Notes: Business as usual scenario of fuel consumption of new vehicles - assuming no incentives or legislative CO_2 for HDV
(a) Natural p.a. improvement in powertrain efficiency includes transmission and engine auxiliaries
(b) Assume overall circa 10% reduction using vehicle aids by 2030
(c) Some aero improvements and weight reduction
(d) Forecast reduction in vehicle mass to increase fuel economy of vehicles - assume 1% reduction in weight every 5 years - 0.8% fuel consumption improvement every 5 years
(e) Penalty from increasing emissions legislation in 2013 and then potential Euro VII around 2018

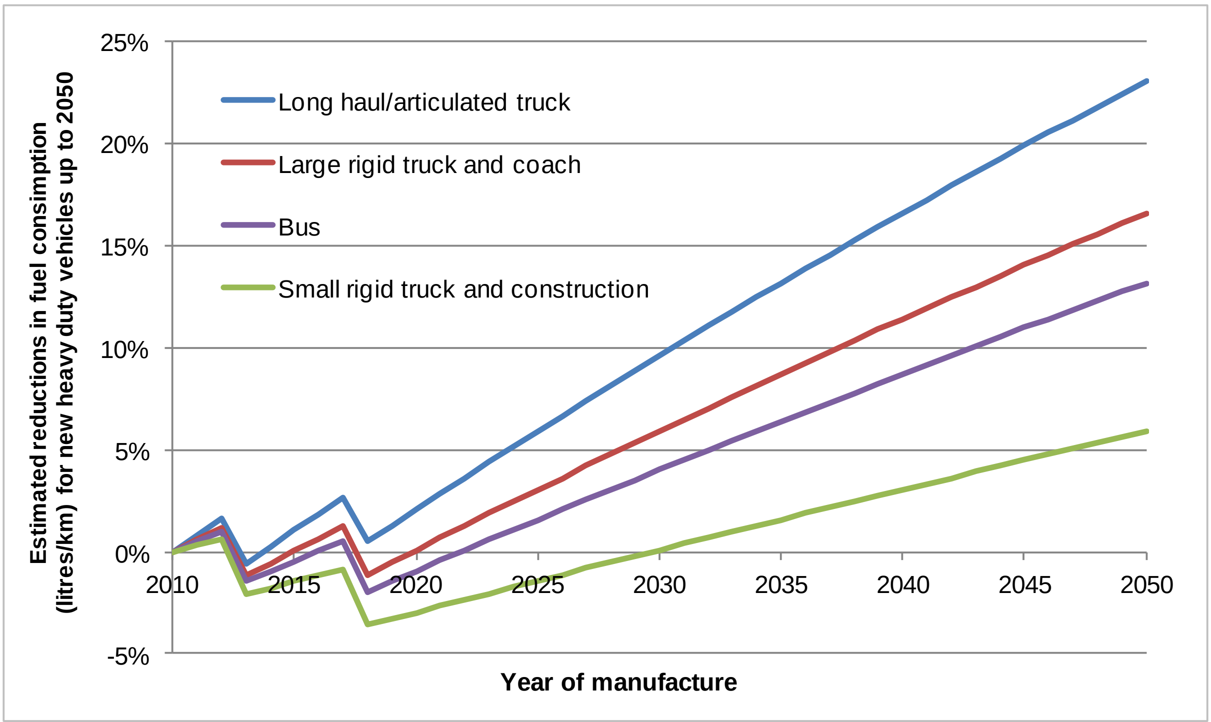
The categories used in the EC Lot 1 report (AEA-Ricardo, 2011) correlate with the categories considered in this study as indicated in Table 7.4:

Table 7.4: Correlation between the truck categories used in this study and vehicle categories in AEA-Ricardo (2011)

Vehicle category for this study	Equivalent vehicle category in EC Lot 1 study
Rigid trucks up to 15 tonnes gross vehicle weight	Truck
Rigid trucks above 15 tonnes gross vehicle weight	Long haul truck
All articulated trucks	Long haul truck
Bus	Bus
Coach	Coach

If the reductions in fuel consumption between 2010 and 2030 are extrapolated (i.e. set to be the same as) between 2030 and 2050 (caused by both improvements in the powertrain and in the rest of the vehicle) then the cumulative **reduction** in fuel consumption predicted is shown in Figure 7.13.

Figure 7.13: The estimated reductions in fuel consumption (and CO_2 emissions) as a function of time for three different sized heavy duty vehicles (as reported to EC DG CLIMA)



It is emphasised that these predictions are made in the absence of there being any regulations regarding CO_2 emissions from large trucks in place. Also, these predictions are for new vehicles. Consequently, the average for the fleet will lag behind this.

It is also interesting to note how there is a similarity between the predictions over the next 15 years, and those reported to have happened during the last 15 years from inventory compilation emission factors.

7.4.3 Trends in increasing weight and the impact of environmental and safety regulations

It is acknowledged that there is a trend for vehicles to get heavier. This is not uniform, with higher levels of comfort, and indeed larger cabs, being more prevalent for the trucks undertaking the long haul journeys, and occurring less for the small rigid trucks. There are also changes to the regulations controlling vehicles led by safety. The estimates of changes in fuel consumption caused by changes in the rest of the vehicle includes a component covering these. Therefore, no further compensation is required.

