elementenergy

Influences on the Low Carbon Car Market from 2020–2030

Final Report

for

Low Carbon Vehicle Partnership

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Contents

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Caveat

While the authors consider that the data and opinions contained in this report are sound, all parties must rely upon their own skill and judgement when using it. The authors do not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the report.

Glossary

AA	The Automotive Association
Alternative vehicles	Vehicles using any powertrain technology in addition to the ICE architecture
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
Charge/Discharge cycle	One full cycle of a battery; discharging and recharging the battery by 80% of its quoted usable capacity
CO_2	All values are in Carbon Dioxide Equivalent (CO_2e)
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DOD	Depth of discharge
Electric range	The distances over which a vehicle can travel in pure electric mode
EV	Battery Electric Vehicle
FC	Fuel Cell
Glider	Vehicle chassis and non-powertrain specific components
Hybrid vehicle	ICE vehicle with additional electric drivetrain allowing the vehicle to travel up to 2km in electric mode
Hydrocarbon fuel	A petrol or diesel fuel, used throughout in a ‘blend’ of fuel properties
Hydrogen RE-EV	An electric vehicle range extended by a hydrogen fuel cell
Hydrogen vehicle	Vehicle powered by a hydrogen fuel cell
ICE	Internal Combustion Engine
Low CVP	Low Carbon Vehicle Partnership
MIT	Massachusetts Institute of Technology
MPG	Miles Per Gallon
MPV	Multi-Purpose Vehicle
NTS	National Travel Survey
PHEV	Plug-in Hybrid Electric Vehicle
RE-EV	Range Extended Electric Vehicle
SMMT	The Society of Motor Manufactures and Traders
Tailpipe emissions	Emissions produced by the vehicle in use
TCO	Total Cost of Ownership
kWh	Kilowatt hour (unit of energy)
US ABC	United States Advanced Battery Consortium
OEM	Original Equipment Manufacturer
VED	Vehicle Excise Duty
WTW	Well to wheel

1 Executive Summary

1.1 Introduction

Over the next decade EU CO_2 targets will drive a dramatic shift in the types of new cars produced. By 2020 consumers will be faced with a proliferation of low carbon vehicles, using a diversity of fuels and powertrain technologies, as well as increasingly efficient 'conventional cars'. These will represent a very different offer to the consumer compared to today's market, promising lower annual running costs but potentially higher purchase prices. This suggests that the Total Cost of Ownership (TCO) will become a more useful metric for private consumers comparing vehicles than the current focus on purchase price.

If TCO does become the dominant purchase decision metric for private consumers, as it is already for fleet managers, the business of selling (and legislating for) low carbon vehicles will become more complex due to the number of variables defining the TCO. Industry and policy stakeholders need to understand the direction of technology development, so that they can develop new products and business models, or provide cost effective policy support to drive this transition.

This study investigates the factors influencing the total costs of ownership for a wide variety of powertrains in three vehicle size classes, and analyses to what extent low carbon vehicles will close the current cost premium over conventional cars.

1.2 Methodology

The approach to calculating the TCO of alternative vehicles was based on an analysis of vehicle component costs and performance assumptions combined with assumptions on future ongoing cost such as fuel and insurance. All assumptions have been extensively peer-reviewed by the project Steering Group and through consultation with the wider LowCVP membership.

Future vehicle characteristics were defined based on expected incremental improvements of current (2010 model year) vehicles. These vehicles were separated into A&B, C&D and E&H class vehicles. Cost and performance attributes for an 'average' vehicle in each class were then calculated from publicly available data.

Having established suitable 2010 baseline vehicles, performance evolutions were applied to generate the vehicle properties in 2020, 2025 and 2030. The vehicles powertrains considered were:

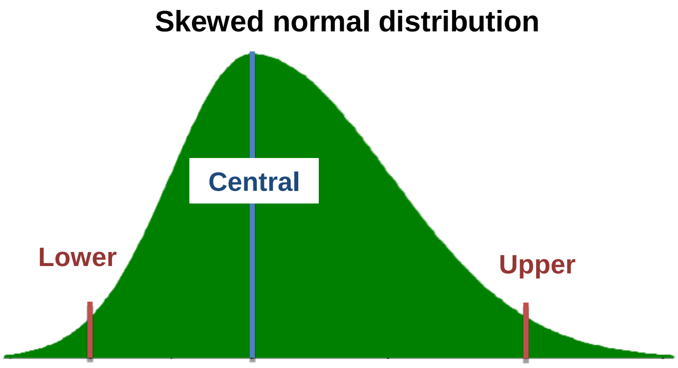
- Conventional internal combustion engine vehicles
- 'Conventional', non-plug-in hybrids
- A Plug-in Hybrid Electric Vehicle (PHEV) with a 30km electric range
- A Range-Extended Electric Vehicle (RE-EV) with a 60km electric range
- Battery electric vehicles
- Two H_2 fuel cell cars, in hybridised and non-hybridised configurations.

Capital costs for each powertrain were calculated by starting with a common 'glider' (body plus chassis without powertrain components). For each vehicle type, powertrain components were then specified and costed separately and added to generate a final selling price. All additional drivetrain specific costs were costed using a lower, central and upper bound to generate a distribution for future vehicle costs.

The following ongoing costs were added to the capital costs to calculate the total costs of ownership for each vehicle type:

- Fuel and electricity costs, based on trip statistics data from the National Travel Survey and improvements on current vehicles.
- Insurance costs, taking into account overall market trends as well as specific costs for insuring novel powertrains
- Servicing and maintenance costs
- Depreciation

The distributions constructed for each component in the TCO were then used in a Monte Carlo analysis, to generate an overall distribution of total costs for each vehicle. This approach provides clear insight into the degree of 'overlap' in the costs of competing technologies, as well as an assessment of the most likely values.



Following the Monte Carlo analysis, a series of scenarios was used to test the effects of disruptive changes in technology costs and macroeconomic factors on the economics of low carbon cars. The scenarios considered included;

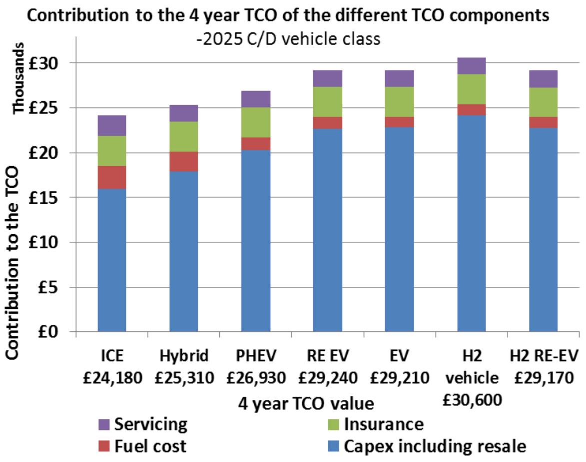
- Policy interventions to equalise the TCO for low carbon and conventional cars
- Battery and fuel cell cost reductions
- Fuel shocks inflating the fuel price
- The use of different discount rates
- The effect of changing the ownership period on the TCO calculation.

Key TCO assumptions:

- TCO calculation performed over 4 years
- A discount rate of 10% was used throughout
- Fuel costs and emissions factors taken from DECC for hydrocarbons and electricity. The hydrogen costs were taken from McKinsey's Powertrains for Europe study and the emissions factors from the Well-to-Wheel report by Concawe.
- The analysis takes into account the resale value of the vehicle in year 4
- Insurance costs were deduced from the historical evolution of insurance costs
- Annual vehicle mileage of 15,000km was used

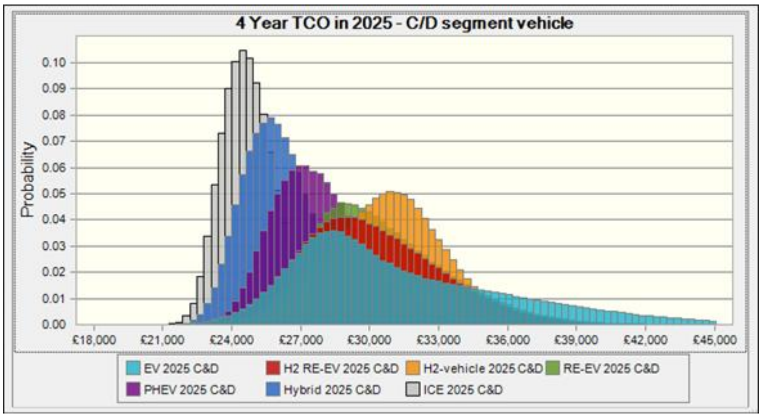
1.3 Results

Our analysis shows that low carbon cars make substantial progress in bridging the current cost gap between 2010 and 2030. By 2025, the TCO premium for plug-in vehicles has decreased to £2,700 for the PHEV and £5,000 for the pure EV and RE-EV. In 2010, this cost differential is closer to £20,000 for the pure EV, excluding current incentives and OEM discounts.



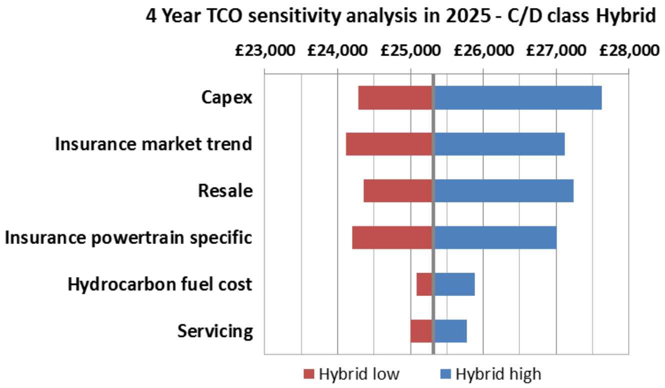
The capital cost of the vehicles is the most important factor affecting the TCO throughout the modelled period. As the fuel types of the vehicles move away from hydrocarbon fuels towards hydrogen and electrically fuelled vehicles the fuel cost proportion of the TCO decreases significantly. Although the ongoing costs are significantly lower for alternative vehicles this is more than offset by their increased selling prices.

The Monte Carlo analysis shows the probability distributions of the four year TCOs of the different vehicle types. These distributions give an indication of the likely ranges of the TCO for the different vehicle types.



The ICE and hybrid vehicles have the lowest TCOs. The spread of their TCOs are much smaller than the alternative vehicles as there is much more certainty about the capital costs of these vehicles. All of the alternative vehicles have a wide distribution on possible TCOs, particularly the EV where battery costs are the biggest contributor to the total vehicle cost.

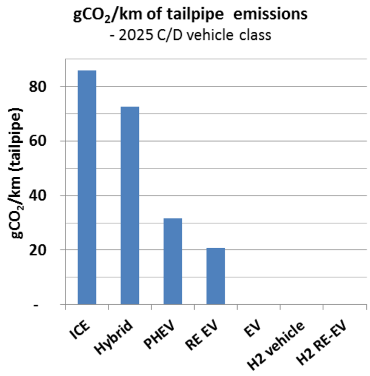
By 2030 the distributions of the TCOs for different powertrains have narrowed and have started to converge to £2k–£3k more than the ICE vehicle. Plug-in vehicles now have a higher TCO than EVs, which implies that there is a cross-over point where providing extra battery capacity is cheaper than the additional costs of a hybrid-powertrain. This assumes that by this time the range of battery electric vehicles (240km for a medium size car) is sufficient to meet consumers' needs. Where greater range is required, H_2 vehicles are considerably more cost-effective than battery electric vehicles.

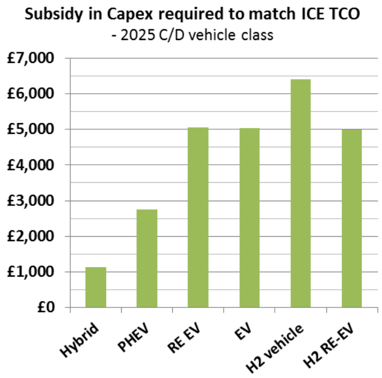


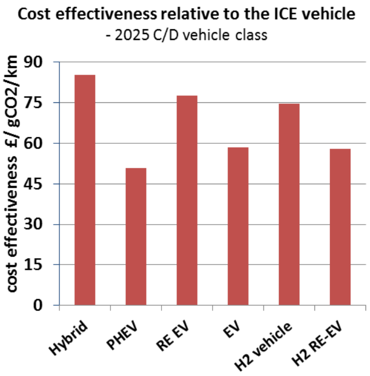
Future insurance costs could have a significant impact on the relative attractiveness of low carbon vehicles. Insurance costs have risen by 200% in real terms in the last 17 years, with a 40% rise in 2010 alone. Rising insurance costs make an increasingly large contribution to the costs of running a car, and have the effect of 'masking' the fuel bill savings of low carbon cars. An additional factor in insurance costs is whether premiums will be higher for novel powertrains such as battery electric vehicles, due to uncertainty over costs of repairs or due to their higher purchase prices. Higher insurance costs for low carbon vehicles, if they persist, will potentially negate a significant proportion of their fuel bill savings.

The relative cost effectiveness of each low carbon powertrain can be quantified by calculating the financial support required to equalise its Total Cost of Ownership with that of a conventional ICE car and dividing by the relative CO_2 savings per kilometre. This '£/g/km' metric allows all powertrains to be compared against the conventional ICE car in a given year.

The figures below show that the PHEV is the most cost-effective solution for reducing tailpipe emissions in 2025. This vehicle is able to electrify a large number of trips at a low on-cost relative to conventional cars. A RE-EV with a higher range lowers emissions and fuel costs (by £70-£100 per year), but this is outweighed by the cost of a larger battery, even based on 2030 battery costs. The tailpipe emissions of PHEVs are projected to reach c.30gCO_2/km by 2030, with incentives equivalent to £750 per year required to be competitive against a conventional car. More stringent emissions targets (below 30g/km) will require deployment of H_2 and pure electric vehicles. Our analysis suggests that these vehicles will have similar TCOs over the 2020-2030 timeframe, and the relative market shares will depend on other factors such as vehicle functionality and the availability of recharging versus refuelling infrastructure.


gCO_2/km of tailpipe emissions
- 2025 C/D vehicle class


Subsidy in Capex required to match ICE TCO
- 2025 C/D vehicle class


Cost effectiveness relative to the ICE vehicle
- 2025 C/D vehicle class

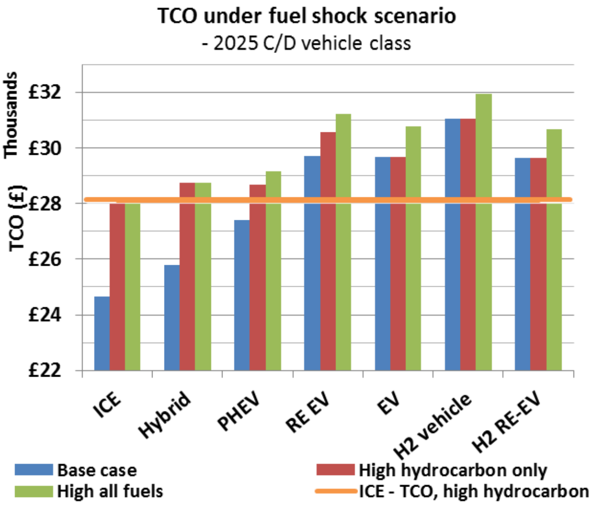
Scenarios

We conducted a sensitivity analysis on the components contributing to the total cost of ownership of low carbon cars, to investigate the effects of disruptive events or step-changes, for example in technology costs or fuel prices.

Battery and fuel cell cost reductions

With large reductions in battery and fuel cell costs (to £67/kWh and £20/kW respectively) EVs and hydrogen RE-EVs become cost comparable to ICE vehicles on a TCO basis. This suggests that a radical reduction in the costs of these components (beyond the cost reductions assumed in the first part of this study) will be required if pure EVs and H_2 vehicles are to compete against conventional vehicles without ongoing incentives or regulation.

Fuel Shocks



Significant fuel prices rises go some way to levelling the TCO across the various powertrains. Fuel prices of £3/l (in real terms) for hydrocarbon fuel, 40p/kWh for electricity and £8/kg of hydrogen were used. This is almost sufficient to equalise the TCOs of the conventional car and the PHEV. The differential for the pure EV also drops from £5,000 to only £1,500. It is also clear that the pure EV is relatively insensitive to the costs of electricity (even with a tripling relative to today's prices). This may become a key selling point for EVs, especially compared with the exposure of the conventional car to shocks in fuel prices.

1.4 Conclusions

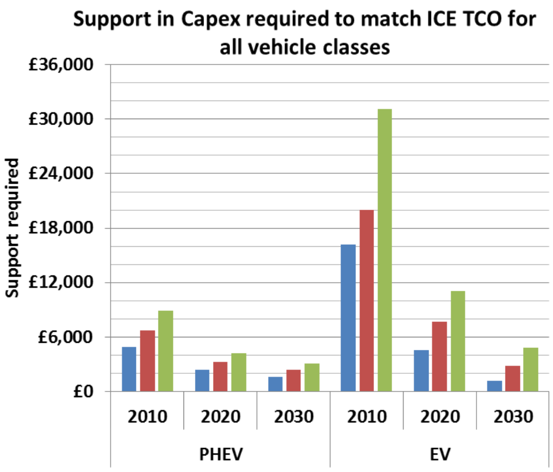
Headlines

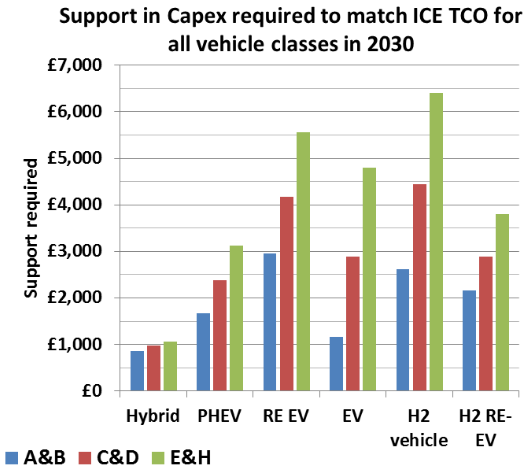
1. The TCO of alternative vehicles in relation to conventional ICE vehicles narrows substantially over the coming decade. It narrows further from 2020-2030 in most scenarios.
2. Conventional cars using improved internal combustion engines have lower total costs of ownership than electric or hydrogen powertrains throughout the modelled period to 2030.
3. 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.
4. As the conventional ICE vehicles increases in efficiency the effect of changes in fuel cost become less important as fuel costs contribute to a lower portion of the TCO.
5. Other factors such as insurance have an increasingly large effect on the TCO of vehicles if current trends continue. Differentials in insurance or maintenance costs between conventional and low carbon cars must be minimised if drivers are to benefit from the significantly lower fuel costs of new technologies.

Vehicle Costs

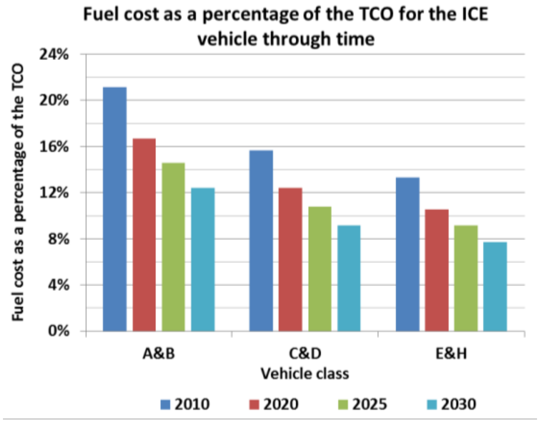
- Conventional cars provide the lowest total costs of ownership of all powertrains in 2010, before incentives are taken into account.
    - The current capital cost premium for plug-in vehicles of over £10,000 (for the C&D class) far outweighs the benefits of lower ongoing costs.
    - This continues through to 2030 with the increase in ICE vehicle efficiency offsetting the increase in the ICE vehicle capital costs. This allows the TCO of ICE vehicles to remain relatively constant with only a slight increase with time.

- By 2020, low carbon vehicles are expected to make substantial progress in bridging the current differential in the TCOs. There is however still a cost premium for alternative vehicles in 2030. The premium for the pure EV drops from £20,000 in 2010 to £3,000 in 2030, while the PHEV falls from £6,800 to £2,400.





- As battery costs decrease through time, the TCO of the pure EV falls below that of the RE-EV by 2025 for the A&B class and after 2025 for the other vehicle classes. As the extra battery capacity required for the EV becomes cheaper the additional complexity of a hybrid powertrain adds additional costs to the RE-EV. However, we assume that the range of the pure EV is 240km in 2030, which is still substantially below that of a RE-EV or conventional vehicle. If the EV was required to have the same range as a RE-EV or ICE vehicle (>500km) the battery would have to be doubled in capacity, making the EV the most expensive alternative vehicle.



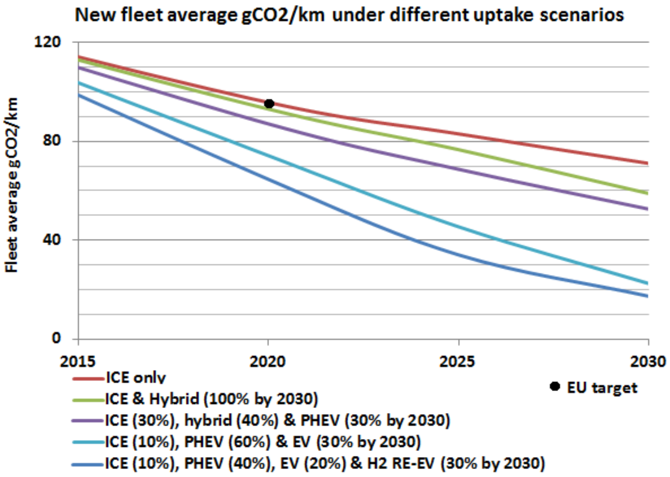
- Battery costs are required to drop below £68/kWh for EVs with a 240km range to be comparable to the ICE vehicle on a TCO basis in 2025. This is considerably lower than what most experts believe is likely or possible with current technology.
- The predicted improvements in conventional internal combustion vehicles over the next 20 years significantly reduce the contribution of fuel costs to total costs of ownership. Improvements in the ICE cars' fuel efficiency are expected to deliver large fuel bill savings in these vehicles, in turn reducing the potential benefit of using an alternative fuel or powertrain. The fuel contribution to the TCO changes from 16% in 2010 (for the C&D class ICE vehicle) to 9% by 2030.
- Delivering the improvements in conventional ICE vehicles will require several major changes in the current market trends in new ICE vehicles. For example, we assume the reversal of the current market trend in increasing vehicle mass, and a shift in focus by OEMs to fuel efficiency over increasing performance. These

improvements in the ICE vehicle with time mean that the alternative vehicles are being compared against a continually improving baseline.

- Pure (non-hybridised) hydrogen vehicles remain the most expensive vehicle option in the central scenario. The fuel cell cost for the hydrogen vehicle remains high, as it is sized to meet the peak load of the vehicle (over 100kW for a C&D vehicle).
- Hydrogen RE-EVs become more attractive as the vehicle size (class) is increased and have an equal or lower TCO to liquid-fuelled RE-EVs post 2025 for vehicle classes C&D and above. A fully hybridised H_2 vehicle offers access to a lower cost fuel (electricity) while delivering the same overall range and functionality of a conventional car with zero tailpipe emissions.
- Business users with high annual driving distances potentially gain the most from vehicles with low running costs per km such as plug-in vehicles. However, since these vehicles deliver their running cost benefits only when using electricity as an energy source, sufficient infrastructure would need to be available to allow charging at the end of individual trips (rather than charging only at home at the end of the working day). Due to their high range, hydrogen cars may offer more cost-effective ultra-low carbon motoring for these high mileage drivers.