7.4.4 Summary of data on trucks

Three categories of trucks are considered, rigid trucks <15 tonnes GVW, rigid trucks >15 tonnes GVW and all articulated trucks. The EC “Reduction and testing of GHG emissions from heavy duty vehicles: Lot 1 Strategy” project provides an evidence based baseline for trucks up to 2030. It concludes that in the absence of CO_2 regulations the CO_2 emissions (and by inference the fuel consumption) of the larger rigid and the articulated trucks will decrease by 10%, whereas for the smaller rigid trucks the decrease will be 6%.

The CO_2 emissions (and by inference the fuel consumption) of trucks during the past 15 years has been calculated using inventory compilation emission factors. This enables a like for like comparison to be undertaken. Data on average fuel consumed by trucks per vehicle km driven also contain contributions from changes (increases) in average payload carried, and increases in the average size of truck used. Hence these data are not able to provide a like for like comparison to be made.

In summary, we believe that there is good evidence to suggest that the assumption of a flat counterfactual is incorrect for specific sizes of heavy trucks. However, the general trend of increasing vehicle sizing (presumably in a drive to increase operational efficiency on a tonne-km basis) means that the fleet as a whole has a trend to increasing MPG . CCC should therefore factor these elements into its modelling work to reflect annual increases in heavy truck efficiency, but factoring in changes in relative vehicle sizing affecting actual energy consumption per km.

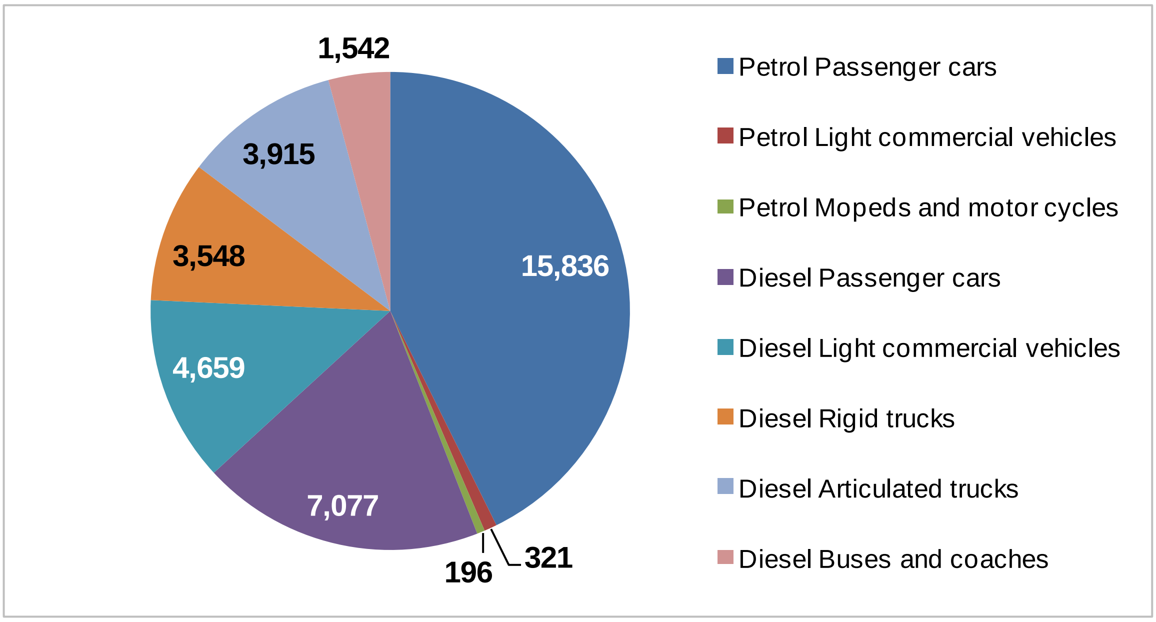
7.5 Other Vehicles

7.5.1 Summary of fuel usage by different road vehicle types

It is useful to appreciate the importance of “other vehicles” (buses, coaches, motorcycles and mopeds) to the UK road transport fuel usage overall. The data from the 2009 UK GHG inventory assigns the consumption of petrol and diesel among road vehicles. This is presented as a pie chart in Figure 7.14, with the fuel usage (in ktonnes) provided.

As a fraction of all fuel, buses and coaches consume 4.2% of all road transport fuel, whereas two wheeled vehicles consume 0.5%.

Figure 7.14:The quantities of fuel used by different vehicle types in 2009



7.5.2 Diesel – petrol vehicle ratio

As indicated in Figure 7.14, buses and coaches use, virtually exclusively diesel fuel, whereas two wheeled vehicles use virtually exclusively petrol fuel. This ratio is unlikely to change in the future.

7.5.3 Trends in increasing vehicle efficiency

There are modest improvements in the fuel efficiency of two wheeled vehicles in the absence of CO_2 regulations. However, there is little hard evidence available. Also, because their fuel consumption is such a minor fraction of road transport fuel as a whole, large changes in the fuel efficiency of these vehicles would make negligible overall difference. Therefore, two wheeled vehicles are not considered further in this study.

Buses and coaches, whilst often grouped together because both are public service vehicles, have very different drive cycles and are best considered separately.

The powertrain of coaches are quite similar to those of rigid trucks of up to around 18 tonnes GVW, whereas buses, with their stop-start urban usage have powertrains somewhat different to those of trucks. For both groups of vehicles there are improvements in fuel efficiency that are occurring for new vehicles, both from changes in the powertrain and changes in the rest of the vehicle (e.g. light weighting, or aerodynamics and changes is weight and safety equipment). This was discussed in Section 7.4, using data from the EC Lot 1 report, where a baseline for future fuel use and GHG emissions was developed (see Table 7.3 and Figure 7.13). This concluded that for coaches (and small rigid trucks) over the period 2010 – 2030 an overall 6% improvement in fuel efficiency was predicted, whereas for buses it was 4%. Projecting forward to 2050 the cumulative reductions, relative to 2010, are predicted to be 18% for coaches and 14% for buses.