Emissions

- The tailpipe emissions of conventional non-hybridised ICE vehicles are expected to fall from 138g/km in 2010 to 74g/km in 2030 for the medium sized (C&D) vehicle. Assuming no changes in market shares of each segment and the future provision for biofuel (10% by energy[1]) the fleet average tailpipe emissions from ICE vehicles changes from 144gCO$_2$/km[2] in 2010 to 71gCO$_2$/km in 2030.



- It is possible for ICE vehicles to deliver the required efficiency savings for the EU new sales fleet average emissions of 95gCO$_2$/km in 2020. Assuming the current market shares for each vehicle segment remain constant, fleet average vehicle emissions from ICE vehicles alone would be 95.7gCO$_2$/km in 2020, including the future provision for biofuels (10% by energy[1]).
- Substantially reducing fleet average emissions after 2020 will require the deployment of non-plug-in and plug-in hybrid vehicles, as ICE vehicles alone can reduce the fleet average emission by a further 14gCO$_2$/km only[3]. The most cost-effective solution to reduce vehicle emissions further is the PHEV with an electric range of approximately 30km. A new car fleet comprised entirely of PHEVs would have emissions of c.30gCO$_2$/km by 2030.

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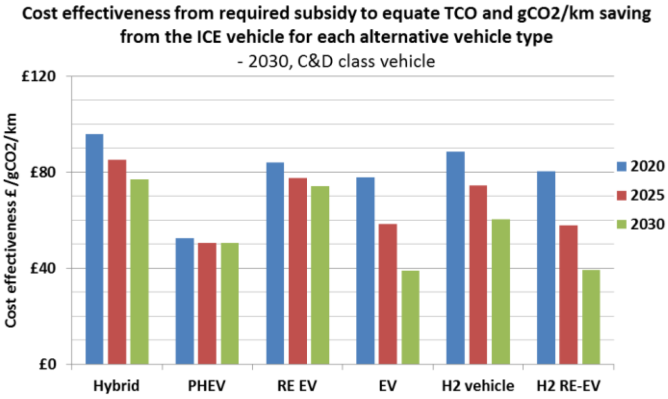
[1] Consistent with the DECC and DfT's projections on biofuel use. The minimum carbon savings this 10% (by energy) of biofuels produces is a 6% reduction in the carbon intensity of the hydrocarbon fuel (Renewable Energy Directive, RED)

[2] SMMT New Car CO$_2$ report 2011

[3] Assuming no change in vehicle sales distributions and no increase in biofuels beyond 10%

- The PHEV continues to outperform the RE-EV (with a 60km range) in terms of cost-effectiveness to 2030, since the cost of providing extra electric range outweighs further reductions in emissions and fuel bills. However, this conclusion is dependent on the real world range electric range (and hence fuel bill savings) offered by these vehicles in under different driving patterns. The hydrogen RE-EV and EV become the most cost effective vehicle technology in the C&D class vehicle in 2030.

- If future vehicle emissions targets move below c.20g/km (tailpipe emissions only), PHEV and RE-EVs cannot deliver this level of reduction even with predicted efficiency improvements in internal combustion engines. Only pure electric and hydrogen vehicles can offer such low tailpipe emissions.



Policy implications

- Current incentives available to all drivers (e.g. differential VED bands) are not sufficient to close the TCO gap between low carbon and conventional cars.

- For drivers who benefit from Congestion Charging and free parking by driving low emission vehicles, the value of these incentives (up to £10,000 over four years) is sufficient to equalise the TCO across all powertrains except the pure hydrogen vehicle by 2020.

- By 2025, the differential in the TCOs requires £870 of incentives per year to break even with the conventional car for the PHEV, and £1590 for the pure EV. This is in addition to the benefits from lower fuel bills.

- The relative cost-effectiveness of the PHEV means that any policy to support plug-in vehicles will lead consumers to favour these vehicles over pure electric ones, unless differential support or exemptions are in place. This suggests that in the long term, current incentives aimed at all plug-in vehicles will need to distinguish between hybrid and fully electric powertrains to ensure that neither is over- or under-supported

- Our analysis suggests that only large fuel price shocks (up to £3/l in 2025) are sufficient to equalise the TCOs of battery electric and conventional cars. This is because fuel prices account for a relatively small portion of the TCO by that year due to efficiency improvements in all powertrains.

Vehicle type	Hybrid	PHEV	RE-EV	EV	H_2	H_2 RE-EV
Support required to equate to the ICE TCO in 2025 (£)	£1,130	£2,750	£5,060	£5,020	£6,410	£4,980
Annualised support required (£/yr)	£360	£870	£1,600	£1,590	£2,020	£1,570

2 Introduction

Over the next decade EU CO_2 targets will drive a dramatic shift in the types of new cars produced. By 2020 consumers will be faced with a proliferation of low carbon vehicles, using a diversity of fuels and powertrain technologies, as well as increasingly efficient 'conventional cars'. These will represent a very different offer to the consumer compared to today's market, promising lower annual running costs but potentially higher purchase prices. This suggests that the Total Cost of Ownership (TCO) will become a more useful metric for private consumers comparing vehicles than the current focus on purchase price.

If TCO does become the dominant purchase decision metric for private consumers, as it is already for fleet managers, the business of selling low carbon vehicles will become more complex due to the number of variables defining the TCO. Industry and policy stakeholders need to understand the direction of technology development, so that they can develop new products and business models, or provide cost effective policy support to drive this transition. The LowCVP wishes to investigate how technology and policy factors influence the TCO, and hence the relative attractiveness of various vehicle types.

The first part of this report is designed to provide the LowCVP with robust data on the range of TCOs for different powertrains, vehicle segments and years. A simulation-based, Monte Carlo statistical approach has been used to account for the often considerable uncertainty in future technology cost and performance, as well as uncertainty over future fuel and insurance costs.

The second part of this report uses a scenario based approach to analyse specific sensitivities and input assumptions. The scenarios are designed to test the input assumptions under extreme conditions and provide insight into how certain variables affect the TCO and vehicle emissions.

This report is structured such that the input assumptions methodology is described in the main body of the report but the full list of input assumptions and references are confined to the appendices. The focus of the report is on the results of the TCO and sensitivity scenarios.

3 Methodology

3.1 Overview of methodology

The approach to calculating the TCO of alternative vehicles was based on an analysis of vehicle component costs and performance assumptions combined with assumptions on future ongoing cost such as fuel and insurance. The future vehicle performance and costs were determined from an extensive literature review, consultation and peer review process. The ongoing costs of the vehicles were generated from primary analysis of historical data such as national trip statistics, as well as fuel price projections between 2010 and 2030. The process is summarised below:

- Literature review and consultation on vehicle attribute and component costs
- Primary analysis of ongoing TCO components such as insurance
- Peer review of TCO breakdown, inputs components, vehicle characteristics and costs outputs
- Update of vehicle characteristics and running of Monte Carlo simulation.

A fundamental part of the approach in these initial simulations is that future projections for vehicle costs and performance are based on incremental improvements, for example changes in vehicle mass or aerodynamics. Costs for major components such as batteries are also based on gradual improvements, rather than step changes resulting from new chemistries or manufacturing techniques.

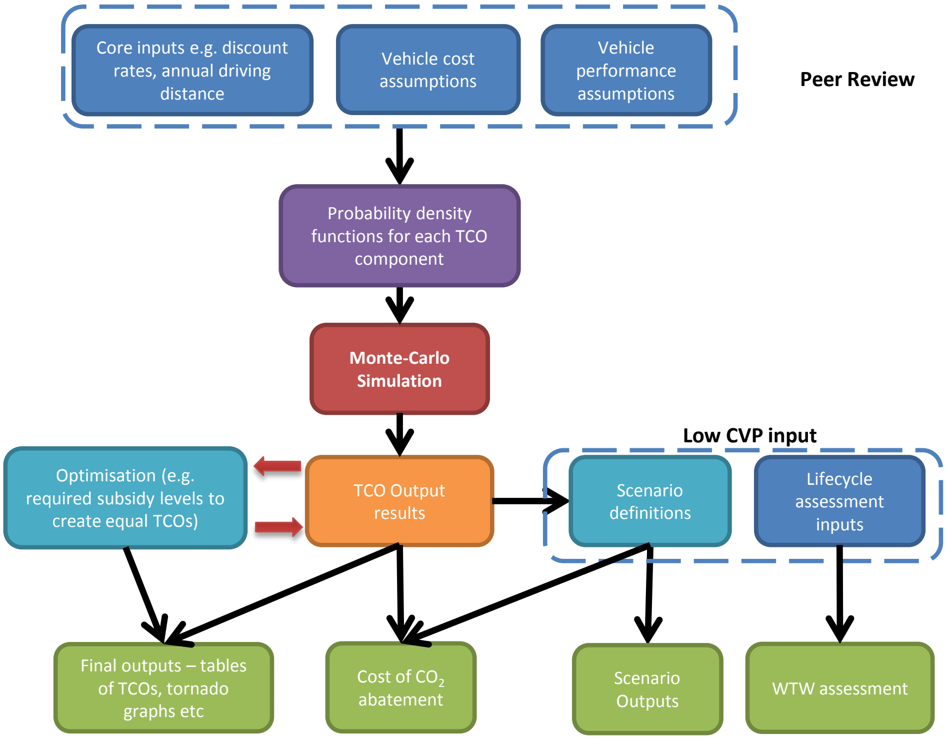


Figure 1 – Project workflow diagram detailing the data flow and review stages

In addition to the Monte Carlo analysis of TCOs, we have also used a scenario-based approach to examine disruptive changes in vehicle costs or external factors such as fuel costs. These scenarios are intended to model less probable but high impact events, and show how they influence the relative costs of different powertrains. Again, the process for developing the scenarios was iterative and involved:

- Development of initial scenarios and presentation of results
- Review and discussion with project Steering Group
- Generation of new and updated scenarios.

The overall project workflow is shown in Figure 1.

3.2 Peer review process

Initial inputs to the TCO calculation, derived from the literature review and primary analysis, were reviewed by project Steering Group within the LowCVP. Through this process the initial assumptions were challenged and revised before being released to the wider LowCVP membership for comment and review.

Following this wider review process the TCO input assumption and outputs were finalised.

3.3 Monte Carlo approach

Monte Carlo analysis is a statistical approach to modelling the effects of uncertainty. As there are many uncertain variables contributing to the vehicle TCO this method is ideal as it provides a distribution curve of TCOs for the different vehicles.

Defining the uncertainty in the input parameters of the TCO is key to performing Monte Carlo analyses. Input parameters for each independent variable are defined by Lower, Central and Upper bounds. These boundaries are used to define a normal distribution where the lower and upper bounds represent the 2.5% and 97.5% confidence limits and the central value the mean. The Central value does not necessarily lie half way between the Lower and Upper values, and in such cases the distribution will be skewed, as shown below.

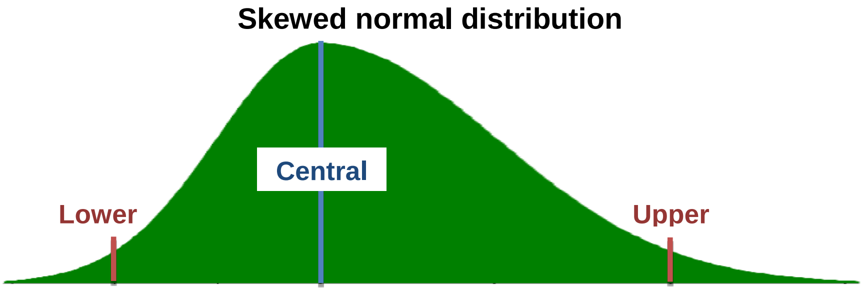


Figure 2 – Example of a skewed normal distribution

The distributions for each independent variable form the basis of the Monte Carlo analysis, which draws data from each distribution to produce distribution curves for the TCO of the vehicles, an example output curve is shown in Figure 3.

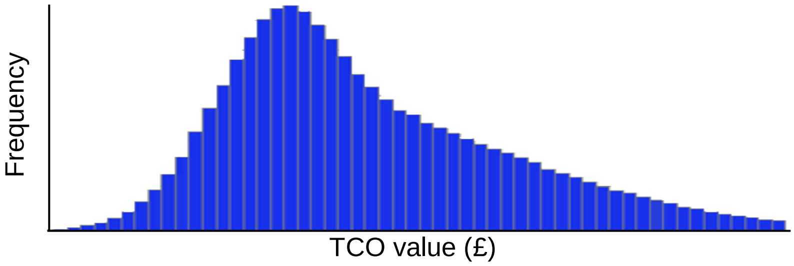


Figure 3 – Example of the output distribution generated by the Monte Carlo analysis

4 Vehicle performance assumptions

To generate the characteristics of future vehicles two components are required: an accurate description of current vehicles and the probable trends or improvement in vehicle characteristics. With both of these components new future vehicle characteristics can be generated. There is no distinction made between petrol and diesel vehicles in in the baseline vehicles. This requires the averaging of the petrol and diesel vehicles and petrol and diesel fuels.

4.1 Description of illustrative 2010 vehicles

The following process was used to generate the existing vehicle characteristics:

1. From SMMT data the five most popular vehicle models in each vehicle class by sales in 2010 were selected.
2. The properties of these vehicles (weight, power, capital cost etc.) were taken from What Car? The vehicle models selected were the lowest cost versions of the smallest and largest engines in the model range[4], for both petrol and diesel versions of the model.
3. The vehicle properties for the petrol models and diesel models were averages to give petrol and diesel model averages. The average petrol and diesel models were subsequently averaged, using the sales weighted average of petrol and diesel vehicles in the vehicle class.
4. Representative vehicle properties by vehicle class were averaged and weighted according to model sales figures. This generated a single average vehicle for each SMMT vehicle class.
5. The properties of each vehicle class were directly averaged between classes to provide three hybrid classes of vehicle to give illustrative vehicle classes. These were defined as A&B, C&D and E&H class.

The top five vehicles by sales in 2010 in Class H (4x4s) only account for 36% of the vehicles sold in that segment, compared to 80% for the top five models in class A. Furthermore, the majority of sales of the most popular vehicles in class H are the smaller, lighter and less powerful cars such as the Ford Kuga. To more accurately represent this class the following ‘full sized’ vehicles were added: Volvo XC90, Audi Q7, BMW X5, Porsche Cayenne and the Land Rover Discovery.

The vehicle characteristics of these generated vehicle classes are shown in Table 1.

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[4] This approach was designed to avoid biasing the results towards the smallest engine in a model range (which is usually not the best-selling model), while avoiding biases due to high performance and high specification variants.

Table 1 – Vehicle characteristics from the SMMT analysis of the combined vehicle classes

Vehicle segment	A&B	C&D	E&H
Vehicle price (ex. VAT)	£9,458	£17,817	£28,852
Max power (bhp)	84	144	212
Kerb weight (kg)	1037	1407	1844
Power to weight ratio (kW/kg)	0.081	0.102	0.115
Average mpg	55.9	49.2	39.7
CO_2 Rating (gCO_2/km)	120	142	192

4.2 Vehicle evolution

To predict the characteristics of future low carbon vehicles, we begin with the expected improvements in the conventional internal combustion engine vehicle. This approach provides a future ‘baseline’ vehicle, against which other powertrains can be compared. It also allows improvements outside the powertrain, such as aerodynamic improvements and vehicle ‘lightweighting’, to be quantified and applied across all vehicle types. This section explores the changes to the ICE vehicle over time.

4.2.1 Physical characteristics

Weight and size

Weight reduction is a key variable in predicting fuel consumption of future cars[5]. It is expected that OEMs will increase efforts to limit vehicle weight in the coming decades due to EU emission targets. This is often more important in plug-in or hydrogen vehicles, as the costs or providing extra power or energy storage for a heavier (and hence less fuel efficient) vehicle are significantly higher than for a conventional car.

Historically, the weight of vehicles increased steadily from 1990–2000. However, in the last ten years there has been a levelling off of vehicle weight and we expect that absolute vehicle mass will decrease in the period 2010 to 2030 (e.g. through increased use of lightweight materials, lightweight high strength steel, aluminium etc.).

A recent technical study by Lotus[6] shows that a reduction of 38% in non-drivetrain weight is possible[7]. This corresponds to a reduction in total vehicle mass of 30%. This is similar to the weight reduction anticipated by MIT[8], albeit on a slightly longer timescales. The weight reduction assumptions used in this study are given in Table 2.

Table 2 – Reduction in non-drivetrain weight

Year	2020	2025	2030
Reduction in non-drivetrain weight (%)[9]	14	21	28

Improvements in safety and comfort levels (or the physical dimensions) of future vehicles may reduce the potential weight savings. For consistency with the Lotus and MIT papers this potential change is not included in this study.

The size (frontal area) of vehicles of a given class has increased in the past 20 years but has levelled out and is unlikely to increase further due to physical restrictions (road width and parking provision) and more focus on vehicle efficiency.

Power to weight

The power to weight ratio of passenger cars historically has increased at a rate of 0.5–2.5% p.a. from 1995–2001[10]. In this study we assume that the average rate of increase

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[5] A 10% reduction in vehicle weight reduces fuel consumption by between 5.6 and 8.2% (Fundamentals of Vehicle Dynamics, SAE international)
[6] An Assessment of Mass Reduction Opportunities, *Lotus Engineering Inc. 2010*
[7] Where 78.4% of the vehicle weight is non-drivetrain.
[8] ‘On the Road in 2035’ *MIT (2008)*
[9] Range of savings between 20–35% in 2035, *On The Road In 2035, MIT 2008*
[10] Europe’s Evolving Passenger Vehicle Fleet: Fuel Use and GHG Emissions Scenarios through 2035, *MIT 2008*

over this period (1.3% p.a.) continues through to 2030. This figure has been further substantiated by calculating the average power to weight ratio for selected vehicles in the UK[11] from 1990–2010 which resulted in an average increase of 2%, which is within the 1.3–2.5% average for all new vehicle sales from 1995–2001.

Figure 4 shows some historical and projected values for the power to weight ratio. Historical data show changes in the P/W ratio of vehicle classes[12].

Assuming an annual 1.3% increase in power to weight and the total vehicle weight reduction assumption of 22% relative to 2010 levels (in 2030), the engine power of the vehicles remains relatively constant; the average power of a C/D class vehicle in 2010 is 108kW and in 2030 it is 109kW. This is consistent with the historical trend of OEMs not reducing the power of the engines in their base models. Table 3 shows the vehicles' power, power to weight and total mass for ICE vehicles in the years 2010, 2020, 2025 and 2030.

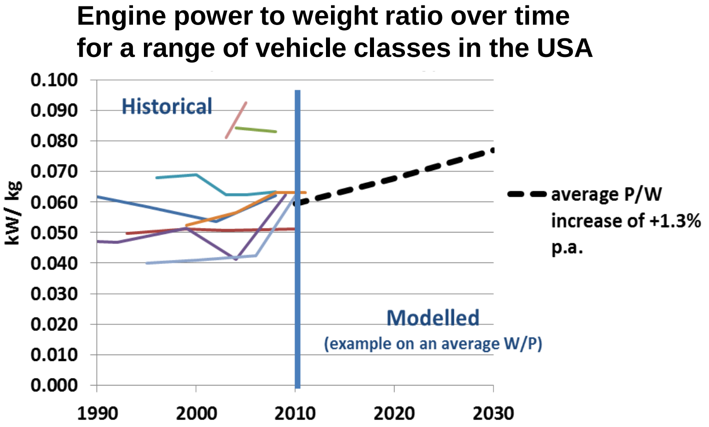

Figure 4 – historical and modelled power to weight ratio

Table 3 – Future vehicle performance characteristics

Vehicle Segment	Year	A&B	C&D	E&H
Engine Power (bhp)	**All**	64	109	159
Power to weight ratio (kW/kg)	**2010**	0.081	0.102	0.115
	2020	0.092	0.117	0.131
	2025	0.098	0.124	0.139
	2030	0.104	0.133	0.149
Total vehicle mass (kg)	**2010**	1,037	1,407	1,844
	2020	934	1,258	1,634
	2025	878	1,181	1,533
	2030	821	1,103	1,430

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[11] Vehicles used for market check: Ford Fiesta (1976 – 2008), VW Golf (1974 – 2009), Fiat Punto (1993 – 2010), Ford Galaxy (1995 – 2010), Audi A3 (1996 – 2008), Citroen Xsara Picasso (1999 – 2011), Citroen C2 (2004 – 2008)

[12] www.automobile-catalog.com

4.2.2 Vehicle improvements

To calculate current and future vehicle energy demands the existing vehicle losses and how these are likely to change are needed. For a full list of existing vehicle losses, efficiencies and references see the Appendix. The key areas of improvement for future vehicles are: aerodynamics, rolling resistance, drivetrain transmission, reduced idling and ICE efficiency. The values used in the analysis are shown in Table 4 with the total improvements in efficiency that each of the vehicle characteristics creates.

Table 4 – Improvements in vehicle properties through time

Property	Annual improvement	Overall improvement to vehicle efficiency relative to 2010		
		2020	2025	2030
Aerodynamics	1.0%	2.1%	3.2%	4.4%
Rolling	1.0%	3.1%	4.9%	6.7%
Driveline transmission	0.2%	0.4%	0.7%	0.9%
Total improvement relative to 2010 values		**5.7%**	**8.8%**	**12.0%**

Additional improvements not mentioned in the above table include reduction in ICE idling and ICE efficiency improvements. The total contribution of ICE idling to vehicle losses are 8%[13], this can be improved by adding stop start functionality to the ICE. Stop start functionality can reduce the losses from idling by 58%[14], reducing idling losses to 3.4%[14]. Improvements in ICE efficiencies are set at 1% over the incumbent annually, with an initial overall (thermodynamic) efficiency of 22% in 2010[13]. Both stop start and ICE efficiency improvements are included in the future ICE vehicles.

Using these incremental improvements in vehicle characteristics new gCO_2/km figures can be generated using the 2010 values as a starting point (Figure 5). The series for A/B, C/D and E/H vehicles is based on current levels of biofuel blending (c.5% in 2010). DfT/DECC forecast that the biofuel blend fraction will increase to 10% by energy by 2020[15]. This is shown in Figure 5 to highlight the impact on the fleet average emissions trend.

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[13] Averaged from: Low CVP presentation “Low Carbon Cars and Fuels for Fleets” 10th Dec *2010*, On The Road in 2035 *MIT 2008, World Steel Association 2007*, Cars on a Diet *MIT 2010.*

[14] The King Review of low-carbon cars, K*ing review 2007*

[15] EU target of 10% by energy, producing a minimum hydrocarbon CO_2 emissions reduction of 6%, under the Renewable Energy Directive (RED) 2009

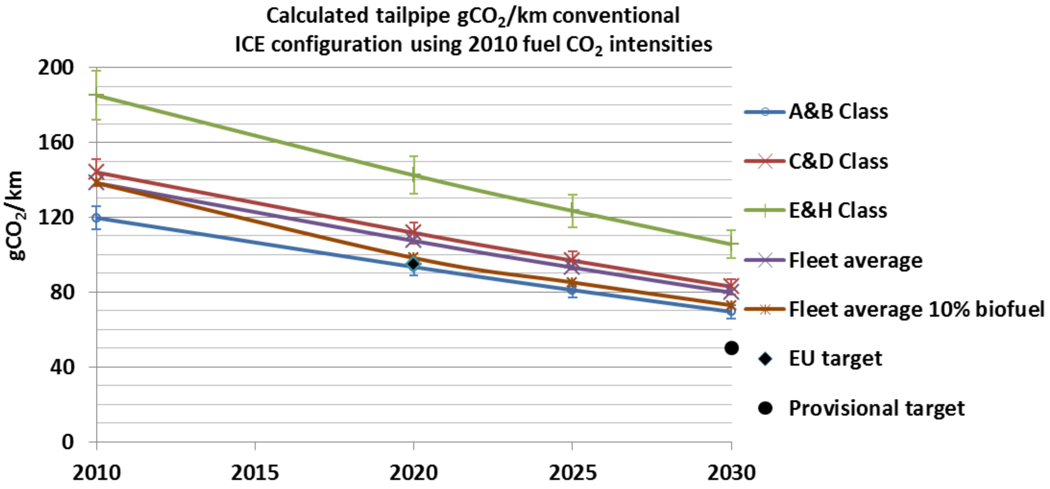

Figure 5 – Calculated tailpipe emission of ICE vehicles based on model assumptions. Provisional 2030 target from the CCC's "4th Carbon Budget (Path to 2030)"

4.2.3 Alternative vehicle properties

Defining the vehicle types

Hybrid – hybrid configuration consisting of regenerative braking, small battery (2km electric range) and small electric motor. There is no provision for charging this vehicle from the mains. The electric motor is sized to meet power requirements for low speed driving and to supplement the internal combustion engine. Examples of this vehicle are the original Toyota Prius and the Lexus RX450h.