In summary, we believe that there some evidence to suggest that the assumption of a flat counterfactual for bus and coach efficiency is incorrect and that the CCC should therefore consider revising this assumption in its modelling work. For motorcycles there is insufficient evidence to make a qualified judgement either way, so we would recommend CCC continue to use its existing assumption.

7.6 Capital Costs of Vans, Trucks and Other Vehicles

The purpose of this section was to review the evidence for changes in the capital costs of the dominant vehicle technologies within each vehicle category as another dimension in the development of a baseline scenario.

The cost of an item of technology over a period of time is often difficult to establish because of advances in technology making it extremely difficult to establish a like for like comparison. The capital costs of such items are also affected not only by their intrinsic price but also by:

- The impact of inflation,
- Changes in exchange rates for imported items.

Research into the capital costs of vans, trucks and other vehicles (excluding passenger cars) has provided virtually no hard evidence for trends. In addition to general internet searches, a number of specific sites were visited and searched including:

- SMMT
- ACEA
- FTA
- RHA

Searches aimed to find the evolution of the cost of buying, or operating, vehicles. Whilst it was relatively easy to find trends in the average cost of a commodity, e.g. fuel prices, there was a lack of information on average new prices paid. Data for the number of vehicles sold, or registered, was found, but not for the average price paid.

Further, whilst we have data that would enable the average price of, for examples, new vans to be weighted by sales volume, for 2010 and also for 2008 examination of these shows that the pattern of buying has changed, with the current poorer economic climate leading to a reduction in sales of class III (the heaviest light duty vans) relative to their lighter counterparts, the Class I vans. Consequently, such a comparison, when the effects of inflation are stripped out, are not comparing like for like because of the changing purchasing patterns.

The challenge of comparing like for like data becomes even more challenging for heavy duty vehicles, trucks, buses and coaches. The twin challenges here are the relatively low numbers of units sold (for example the UK fleet comprises around 27 million passenger cars but under 0.4 million trucks) and the wide diversity of different models available. The diversity of trucks often means that each order is close to bespoke, with the basic powertrain vehicle GVW specification being augmented with the type of cab, and all the accessory options being offered. The ordering of a truck (or fleet of trucks) is therefore more complex than for passenger cars. Furthermore, with the flexibilities in vehicle accessory specifications there are also flexibilities in price. Hence, whilst there are generic guide prices, the price paid by a customer for heavy duty vehicle(s) is also bespoke. All these factors go some way towards explaining why what is conceptually simple, trends in average price, is both difficult to find, and when data are available, difficult to interpret.

At a qualitative level it can be reasoned that there are a number of different manufacturers for trucks, buses, coaches and other vehicles. The competition of the free market leads to there being a “current going price” for like for like new vehicles. As time passes there are two competing driving forces on price:

- The desire of manufacturers to maintain, indeed to increase, their market share means that innovation and efficiencies in production generally cause like for like vehicles to become less expensive over time, despite there being advances in technology.
- The regulations that vehicles have to comply with, in terms of emissions, and safety, force vehicle manufacturers to adopt certain technologies otherwise their vehicle will not be certified for sale. This drive leads to vehicles generally becoming more expensive over time.

These two factors generate pressures in opposite directions. To a first approximation it is assumed**: that the price of new vehicles has remained relatively flat** (in real terms for like for like vehicle utility) **over the last 20 years but that the sophistication of vehicles has markedly increased.**

In summary, we believe that there is not sufficiently strong evidence to suggest that the assumption of a flat counterfactual is incorrect and that the CCC should therefore continue to use this assumption in its modelling work for the capital costs of other vehicles.

7.7 Summary of Recommendations

The following Table 7.5 provides a summary of this study’s recommendations in terms of future changes in the vehicle fuel consumption for the dominant vehicle technologies within each vehicle category in the absence of any government policy to reduce GHG emissions.

It should be noted that the estimates provided in Table 7.5 assume no changes in average vehicle sizes in each category, nor changes in average loading/utilisation of capacity by weight. For heavy duty trucks in particular there has been a historic trend in both increasing vehicle size within the broad weight categories, and improvements in utilisation are likely to have increased the average weight of the loads carried. These effects have appear to have counter-acted the overall improvements in vehicle efficiency seen at a vehicle level historically. If it were possible to suitably quantify further changes in these aspects in the future, the resulting impacts on fuel consumption should be taken into account. It was not possible to account for such effects for this study.

The study has found that there is either *no evidence* or *no sufficiently strong evidence* to suggest that the current assumption on costs is incorrect – i.e. that costs will remain approximately constant in the absence of any government policy to reduce GHG emissions.