PHEV – plug in hybrid where the vehicle can be charged from mains electricity and runs in electric mode until the battery is depleted (or high power is demanded), at which point the ICE takes over. The electric motor power sized similarly to the hybrid vehicle. The range of the vehicle is between 20–30km (see next section on range for more details). An example of this vehicle is the Plug-in Prius.

RE-EV – range extended electric vehicle with a range greater than the PHEV. This has a different drivetrain configuration compared to the PHEV. The wheels are driven by one or more electric motors powered by an on board battery that is charged primarily from the mains. There is also an on-board ICE generator that is used during 'charge sustaining' operation[16]. The range of this vehicle is set at 60km for the purpose of this study (see next section on range for more details). Examples of this vehicle type are the Chevrolet Volt and Vauxhall Ampera.

EV – a pure electric vehicle contains a battery and an electric motor only. The vehicle is charged by mains electricity. Examples include the Nissan Leaf and Mitsubishi I-MIEV.

Hydrogen vehicle – the pure hydrogen vehicle has a limited degree of hybridisation such that the hydrogen fuel cell is sized to meet the peak load of the vehicle with the battery/capacitor used for load smoothing only. This vehicle has a hydrogen tank that gives the vehicle a range comparable to the ICE vehicle (500km). An example of this vehicle is the Honda FCX Clarity

Hydrogen RE-EV – the hydrogen RE-EV is a fully hybridised hydrogen vehicle. The vehicle can be plugged into the mains for charging and can run for extended periods on the battery alone (60km); once this is reached the fuel cell starts and is designed to run at high load to directly run the vehicle or to recharge the battery. The fuel cell is sized to meet just more than the base load of the vehicle (c.50% of the rated motor power).

Each vehicle has a different kerb weight depending on its components but the performance of all vehicles is the same with the exception of range. For a full list of the vehicle characteristics and component performance (motor and fuel cell efficiency etc.) refer to the Appendix.

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[16] The Chevrolet Volt also has a mechanical connection between the ICE and the driving wheels for use during high speed (motorway) driving.

Throughout this report, the term Base ICE is used to refer to a conventional ICE car with no hybridisation. The term 'Hybrid' is used specifically to mean a non-plug-in hybrid such as the current Toyota Prius or Honda Insight, rather than as a generic term for any vehicle with a hybrid powertrain (which would include PHEVs or RE-EVs).

Electric range

The range of conventional vehicles is effectively unlimited, with many vehicles capable of 800km or more from a single tank of fuel, and an extensive refuelling infrastructure in place. In contrast, the *electric range* of electric vehicles is limited by the capacity of the on board battery and the availability of recharging infrastructure. For pure battery electric vehicles (EVs), range (more specifically concerns over range) is one of the key determinants of how attractive (or not) the vehicle is to consumers. For hybrid electric vehicles the electric range has implications for the proportion of total mileage done in electric mode, which in turn affects running costs and CO_2 emissions.

Battery capacity (and thus range) offered is a trade-off between issues such as cost and weight, and the need to provide sufficient utility (range) to meet drivers' needs. In practice electric ranges of future alternative vehicles will be set by user requirements, cost considerations and OEM marketing decisions. The purpose of this study is not to attempt to predict OEM decisions on range offered, so simple rules have been used to provide illustrative range estimates for each powertrain and model year, as shown below.

Table 5 – Electric range of alternative vehicles in pure electric mode

Electric range by vehicle type (km)	Hybrid	PHEV	RE-EV	H_2	H_2 RE-EV
2010	2	20	60	2	60
2020	2	30	60	2	60
2025	2	30	60	2	60
2030	2	30	60	2	60

Table 6 – Electric range of EVs through time

EV range (km)	A&B	C&D	E&H
2010	150	160	200
2020	150	200	230
2025	150	220	260
2030	150	240	300

The ranges of PHEVs and RE-EVs are kept constant from 2020, at 30km and 60km respectively, as these values allow the vehicles to do a large proportion, 42% and 62% respectively, of their annual mileage in electric mode (see Section 4.3). In reality OEMs may specify higher electric ranges for the RE-EVs of 80-100km, though as the TCO results show, the costs of providing this extra range outweigh the benefits of more electric driving and lower running costs.

For pure electric vehicles, it is assumed that OEMs 'split' the future battery cost/performance improvements between increasing vehicles' ranges and reducing cost. The range of pure EVs is assumed to rise by 50% between 2010 and 2030 for the C/D vehicle, but this remains substantially lower than that of a conventional vehicle. This is justified by the very high costs (and added mass) of providing a very large battery suitable for very rare long distance trips.

4.3 Calculating emissions

Calculating the emissions of future vehicles is a key component to understanding the merits of the different vehicles. Vehicles' emissions are calculated by estimating fuel consumption and the carbon content of each fuel[17], based on incremental improvements. For plug-in vehicles, we must also calculate the relative distance driven using liquid fuels (or hydrogen) and electricity, as this has a major influence on emissions and running costs. This approach requires an understanding of driving patterns of UK consumers, including total annual driving distances and the distribution of trip distances.

The assumed annual driving distance of all vehicle types is 15,000km, to allow a fair comparison across all powertrains. Due to their limited range, pure electric vehicles cannot complete the very longest trips (unless widespread infrastructure is available), suggesting that the annual driving distance may be lower for these vehicles. However, 15,000km is equivalent to only 40km per day and, as shown below, 90% of annual mileage occurs in trips shorter than 160km, the range of the current Nissan Leaf. This suggests that the driving distance assumption for the pure electric vehicle will not significantly overestimate the potential running cost and emissions savings.

National Travel Survey (NTS) data were used to generate profiles of number of journeys completed by journey length. This dataset, published by the Department for Transport, records the start and end times and distances of nearly 100,000 trips. The trip records can be aggregated to calculate the percentage of annual distance travelled for journeys of a particular length, as shown in Figure 6.

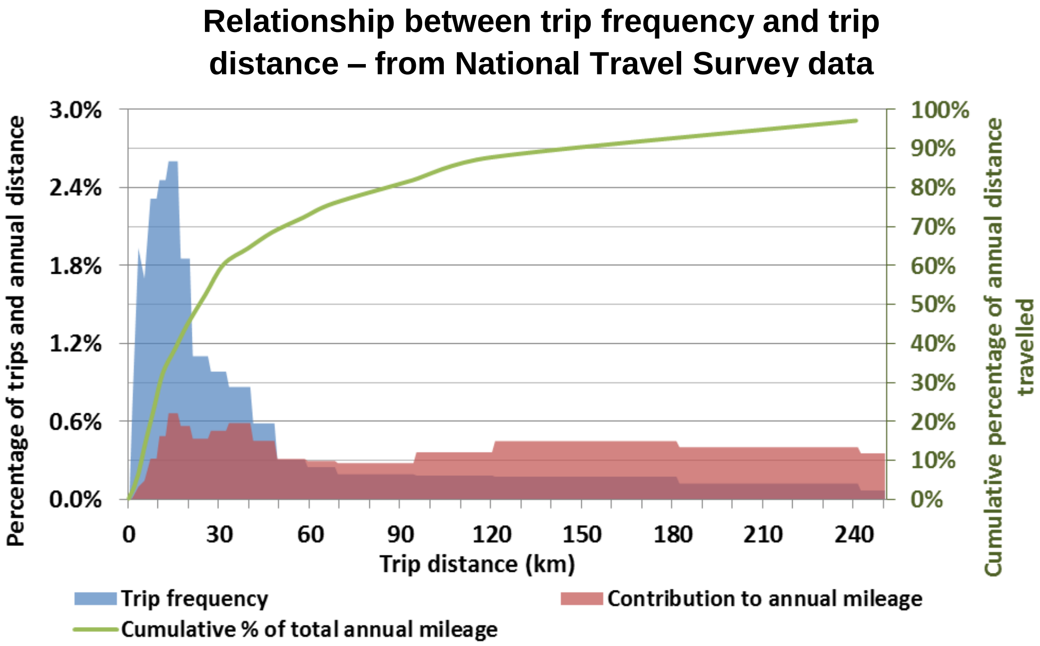

Figure 6 – Histogram generated from NTS data on journey frequency by journey length

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[17] Hydrocarbon and electricity carbon content taken from DECC projections and hydrogen from the 'A portfolio of power-trains for Europe' report by McKinsey.

Figure 6 shows that although there are a large number of short journeys these account for a low proportion of total annual mileage (as demonstrated by the red series of Figure 6). The green line in Figure 6 showing the cumulative annual mileage by journey distance, allows the annual distance travelled in electric mode to be calculated based on vehicle electric range.

This simple calculation assumes that at the end of every journey the vehicle is able to recharge before starting another journey. This is an overestimate of the total annual distance travelled in electric mode, as it is unlikely that recharging facilities will be available at every destination. An alternative method would be to assume that the vehicle does the same return journey on a single charge thus halving the effective range in electric mode. This method underestimates the likely annual mileage travelled in electric mode. In reality, several other factors will influence the proportion of annual mileage that can be covered using electricity. These include combinations of trips and destinations (for example commuting and shopping) that are more complex than the simple 'out and back' trips considered here. The PHEV is also affected by the type of driving, as these vehicles tend to use the internal combustion engine for motorway driving even when the battery has charge remaining. However, averaging the 'optimistic' and 'pessimistic' cases described above gives an adequate representation of likely emissions for plug-in vehicles for this analysis. More detailed analysis of the influences of driving patterns on emissions and running costs is carried out in Section 9.

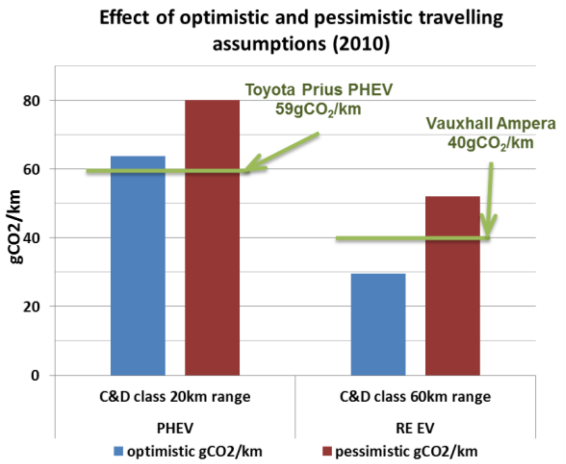

Figure 7 – The effect of optimistic and pessimistic travelling assumptions on the gCO_2/km calculation

Using this trip statistic method to calculate annual distance travelled in electric and non-electric mode and the vehicle performance, estimated fuel and electricity use is calculated. Using the emissions factors[18] of the fuels and the annual mileage, the gCO_2/km figure can be generated. This method has been validated against the quoted figures for the Toyota Prius PHEV and the Vauxhall Ampera (Figure 7).