Table 7.5: Recommended projection of changes in road vehicle fuel consumption in the absence of any government policy to reduce GHG emissions*

Mode	Category	Projected % change in fuel consumption				
		2010	2020	2030	2040	2050
Cars	All	0.0%	0.0%	0.0%	0.0%	0.0%
Vans	All	0.0%	-2.2%	-4.8%	-7.3%	-9.9%
Motorcycles	All	0.0%	0.0%	0.0%	0.0%	0.0%
Heavy Duty Trucks	Small rigid	0.0%	3.0%	-0.1%	-3.0%	-5.9%
	Large rigid	0.0%	-0.1%	-5.9%	-11.4%	-16.6%
	Articulated	0.0%	-2.1%	-9.6%	-16.6%	-23.0%
	Construction	0.0%	3.0%	-0.1%	-3.0%	-5.9%
Buses and Coaches	Bus	0.0%	0.9%	-4.0%	-8.7%	-13.2%
	Coach	0.0%	-0.1%	-5.9%	-11.4%	-16.6%

Notes: * Estimates assume no changes in average vehicle sizes in each category, nor changes in average loading/utilisation of capacity by weight.

8 References

This section provides a complete summary of all references for this study (i.e. including reviewed principal literature sources that are not directly referred to in the report body).

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Appendices

Appendix 1: Technology Specific Characteristics

Appendix 1 – Technology Specific Characteristics

This appendix provides information on the assumptions for specific vehicle and powertrain characteristics for all vehicle types used in the study calculations.

Table A1: Technology Specific Characteristics for all vehicle types

Category	Item	Powertrain	2010	2020	2030	2040	2050
Car	New vehicle lifetime, years	All	14	14	14	14	14
Car	ICE range (km)	NG ICE	500	500	500	500	500
Car		Other	500	500	500	500	500
Car	Hydrogen range (km)	H2FC	500	500	500	500	500
Car	Electric range (km)	Petrol HEV	2	2	2	2	2
Car		Diesel HEV	2	2	2	2	2
Car		Petrol PHEV	30	30	30	30	30
Car		Diesel PHEV	30	30	30	30	30
Car		Petrol REEV	60	60	60	60	60
Car		Diesel REEV	60	60	60	60	60
Car		H2FC	2	2	2	2	2
Car		H2FC PHEV	30	30	30	30	30
Car		H2FC REEV	60	60	60	60	60
Car		BEV	160	200	240	280	320
Car	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE	100%	100%	100%	100%	100%
Car		Diesel ICE	100%	100%	100%	100%	100%
Car		Petrol HEV	100%	100%	100%	100%	100%
Car		Diesel HEV	100%	100%	100%	100%	100%
Car		Petrol PHEV	69%	57%	57%	57%	57%
Car		Diesel PHEV	69%	57%	57%	57%	57%
Car		Petrol REEV	38%	38%	38%	38%	38%
Car		Diesel REEV	38%	38%	38%	38%	38%
Car		BEV	100%	100%	100%	100%	100%
Car		H2FC	100%	100%	100%	100%	100%
Car		H2FC PHEV	69%	57%	57%	57%	57%
Car		H2FC REEV	38%	38%	38%	38%	38%
Car		NG ICE	100%	100%	100%	100%	100%
Car		Diesel FHV					
Car		Diesel HHV					
Car		DNG ICE					
Car	# New vehicles/year (UK approx.)	All	1,996,325	2,934,598	3,081,328	3,235,394	3,397,164
Car	# Fleet vehicles (UK approx.)	All	27,948,550	29,345,978	30,813,276	32,353,940	33,971,637
Car	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Car		HEV	75%	75%	75%	75%	75%
Car		PHEV	75%	75%	75%	75%	75%
Car		REEV	38%	38%	38%	38%	38%
Car		BEV	0%	0%	0%	0%	0%
Car		H2FC	0%	0%	0%	0%	0%
Car	Basic real-world % increase	ICE	19.5%	19.5%	19.5%	19.5%	19.5%
Car		HEV	21.7%	21.7%	21.7%	21.7%	21.7%
Car		PHEV	22.6%	23.0%	23.0%	23.0%	23.0%
Car		REEV	23.5%	23.5%	23.5%	23.5%	23.5%
Car		BEV	24.6%	24.6%	24.6%	24.6%	24.6%
Car		H2FC	24.6%	24.6%	24.6%	24.6%	24.6%
Car	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%

Category	Item	Powertrain	2010	2020	2030	2040	2050
Car	Ratio fuel cell size to max power	H2FC REEV	50.0%	50.0%	50.0%	50.0%	50.0%
Car	% Max power ICE for electrified drivetrains	BEV	85.1%	85.1%	85.1%	85.1%	85.1%
Car		H2FC	85.1%	85.1%	85.1%	85.1%	85.1%
Car		REEV	138.1%	138.1%	138.1%	138.1%	138.1%
Car		Other	124.8%	124.8%	124.8%	124.8%	124.8%
Van	New vehicle lifetime, years	All	14	14	14	14	14
Van	ICE range (km)	NG ICE	500	500	500	500	500
Van		Other	500	500	500	500	500
Van	Hydrogen range (km)	H2FC	500	500	500	500	500
Van	Electric range (km)	Petrol HEV	2	2	2	2	2
Van		Diesel HEV	2	2	2	2	2
Van		Petrol PHEV	30	30	30	30	30
Van		Diesel PHEV	30	30	30	30	30
Van		Petrol REEV	60	60	60	60	60
Van		Diesel REEV	60	60	60	60	60
Van		H2FC	2	2	2	2	2
Van		H2FC PHEV	30	30	30	30	30
Van		H2FC REEV	60	60	60	60	60
Van		BEV	160	200	240	280	320
Van	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE	100%	100%	100%	100%	100%
Van		Diesel ICE	100%	100%	100%	100%	100%
Van		Petrol HEV	100%	100%	100%	100%	100%
Van		Diesel HEV	100%	100%	100%	100%	100%
Van		Petrol PHEV	69%	57%	57%	57%	57%
Van		Diesel PHEV	69%	57%	57%	57%	57%
Van		Petrol REEV	38%	38%	38%	38%	38%
Van		Diesel REEV	38%	38%	38%	38%	38%
Van		BEV	100%	100%	100%	100%	100%
Van		H2FC	100%	100%	100%	100%	100%
Van		H2FC PHEV	69%	57%	57%	57%	57%
Van		H2FC REEV	38%	38%	38%	38%	38%
Van		NG ICE	100%	100%	100%	100%	100%
Van		Diesel FHV					
Van		Diesel HHV					
Van		DNG ICE					
Van	# New vehicles/year (UK approx.)	All	226,135	332,418	349,039	366,491	384,816
Van	# Fleet vehicles (UK approx.)	All	3,165,890	3,324,185	3,490,394	3,664,913	3,848,159
Van	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Van		HEV	75%	75%	75%	75%	75%
Van		PHEV	75%	75%	75%	75%	75%
Van		REEV	38%	38%	38%	38%	38%
Van		BEV	0%	0%	0%	0%	0%
Van		H2FC	0%	0%	0%	0%	0%
Van	Basic real-world % increase	ICE	19.5%	19.5%	19.5%	19.5%	19.5%
Van		HEV	21.7%	21.7%	21.7%	21.7%	21.7%
Van		PHEV	22.6%	23.0%	23.0%	23.0%	23.0%
Van		REEV	23.5%	23.5%	23.5%	23.5%	23.5%
Van		BEV	24.6%	24.6%	24.6%	24.6%	24.6%
Van		H2FC	24.6%	24.6%	24.6%	24.6%	24.6%
Van	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Van	Ratio fuel cell size to max power	H2FC REEV	50.0%	50.0%	50.0%	50.0%	50.0%
Van	% Max power ICE for	BEV	85.1%	85.1%	85.1%	85.1%	85.1%

Category	Item	Powertrain	2010	2020	2030	2040	2050
Van	electrified drivetrains	H2FC	85.1%	85.1%	85.1%	85.1%	85.1%
Van		REEV	138.1%	138.1%	138.1%	138.1%	138.1%
Van		Other	124.8%	124.8%	124.8%	124.8%	124.8%
Small rigid	New vehicle lifetime, years	All	12	12	12	12	12
Small rigid	ICE range (km)	NG ICE	500	500	500	500	500
Small rigid		Other	500	500	500	500	500
Small rigid	Hydrogen range (km)	H2FC	500	500	500	500	500
Small rigid	Electric range (km)	Petrol HEV	2	2	2	2	2
Small rigid	Electric range (km)	Diesel HEV	2	2	2	2	2
Small rigid		Petrol PHEV					
Small rigid		Diesel PHEV					
Small rigid		Petrol REEV					
Small rigid		Diesel REEV					
Small rigid		H2FC	2	2	2	2	2
Small rigid		H2FC PHEV					
Small rigid		H2FC REEV					
Small rigid		BEV	160	200	240	280	320
Small rigid	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE					
Small rigid		Diesel ICE	100%	100%	100%	100%	100%
Small rigid		Petrol HEV					
Small rigid		Diesel HEV	100%	100%	100%	100%	100%
Small rigid		Petrol PHEV					
Small rigid		Diesel PHEV					
Small rigid		Petrol REEV					
Small rigid		Diesel REEV					
Small rigid		BEV	100%	100%	100%	100%	100%
Small rigid		H2FC	100%	100%	100%	100%	100%
Small rigid		H2FC PHEV					
Small rigid		H2FC REEV					
Small rigid		NG ICE	100%	100%	100%	100%	100%
Small rigid		Diesel FHV	100%	100%	100%	100%	100%
Small rigid		Diesel HHV	100%	100%	100%	100%	100%
Small rigid		DNG ICE	60%	60%	60%	60%	60%
Small rigid	# New vehicles/year (UK approx.)	All	11,206	14,120	14,826	15,567	16,346
Small rigid	# Fleet vehicles (UK approx.)	All	134,476	141,200	148,260	155,673	163,456
Small rigid	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Small rigid		HEV	75%	75%	75%	75%	75%
Small rigid		FHV	80%	80%	80%	80%	80%
Small rigid		HHV	80%	80%	80%	80%	80%
Small rigid		BEV	0%	0%	0%	0%	0%
Small rigid		H2FC	0%	0%	0%	0%	0%
Small rigid	Basic real-world % increase	ICE	41.3%	41.3%	41.3%	41.3%	41.3%
Small rigid		HEV	42.5%	42.5%	42.5%	42.5%	42.5%
Small rigid		FHV	42.5%	42.5%	42.5%	42.5%	42.5%
Small rigid		HHV	42.5%	42.5%	42.5%	42.5%	42.5%
Small rigid		BEV	43.9%	43.9%	43.9%	43.9%	43.9%
Small rigid		H2FC	43.9%	43.9%	43.9%	43.9%	43.9%
Small rigid	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Small rigid	Ratio fuel cell size to max power	H2FC REEV					
Small rigid	% Max power ICE for electrified drivetrains	BEV	85%	85%	85%	85%	85%
Small rigid		H2FC	85%	85%	85%	85%	85%
Small rigid		Other	125%	125%	125%	125%	125%
Large rigid	New vehicle lifetime, years	All	10	10	10	10	10