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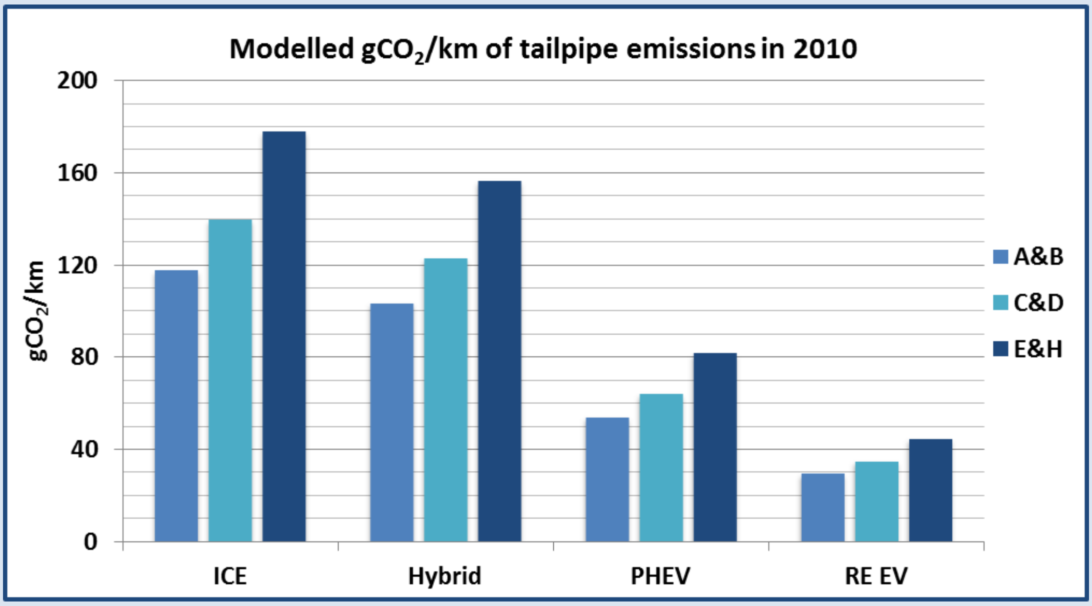
[18] DECC data were used on the carbon intensity of electricity of hydrocarbon fuels.

Key Points Summary

- SMMT and What Car? data were used to populate existing vehicle properties by vehicle class. These were averaged between vehicle classes to generate combined classes of A&B, C&D and E&H.
- Vehicle performance assumptions and future improvements were taken from multiple sources to define the changes to vehicles through time.
- NTS data were used to calculate the distance that each vehicle can travel in electric model annually and this was converted into gCO_2/km figures shown below.



5 Analysis of trends in vehicle component costs

The capital cost of the vehicle is an important contribution to the TCO. Predicted changes in vehicle costs are inherently uncertain, especially for components currently produced in relatively low volumes such as automotive batteries or fuel cells. Throughout this section this uncertainty is accounted for using upper, lower and "best estimate" values for each component to calculate the likely range in capital costs (and hence selling price) of the vehicles.

This study does not aim to perform a full bottom up approach of vehicle component costs, for example down to the costs of windows and suspension. Since there are many common components for the vehicles being studied, instead the cost of the vehicle is broken into the glider[19] and powertrain-specific costs where the cost of the glider is constant for all vehicles types. Glider costs are calculated by subtracting the cost of the ICE drivetrain from the total vehicle cost (as opposed to price), as discussed below.

All costs used in this study are in 2010 pound sterling (GBP) unless otherwise stated.

5.1 ICE vehicle costs

5.1.1 Tax and margins

Vehicle class average prices from SMMT data were used as a starting point for vehicle costs. The VAT and OEM margins need to be removed from these figures to obtain the production cost of the vehicle. The current VAT rate of 20% was used throughout.

Margins vary widely between each manufacturer and are normally higher for larger vehicles compared with A & B segment cars. For simplicity, the average margins[20] from the OEM, dealer and marketing/logistics company are used, as shown in Table 7. Removing VAT and the vehicle margins gives a production cost of the ICE vehicle. Identical factors are used to convert the production costs of low carbon vehicles back into selling prices for use in the TCO analysis.

Table 7 – Average margins[21] for vehicle manufacture and sales

	Component supplier and assembler	OEM	Dealer	Logistics and marketing
Margins (%)	6.5	6.5	11.5	6.3

5.1.2 ICE and glider costs

To calculate the glider cost of the vehicle, the production cost of the ICE needs to be removed from the total vehicle cost. This can then be added subsequently for vehicles which contain ICEs. The data available in the public domain on ICE costs are limited as ICEs are a relatively mature technology and the information is commercially sensitive.

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[19] The glider is defined as all the non-powertrain components of the vehicle. It is also referred to as the 'body in white'.

[20] The vehicle component producers or assemblers are rarely the OEMs and their margins are excluded from this study.

[21] The second century, *MIT 2004;* Automobiles sector profile, *Q-Finance;* The new form of collaboration in the automobile industry, *Mercer and the Fraunhofer Society,Oliver Wyman;* Estimating the New Automotive Value Chain, *Accenture 2002;* Evaluation of Electric Vehicle Production and Operating Costs, *Argonne National Laboratory 1999.*

The current and projected future costs of ICEs are shown in Table 8, expressed in £/kW. As different vehicle classes have different engine power requirements, this metric allows the total engine cost to be calculated for all classes and powertrains. This value is assumed to change with time as ICEs become more efficient and complex, for example through the use of more advanced fuel injection, variable geometry turbochargers and low-friction materials. We have assumed that the costs of smaller engines used in RE-EVs decrease in proportion to their power, so that halving the power output halves the cost. In reality, these small engines may be more expensive per kW as they are engineered to work at optimum power bands, and fixed costs such as labour are unlikely to vary significantly between a small and a large engine. The values used in this study are shown in Table 8 along with the glider cost in 2010 (production cost – ICE costs) in Figure 8.

Table 8 – ICE marginal costs[22] through time

ICE marginal cost (£/kW)	2010	2020	2025	2030
Best fit (central value)	28	30	31	33

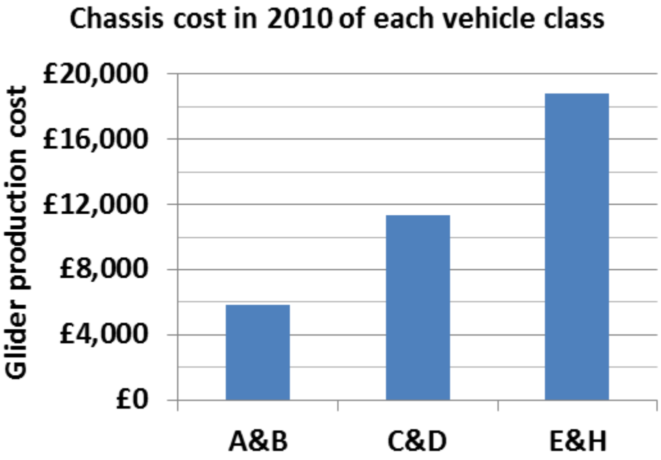

Figure 8 – Chassis production cost in 2010 of each vehicle class

The glider cost element is kept constant through time with the effects of vehicle light-weighting treated separately.

5.2 Powertrain costs

The cost of the additional powertrain components needs to be added to the glider cost to calculate the total cost of the vehicle. A literature review of the component costs of alternative vehicles was carried out and from these data points the best fit (central), lower and upper bounds in each of the calculation years was deduced.

5.2.1 Battery pack

Battery packs consist of the battery control system, cell packaging and the battery cells. Battery cells make up approximately 60% of the battery pack cost[23]. All the battery costs are stated as pack costs as delivered to the OEM.

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[22] Averaged and extrapolated from: Tank to Wheels, Appendix 1, *Concawe 2008*, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, *EPRI 2001*; Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles, *EPRI 2002*.
[23] EV, PHEV & HEV worldwide market 2008-2020, *Avicenne*, 2009

Battery pack cost projections for this study were drawn from nine published sources, several of which contained reviews of costs from other papers. The data in Figure 9 are presented in US Dollars and GB Pounds as most of the data sources use US Dollars. Table 9 shows a summary of all the processed battery pack cost data.

These costs represent the cost to OEMs of a fully assembled pack, including the cells and battery management system, but not the costs of the battery tray to mount the pack in the vehicle (which is considered separately). The costs are based on incremental improvements to existing lithium ion chemistries. The effects of disruptive changes to battery pack costs, for example from new chemistries such as lithium-air, are modelled as a scenario in Section 8.1.

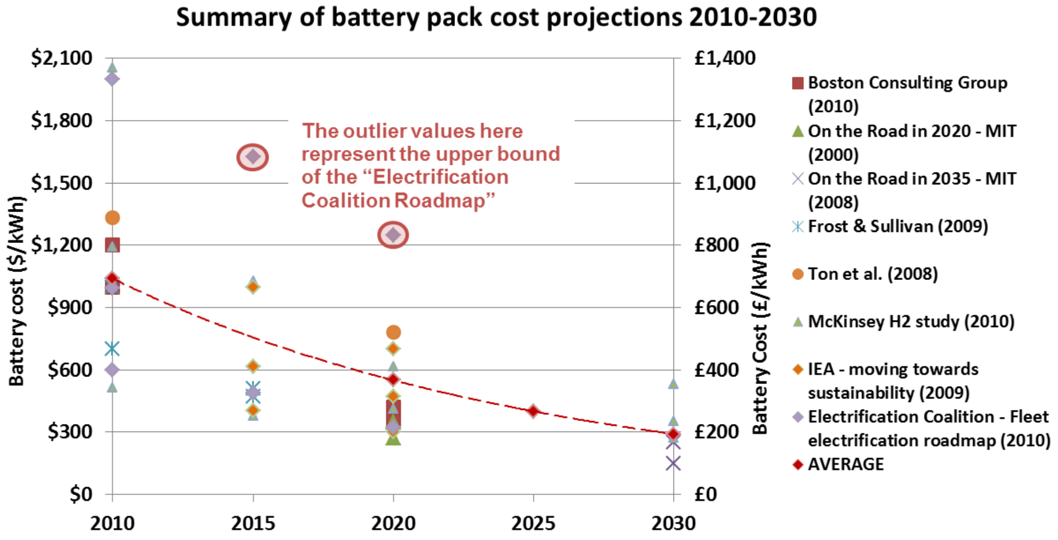

Figure 9 – Battery cost summary of all references, values in $/kWh and £/kWh

Table 9 – Battery costs used for lower, central and upper

Battery pack costs (£/kW)	2010	2020	2025	2030
Best fit (central)	693	367	267	194
Lower	342	181	141	100
Upper	1369	833	681	530

For the central scenario battery costs are expect to reduce by 47% in 2020 and 72% by 2030 relative to 2010 values. For the standard 24kWh battery used in the Nissan Leaf this reduction in battery costs changes the cost of the battery pack from £16,600 in 2010 to £8,800 and £4,700 in 2020 and 2030 respectively.

5.2.2 Fuel cells and hydrogen tanks

The current high costs of automotive fuel cells currently being produced are expected to reduce by an order of magnitude with large production volumes[24] (see references in Figure 10).

A review of published data on fuel cell costs reveals that production volume is the key influence on delivered costs, as shown in Figure 10. This graph shows both the production

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[24] Fuel cell costs are currently high as the research and development costs of this developing technology are spilling over into capital costs of the units. As the production volumes are low the associated R&D costs attributed to each fuel cell sold are high.

volume and the associated cost in $/kWe of the fuel cell. We define the fuel cell as the total fuel cell system including the control system, fuel cell stack, air humidification system, hydrogen recirculation system, condenser and power supply connections.