Category	Item	Powertrain	2010	2020	2030	2040	2050
Large rigid	ICE range (km)	NG ICE	500	500	500	500	500
Large rigid		Other	500	500	500	500	500
Large rigid	Hydrogen range (km)	H2FC	500	500	500	500	500
Large rigid	Electric range (km)	Petrol HEV	2	2	2	2	2
Large rigid	Electric range (km)	Diesel HEV	2	2	2	2	2
Large rigid		Petrol PHEV					
Large rigid		Diesel PHEV					
Large rigid		Petrol REEV					
Large rigid		Diesel REEV					
Large rigid		H2FC	2	2	2	2	2
Large rigid		H2FC PHEV					
Large rigid		H2FC REEV					
Large rigid		BEV					
Large rigid	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE					
Large rigid		Diesel ICE	100%	100%	100%	100%	100%
Large rigid		Petrol HEV					
Large rigid		Diesel HEV	100%	100%	100%	100%	100%
Large rigid		Petrol PHEV					
Large rigid		Diesel PHEV					
Large rigid		Petrol REEV					
Large rigid		Diesel REEV					
Large rigid		BEV					
Large rigid		H2FC	100%	100%	100%	100%	100%
Large rigid		H2FC PHEV					
Large rigid		H2FC REEV					
Large rigid		NG ICE	100%	100%	100%	100%	100%
Large rigid		Diesel FHV	100%	100%	100%	100%	100%
Large rigid		Diesel HHV	100%	100%	100%	100%	100%
Large rigid		DNG ICE	70%	70%	70%	70%	70%
Large rigid	# New vehicles/year (UK approx.)	All	9,167	9,625	10,106	10,611	11,142
Large rigid	# Fleet vehicles (UK approx.)	All	91,666	96,249	101,062	106,115	111,421
Large rigid	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Large rigid		HEV	75%	75%	75%	75%	75%
Large rigid		FHV	80%	80%	80%	80%	80%
Large rigid		HHV	80%	80%	80%	80%	80%
Large rigid		BEV	0%	0%	0%	0%	0%
Large rigid		H2FC	0%	0%	0%	0%	0%
Large rigid	Basic real-world % increase	ICE	9.0%	9.0%	9.0%	9.0%	9.0%
Large rigid		HEV	10.1%	10.1%	10.1%	10.1%	10.1%
Large rigid		FHV	10.1%	10.1%	10.1%	10.1%	10.1%
Large rigid		HHV	10.1%	10.1%	10.1%	10.1%	10.1%
Large rigid		BEV					
Large rigid		H2FC	11.5%	11.5%	11.5%	11.5%	11.5%
Large rigid	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Large rigid	Ratio fuel cell size to max power	H2FC REEV					
Large rigid	% Max power ICE for electrified drivetrains	BEV					
Large rigid		H2FC	85%	85%	85%	85%	85%
Large rigid		Other	125%	125%	125%	125%	125%
Articulated	New vehicle lifetime, years	All	10	10	10	10	10
Articulated	ICE range (km)	NG ICE	1000	1000	1000	1000	1000
Articulated		Other	1000	1000	1000	1000	1000
Articulated	Hydrogen range (km)	H2FC	1000	1000	1000	1000	1000
Articulated	Electric range (km)	Petrol HEV	2	2	2	2	2

Category	Item	Powertrain	2010	2020	2030	2040	2050
Articulated	Electric range (km)	Diesel HEV	2	2	2	2	2
Articulated		Petrol PHEV					
Articulated		Diesel PHEV					
Articulated		Petrol REEV					
Articulated		Diesel REEV					
Articulated		H2FC	2	2	2	2	2
Articulated		H2FC PHEV					
Articulated		H2FC REEV					
Articulated		BEV					
Articulated	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE					
Articulated		Diesel ICE	100%	100%	100%	100%	100%
Articulated		Petrol HEV					
Articulated		Diesel HEV	100%	100%	100%	100%	100%
Articulated		Petrol PHEV					
Articulated		Diesel PHEV					
Articulated		Petrol REEV					
Articulated		Diesel REEV					
Articulated		BEV					
Articulated		H2FC	100%	100%	100%	100%	100%
Articulated		H2FC PHEV					
Articulated		H2FC REEV					
Articulated		NG ICE	100%	100%	100%	100%	100%
Articulated		Diesel FHV	100%	100%	100%	100%	100%
Articulated		Diesel HHV	100%	100%	100%	100%	100%
Articulated		DNG ICE	75%	75%	75%	75%	75%
Articulated	# New vehicles/year (UK approx.)	All	17,037	17,889	18,784	19,723	20,709
Articulated	# Fleet vehicles (UK approx.)	All	170,374	178,893	187,837	197,229	207,091
Articulated	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Articulated		HEV	75%	75%	75%	75%	75%
Articulated		FHV	80%	80%	80%	80%	80%
Articulated		HHV	80%	80%	80%	80%	80%
Articulated		BEV					
Articulated		H2FC	0%	0%	0%	0%	0%
Articulated	Basic real-world % increase	ICE	0.0%	0.0%	0.0%	0.0%	0.0%
Articulated		HEV	1.1%	1.1%	1.1%	1.1%	1.1%
Articulated		FHV	1.1%	1.1%	1.1%	1.1%	1.1%
Articulated		HHV	1.1%	1.1%	1.1%	1.1%	1.1%
Articulated		BEV					
Articulated		H2FC	2.6%	2.6%	2.6%	2.6%	2.6%
Articulated	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Articulated	Ratio fuel cell size to max power	H2FC REEV					
Articulated	% Max power ICE for electrified drivetrains	BEV					
Articulated		H2FC	85%	85%	85%	85%	85%
Articulated		Other	125%	125%	125%	125%	125%
Construction	New vehicle lifetime, years	All	10	10	10	10	10
Construction	ICE range (km)	NG ICE	500	500	500	500	500
Construction		Other	500	500	500	500	500
Construction	Hydrogen range (km)	H2FC	500	500	500	500	500
Construction	Electric range (km)	Petrol HEV	2	2	2	2	2
Construction	Electric range (km)	Diesel HEV	2	2	2	2	2
Construction		Petrol PHEV					
Construction		Diesel PHEV					
Construction		Petrol REEV					