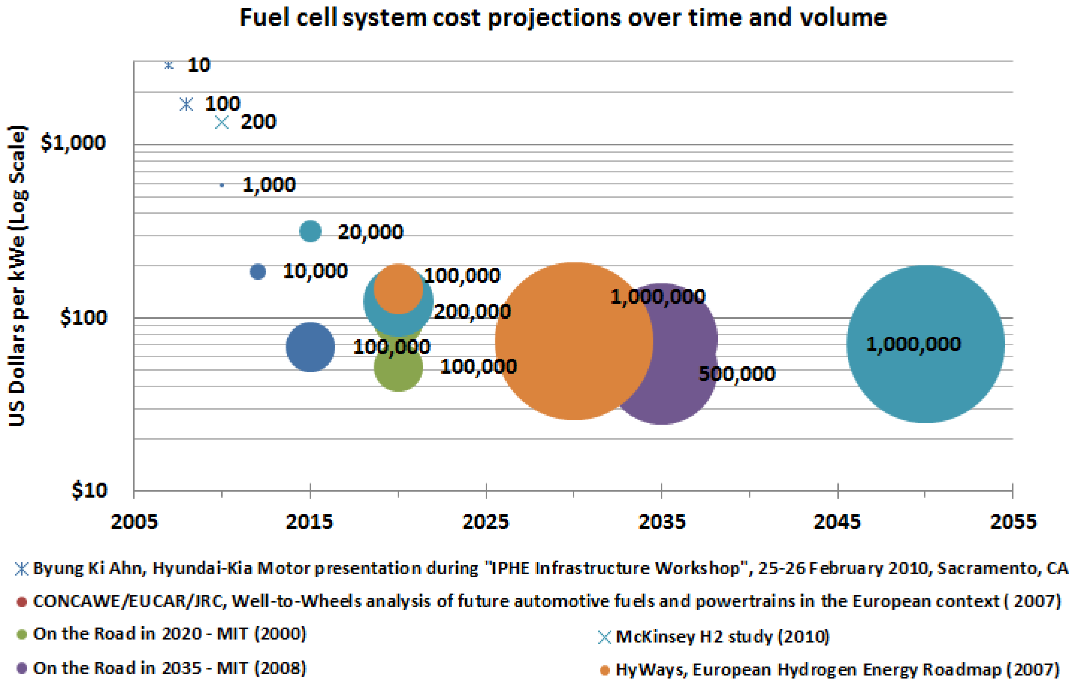

Figure 10 – Bubble Graph of fuel cell system costs through time and with volume. The labelled values on the graph show typical volume requirements for the cost.

It is important to quote the volume assumptions of the fuel cell when displaying the costs in a given year. Table 10 shows the costs and volume assumptions that are used in this report.

Table 10 – Fuel cell system costs through time, with approximate volume assumptions per OEM

Fuel cell system cost (£/kW)	2010	2020	2025	2030
Best fit (central)	811	75	64	53
Lower	391	35	34	34
Upper	902	99	71	70
Volume per OEM required	~100	~100,000	~500,000	>>500,000

A 93% reduction in fuel cell cost by 2030 (relative to 2010) is expected for the central scenario, this dramatic reduction is a result of extremely high prices of current prototypes. For example, the current cost of the Honda Clarity’s fuel cell (100kW) is assumed to decrease from £81,000 in 2010 to £7,500 and £5,300 in 2020 and 2030 respectively.

An additional component associated with using hydrogen is the hydrogen tank cost. Hydrogen tank costs are less explored in the literature. The hydrogen tank costs used are shown in Table 11, and references for the data sources are given in the Appendix.

Table 11 – Hydrogen tank costs through time (700 Bar)

H_2 tank cost £/kWh	2010	2020	2025	2030
Best fit (central)	47	17	13	8
Lower	35	10	7	5
Upper	59	16	13	10

The cost of a hydrogen fuel tank for a C&D class vehicle with a 3kg storage capacity (400km range in 2010[25]) is £6,000 in 2010; this reduces to £2,200 in 2020 and £1,000 by 2030.

5.2.3 Electric drivetrain components

Motors

Electric motors used in vehicles can be broadly divided into two types:

1) Central mounted transmission connected, or
2) Hub mounted individual wheel motors.

The costs stated in this section are for a central motor connected to transmission rather than for individual wheel motors (which require additional electronics). The motor costs include the controller and the motor inverter.

Given the limited published projections on future motor costs, the central and upper limits remain constant from 2020. Projections for the lower value decrease in line with the only publication on motor cost beyond 2020, MIT's On The Road in 2035 study. It should be noted that the cost of £5/kW in 2030 is extremely low, and is likely to be unachievable given the costs of the materials required to make electric motors (e.g. copper, neodymium). There is a possibility that the cost of the motor increases through time as the cost of the rare earth metals that are used in the motor may increase due to supply side constraints. This effect is not considered to be a strong factor and the main cost driver will likely be volume.

Table 12 – Electric motor costs through time

Electric motor cost £/kW	2010	2020	2025	2030
Best fit (central)	33	21	21	21
Lower	35	10	7	5
Upper	53	25	25	25

Electric motor costs of a C&D class EV reduce from £3,600 in 2010 to £2,300 in 2020 and remain constant thereafter in the central scenario.

Other components

Other components of the electric drivetrain include battery chargers, additional transmission, heavy gauge wiring, regenerative braking components, battery systems

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[25] The hydrogen vehicle range is set to 500km from 2020, with improvements in vehicle properties and hydrogen fuel cell efficiency this 500km range can be accomplished with a smaller hydrogen capacity of 2.2kg in 2030 reducing the tank costs further.

hardware including the battery tray and thermal management system. For a full breakdown of these costs see the Appendix. The totals of these costs are shown in Table 13.

Table 13 - Additional cost components of the electric drivetrain, these costs are constant across all vehicle segments

Additional electric drivetrain cost £/vehicle	2010	2020	2025	2030
Best fit (central)	£1,890	£1,450	£1,420	£1,400
Lower	£1,830	£1,360	£1,349	£1,360
Upper	£2,060	£1,500	£1,494	£1,470

5.2.4 Internal combustion engines - additional components

ICE engines are expected to improve with time and therefore are expected to increase in cost, as described in Section 5.1.2. Further improvements to ICE architectures, the costs of which are not included in the ICE cost projections in Section 5.1.2, are also expected. For example, from 2020 all ICE vehicles are expected to include stop start capabilities to reduce losses from engine idling and this has an associated additional cost.

New ICE vehicles are expected to meet new emissions standards for controlled pollutants; this is especially true for diesel vehicles. To meet these new standards a new exhaust system will be needed with measures such as particulate traps and exhaust recirculation. The combined costs of stop-start and emission control measures are shown in Table 14.

Table 14 – Additional ICE component costs through time

Additional ICE component cost £/vehicle	2020	2025	2030
Best fit (central)	£706	£686	£686
Lower	£471	£442	£442
Upper	£941	£930	£930

5.3 Non-powertrain cost trends

5.3.1 Costs of materials

The uncertainty in the cost of raw materials is not directly represented in the costs of the vehicle. However, by using a spread of component costs (lower, central and upper) the effect of variation in raw material cost is represented by the cost ranges. No direct link between the cost of fuel (oil) and the cost of the vehicle components is included in the modelling methodology.

5.3.2 Costs of vehicle light weighting

Assumptions relating to the extent of vehicle light weighting in future years are given in Section 4.2.1. The key metric is the cost per kilogram of mass reduced, which can vary widely depending on the method of weight reduction. Re-engineering the production process and using new low weight but relatively low cost components may even reduce the cost of the vehicle while also reducing the weight[26]. The range of costs per kilogram of weight reduction from a review of the literature is shown in Table 15.

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[26] An Assessment of Mass Reduction Opportunities, *Lotus Engineering Inc.* 2010.

Table 15 – The cost of vehicle weight reduction in £/kg

Cost of weight reduction	£/kg	Cost of weight reduction for the ICE vehicle in 2030 C/D vehicle
Central	1.8	£456
Lower[27]	0.7	£167
Upper[28]	8.7	£2,166

The Lotus study on mass reduction suggests that mass reduction may be possible while decreasing vehicle costs. While this may be technically feasible, it remains to be seen whether the weight reduction strategies of OEMs can deliver savings at no or negative costs. Other sources in the literature show positive values for the cost of weight reduction, most of which were in the lower end of the range shown in Table 13, which explains the small difference between the lower and central values. The central additional cost to a C&D class vehicle from light weighting is £220 in 2020 and £460 in 2030.

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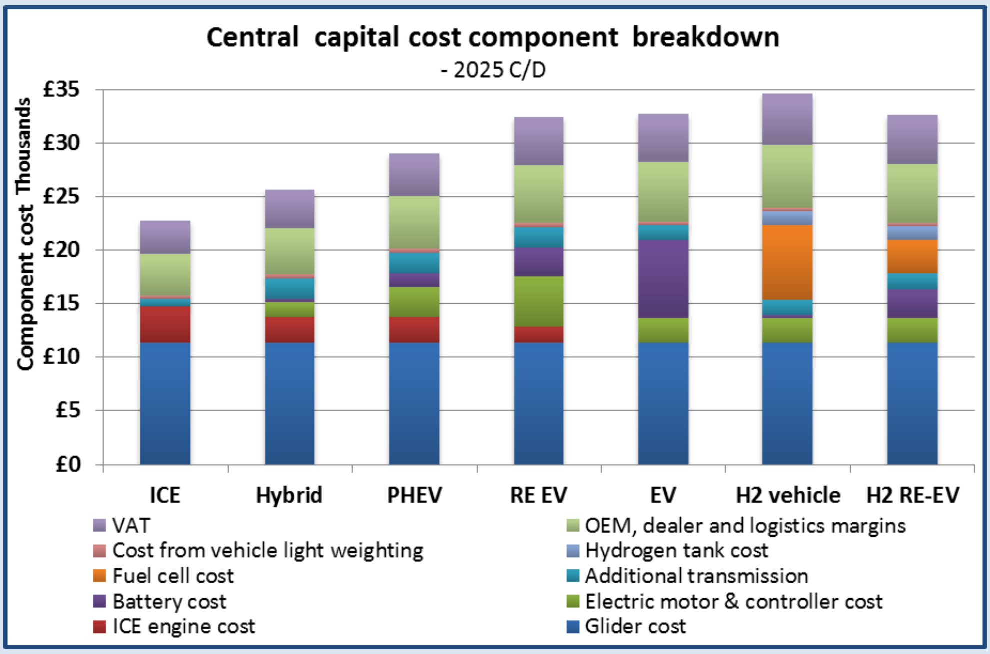
[27] Low figure from reengineering the vehicle production process using broadly similar materials, possibly strengthened or replaced with a lighter alternative.

[28] This represents the upper bond of vehicle light weighting and includes using exotic lightweight material such as carbon or manganese alloys.

Key points

- Margins and VAT remain constant at 24% and 20%
- Battery cost reductions of 60% in 2025 relative to 2010
- Fuel cell cost reductions of 92% in 2025 relative to 2010
- Hydrogen tank cost reductions of 72% in 2025 relative to 2010
- Increase in the marginal ICE engine cost of 11% by 2025 relative to 2010
- Decrease in the marginal electric motor cost of 36% by 2025 relative to 2010
- An average cost of £340 from vehicle light weighting (C&D class vehicle in 2025)
- Additional ICE component (exhausts) cost of £686 in 2025
- Additional electric drivetrain component costs of £1,420



6 Components of the Total Cost of Ownership

The previous section described the steps taken to calculate the manufacturing costs (and hence selling prices) for each low carbon vehicle type. We now explore the other components used in TCO calculations, such as fuel costs, insurance and servicing, and describe the assumptions that have been used in the simulations.

6.1 Vehicle purchase price

The total purchase price of the vehicles used in the TCO and Monte Carlo calculation is broken down in full in Section 5. The total purchase price of the vehicles includes the manufacturers' costs plus the margins and VAT to give the total price seen by the consumer. All of the vehicle capital costs are detailed and broken down in the Appendix. An example of how the vehicle capital costs change through time is shown in Table 16 for PHEV C&D class vehicles under the upper, central and lower cost inputs.