Category	Item	Powertrain	2010	2020	2030	2040	2050
Construction		Diesel REEV					
Construction		H2FC	2	2	2	2	2
Construction		H2FC PHEV					
Construction		H2FC REEV					
Construction		BEV					
Construction	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE					
Construction		Diesel ICE	100%	100%	100%	100%	100%
Construction		Petrol HEV					
Construction		Diesel HEV	100%	100%	100%	100%	100%
Construction		Petrol PHEV					
Construction		Diesel PHEV					
Construction		Petrol REEV					
Construction		Diesel REEV					
Construction		BEV					
Construction		H2FC	100%	100%	100%	100%	100%
Construction		H2FC PHEV					
Construction		H2FC REEV					
Construction		NG ICE	100%	100%	100%	100%	100%
Construction		Diesel FHV	100%	100%	100%	100%	100%
Construction		Diesel HHV	100%	100%	100%	100%	100%
Construction		DNG ICE	70%	70%	70%	70%	70%
Construction	# New vehicles/year (UK approx.)	All	7,361	7,729	8,116	8,522	8,948
Construction	# Fleet vehicles (UK approx.)	All	73,612	77,293	81,157	85,215	89,476
Construction	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Construction		HEV	75%	75%	75%	75%	75%
Construction		FHV	80%	80%	80%	80%	80%
Construction		HHV	80%	80%	80%	80%	80%
Construction		BEV					
Construction		H2FC	0%	0%	0%	0%	0%
Construction	Basic real-world % increase	ICE	9.0%	9.0%	9.0%	9.0%	9.0%
Construction		HEV	10.1%	10.1%	10.1%	10.1%	10.1%
Construction		FHV	10.1%	10.1%	10.1%	10.1%	10.1%
Construction		HHV	10.1%	10.1%	10.1%	10.1%	10.1%
Construction		BEV					
Construction		H2FC	11.5%	11.5%	11.5%	11.5%	11.5%
Construction	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Construction	Ratio fuel cell size to max power	H2FC REEV					
Construction	% Max power ICE for electrified drivetrains	BEV					
Construction		H2FC	85%	85%	85%	85%	85%
Construction		Other	125%	125%	125%	125%	125%
Bus	New vehicle lifetime, years	All	15	15	15	15	15
Bus	ICE range (km)	NG ICE	500	500	500	500	500
Bus		Other	500	500	500	500	500
Bus	Hydrogen range (km)	H2FC	500	500	500	500	500
Bus	Electric range (km)	Petrol HEV	2	2	2	2	2
Bus	Electric range (km)	Diesel HEV	2	2	2	2	2
Bus		Petrol PHEV					
Bus		Diesel PHEV					
Bus		Petrol REEV					
Bus		Diesel REEV					
Bus		H2FC	2	2	2	2	2
Bus		H2FC PHEV					
Bus		H2FC REEV					

Category	Item	Powertrain	2010	2020	2030	2040	2050
Bus		BEV	160	200	240	280	320
Bus	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE					
Bus		Diesel ICE	100%	100%	100%	100%	100%
Bus		Petrol HEV					
Bus		Diesel HEV	100%	100%	100%	100%	100%
Bus		Petrol PHEV					
Bus		Diesel PHEV					
Bus		Petrol REEV					
Bus		Diesel REEV					
Bus		BEV	100%	100%	100%	100%	100%
Bus		H2FC	100%	100%	100%	100%	100%
Bus		H2FC PHEV					
Bus		H2FC REEV					
Bus		NG ICE	100%	100%	100%	100%	100%
Bus		Diesel FHV	100%	100%	100%	100%	100%
Bus		Diesel HHV	100%	100%	100%	100%	100%
Bus		DNG ICE	60%	60%	60%	60%	60%
Bus	# New vehicles/year (UK approx.)	All	5,352	8,429	8,851	9,293	9,758
Bus	# Fleet vehicles (UK approx.)	All	80,280	84,294	88,509	92,934	97,581
Bus	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Bus		HEV	75%	75%	75%	75%	75%
Bus		FHV	80%	80%	80%	80%	80%
Bus		HHV	80%	80%	80%	80%	80%
Bus		BEV	0%	0%	0%	0%	0%
Bus		H2FC	0%	0%	0%	0%	0%
Bus	Basic real-world % increase	ICE	8.8%	8.8%	8.8%	8.8%	8.8%
Bus		HEV	9.9%	9.9%	9.9%	9.9%	9.9%
Bus		FHV	9.9%	9.9%	9.9%	9.9%	9.9%
Bus		HHV	9.9%	9.9%	9.9%	9.9%	9.9%
Bus		BEV	11.4%	11.4%	11.4%	11.4%	11.4%
Bus		H2FC	11.4%	11.4%	11.4%	11.4%	11.4%
Bus	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Bus	Ratio fuel cell size to max power	H2FC REEV					
Bus	% Max power ICE for electrified drivetrains	BEV	85%	85%	85%	85%	85%
Bus		H2FC	85%	85%	85%	85%	85%
Bus		Other	125%	125%	125%	125%	125%
Coach	New vehicle lifetime, years	All	15	15	15	15	15
Coach	ICE range (km)	NG ICE	500	500	500	500	500
Coach		Other	500	500	500	500	500
Coach	Hydrogen range (km)	H2FC	500	500	500	500	500
Coach	Electric range (km)	Petrol HEV	2	2	2	2	2
Coach	Electric range (km)	Diesel HEV	2	2	2	2	2
Coach		Petrol PHEV					
Coach		Diesel PHEV					
Coach		Petrol REEV					
Coach		Diesel REEV					
Coach		H2FC	2	2	2	2	2
Coach		H2FC PHEV					
Coach		H2FC REEV					
Coach		BEV					
Coach	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE					
Coach		Diesel ICE	100%	100%	100%	100%	100%

Category	Item	Powertrain	2010	2020	2030	2040	2050
Coach		Petrol HEV					
Coach		Diesel HEV	100%	100%	100%	100%	100%
Coach		Petrol PHEV					
Coach		Diesel PHEV					
Coach		Petrol REEV					
Coach		Diesel REEV					
Coach		BEV					
Coach		H2FC	100%	100%	100%	100%	100%
Coach		H2FC PHEV					
Coach		H2FC REEV					
Coach		NG ICE	100%	100%	100%	100%	100%
Coach		Diesel FHV	100%	100%	100%	100%	100%
Coach		Diesel HHV	100%	100%	100%	100%	100%
Coach		DNG ICE	70%	70%	70%	70%	70%
Coach	# New vehicles/year (UK approx.)	All	3,568	5,620	5,901	6,196	6,505
Coach	# Fleet vehicles (UK approx.)	All	53,520	56,196	59,006	61,956	65,054
Coach	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Coach		HEV	75%	75%	75%	75%	75%
Coach		FHV	80%	80%	80%	80%	80%
Coach		HHV	80%	80%	80%	80%	80%
Coach		BEV					
Coach		H2FC	0%	0%	0%	0%	0%
Coach	Basic real-world % increase	ICE	9.0%	9.0%	9.0%	9.0%	9.0%
Coach		HEV	10.1%	10.1%	10.1%	10.1%	10.1%
Coach		FHV	10.1%	10.1%	10.1%	10.1%	10.1%
Coach		HHV	10.1%	10.1%	10.1%	10.1%	10.1%
Coach		BEV					
Coach		H2FC	11.5%	11.5%	11.5%	11.5%	11.5%
Coach	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Coach	Ratio fuel cell size to max power	H2FC REEV					
Coach	% Max power ICE for electrified drivetrains	BEV					
Coach		H2FC	85%	85%	85%	85%	85%
Coach		Other	125%	125%	125%	125%	125%
Motorcycle	New vehicle lifetime, years	All	12	12	12	12	12
Motorcycle	ICE range (km)	H2ICE	150	175	200	225	250
Motorcycle		Other	300	300	300	300	300
Motorcycle	Hydrogen range (km)	H2FC	200	225	250	275	300
Motorcycle	Electric range (km)	Petrol HEV	2	2	2	2	2
Motorcycle		H2FC	2	2	2	2	2
Motorcycle		BEV	50	75	100	125	150
Motorcycle	Distance in fuel mode 1 (ICE/H2/NG) (%)	Petrol ICE	100%	100%	100%	100%	100%
Motorcycle		Petrol HEV	100%	100%	100%	100%	100%
Motorcycle		BEV	100%	100%	100%	100%	100%
Motorcycle		H2FC	100%	100%	100%	100%	100%
Motorcycle	# New vehicles/year (UK approx.)	All	100,090	100,090	100,090	100,090	100,090
Motorcycle	# Fleet vehicles (UK approx.)	All	1,234,369	1,234,369	1,234,369	1,234,369	1,234,369
Motorcycle	ICE sizing as % Max Power (*inverse* DOH)	ICE	100%	100%	100%	100%	100%
Motorcycle		HEV	75%	75%	75%	75%	75%
Motorcycle		BEV	0%	0%	0%	0%	0%
Motorcycle		H2FC	0%	0%	0%	0%	0%
Motorcycle	Basic real-world %	ICE	30.2%	30.2%	30.2%	30.2%	30.2%

Category	Item	Powertrain	2010	2020	2030	2040	2050
Motorcycle	increase	HEV	30.2%	30.2%	30.2%	30.2%	30.2%
Motorcycle		BEV	24.6%	24.6%	24.6%	24.6%	24.6%
Motorcycle		H2FC	24.6%	24.6%	24.6%	24.6%	24.6%
Motorcycle	Battery usable SOC for electric range	All	70%	70%	80%	85%	90%
Motorcycle	Ratio fuel cell size to max power	H2FC REEV					
Motorcycle	% Max power ICE for electrified drivetrains	BEV	85.1%	85.1%	85.1%	85.1%	85.1%
Motorcycle		H2FC	85.1%	85.1%	85.1%	85.1%	85.1%
Motorcycle		Other	124.8%	124.8%	124.8%	124.8%	124.8%

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