Table 16 – PHEV C&D class vehicle capital costs through time for the upper, central and lower cost values

PHEV capital cost	2020	2025	2030
Upper	£35,820	£34,950	£34,280
Central	£29,750	£29,000	£28,560
Lower	£26,620	£26,380	£26,200

6.2 Depreciation and resale

The resale value of the vehicle in the final year of the TCO (year four) needs to be included in the calculation as the vehicle is unlikely to have reached the end of its life. Depreciation rates and thus four year resale values vary between vehicle manufacturers and models[29]. The resale value of the vehicle was given a range of 35–50% of the purchase price. This is consistent with the range for retained value after 36,000 miles from What Car?

This resale value is deducted from the purchase price of the vehicle to give a 'net' purchase price. However, since the resale occurs at the end of year four, the value must first be discounted using a consumer discount rate, assumed to be 10% per year (see Section 6.6).

6.3 Annual fuel costs

Fuel costs are an important part of overall vehicle running costs and depend on two factors: the amount of fuel consumed (which is a function of distance driven and vehicle efficiency), and fuel price. Annual fuel consumption figures were derived from average annual mileage per vehicle (from NTS data) and the vehicle performance assumptions.

Hydrocarbon and electricity costs were taken from DECC's 'Updated Energy Prices' (UEP40) dataset[30]. To take into account fuel cost uncertainty three of the four DECC scenarios were used to represent the lower, central and upper values for fuel costs. The DECC scenarios used were: Low, Central and High High.

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[29] The residual value after 36,000 miles (58,000 km) of a BMW 5 series, taken from What Car? ranges from 37–47%. The difference between manufacturers of the same class of vehicle also varies for example a Ford Focus (2L hatchback) is 32% whereas a Volkswagen Golf (2L TSI) residual value is 53% and the (simple) average for the class is 40%.

[30] http://www.decc.gov.uk/en/content/cms/statistics/projections/projections.aspx

As DECC does not publish costs for hydrogen, we used hydrogen cost projections from McKinsey (‘A portfolio of power-trains for Europe’). That study report took into consideration the generation mix of hydrogen in Europe[31] as well as likely production volumes. The McKinsey study does not include a range of costs of hydrogen, so for the purposes of this study upper and lower ranges were introduced by applying a ±30% variation. The hydrogen costs are consistent with previous work by Element Energy on hydrogen costs.

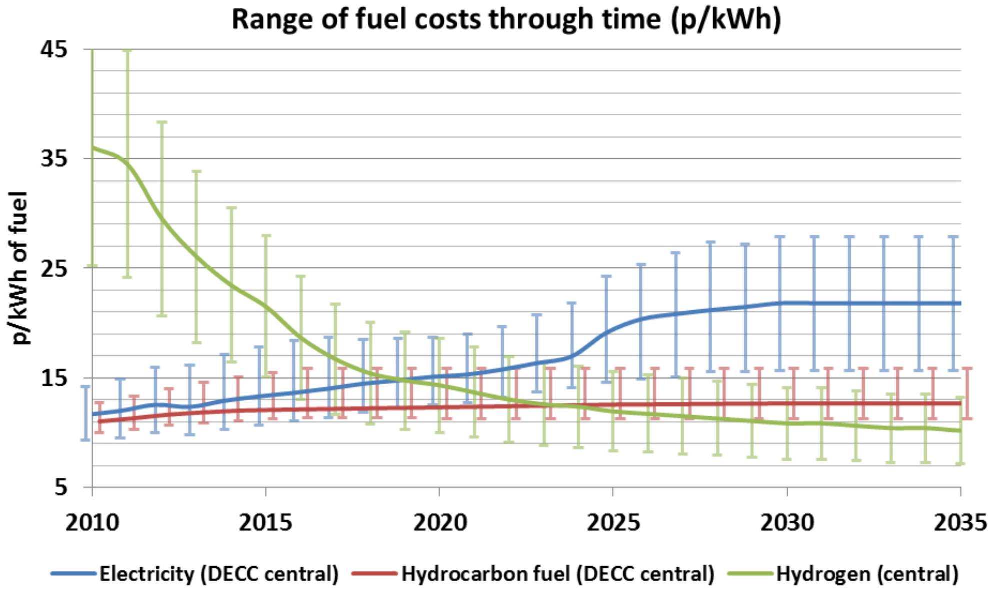

Figure 11 – Fuel cost scenarios used in the TCO. Electricity and hydrocarbon costs are from DECC scenarios. Hydrogen costs from the report on ‘A portfolio of power-trains for Europe’ ±30%. All costs are presented in p/kWh.

6.4 Insurance costs

Vehicle insurance is a large part of the ongoing cost of vehicle ownership, and its contribution to the TCO is expected to increase as fuel costs are reduced through increased vehicle efficiency. Two trends are considered important in determining the future insurance costs of vehicles. The first is the annual increase in insurance cost (based on current market trends) and the second is the effect that different powertrains have on the cost of insurance (powertrain-specific insurance cost).

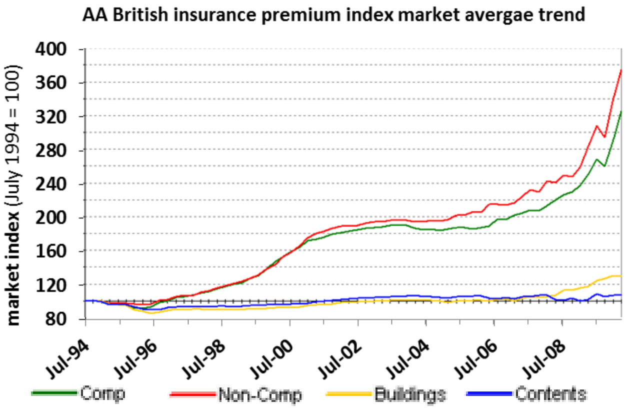

Figure 12 – Insurance historical market index in nominal terms tracking average market cost of insurance premiums. The index starts in July 1994. Graph adapted from the AA[32].

Market trend

The annual cost of insurance has increased significantly over the past 17 years and has become one of the largest annual costs of car ownership. Car insurance premiums have

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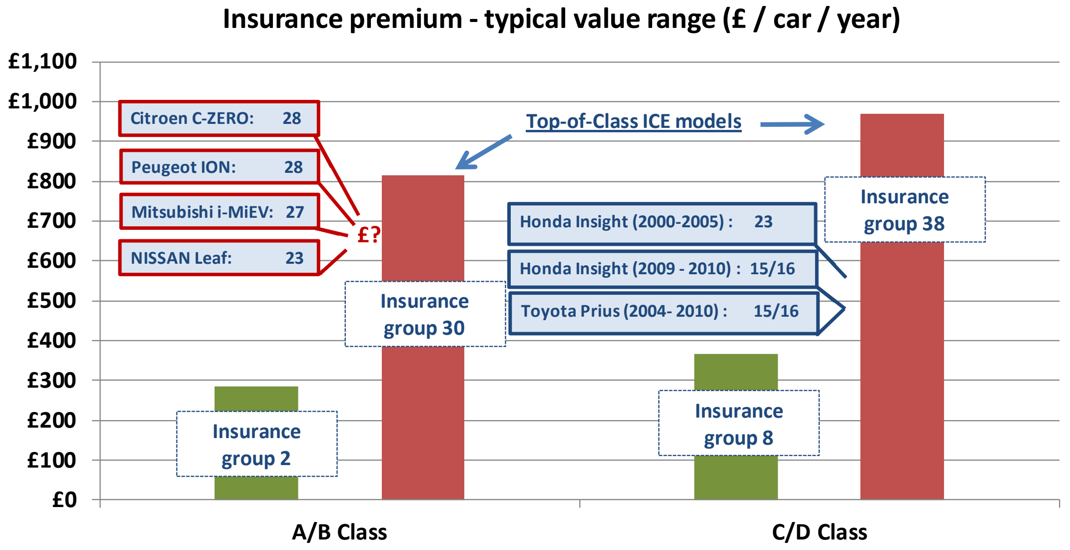
[31] Hydrogen prices are based on the assumption of a rapid scale-up in volume. Since the distribution cost currently constitutes a large proportion of the total cost, this allows the H_2 price to decrease, even though the primary fuel costs (e.g. natural gas) are increasing over time. The H_2 price assumes that there are 100,000 and 1,000,000 vehicles on the road in the EU in 2015 and 2020 respectively.

risen by over 200% in real terms between 1994 and 2010[32], equivalent to 6% year on year growth. According to the AA's Insurance Premium Index, the costs of comprehensive insurance rose by 40% in 2010 alone, with fraud and personal injury claims causing the majority of this increase[33]. Future insurance cost trends will depend on vehicle costs, accident rates, cost of repairs, personal injury claims etc. In this analysis three scenarios are considered for future trends in insurance - 6%, 3% and 0% annual growth rates (in real terms).

Powertrain-specific insurance cost

Historically vehicles with novel powertrains have had higher insurance costs than an equivalent conventional car. This can be attributed to the increased capital cost of these vehicles and insurances pricing in uncertainty over costs of repairs. Over time as 'novel' powertrains become more mainstream this insurance penalty diminishes, eventually reducing to zero. Indeed, insurance premiums for vehicles with 'novel' powertrains can even drop below the market average for the vehicle class over time (Figure 13). This trend was seen in the Honda Insight, where the initial model was in the upper insurance group band (group 23) of the vehicle class but the second generation of the vehicle was below the market average (at group 15/16). However, if the capital costs of low carbon vehicles remain higher than the Base ICE in the long term, insurance costs could remain higher than the incumbent to reflect higher replacement costs if the vehicle is stolen or written-off in an accident.



Data adapted from http://www.whatcar.com/ , http://www.thatcham.org/

Figure 13 – Upper and lower insurance premiums of the A&B and C&D vehicle class with annotation on the insurance groups of alternative vehicles through time

Figure 13 demonstrates that new powertrain vehicles start in the upper insurance bands of the vehicle class. In the short term manufacturers may provide their own insurance with the vehicles (as demonstrated by Nissan for the Leaf) to mitigate the high premiums offered by other providers. As these vehicles become more widely used and tested they are likely to incur similar insurance costs to conventional ICE vehicles.

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[32] The Automotive Association (AA).
[33] According to the Commons Transport Committee's first report on the costs of insurance

Vehicle insurance group grading is a complex subject[34], and forecasting the likely effect of powertrains on vehicle insurance costs is beyond the scope of this study. To calculate the powertrain-specific insurance costs, we took the upper, lower and averaged cost of insurance for the combined vehicle classes for current ICE vehicles (from SMMT and What Car?). This range is shown in Table 17 for each vehicle segment, and provides the following three scenarios for future insurance costs:

- **Upper –** insurance costs for novel powertrains remain at the upper end of the range through to 2020 and 2030.
- **Central –** insurance costs for novel powertrains decrease to the market average by 2020 and remain the same as conventional vehicles to 2030.
- **Lower –** insurance costs for novel powertrains fall below the cost of the incumbent, for example if data emerged that accident risks were lower than in conventional vehicles.

These values will all increase between 2010 and 2030 in line with the overall ‘market trend’ described above.

Table 17 – insurance powertrain specific ranges in 2010 for all vehicle classes

Insurance powertrain specific costs £/vehicle in 2010	A&B	C&D	E&H
Upper	£617	£928	£1,145
Central	£378	£616	£883
Lower	£288	£412	£604

6.5 Maintenance costs

Maintenance costs were split into two segments: the servicing costs and basic component replacement.

Servicing costs were taken from the three year service costs of new vehicles from SMMT and What Car? data. The lower and upper bounds for the servicing costs were also extracted from these data by taking the minimum and maximum values for servicing for each vehicle class and then averaging between vehicle classes.

In addition to these figures the cost of replacing tyres, brake pads and brake discs were added to the servicing costs to establish the total maintenance costs. There is evidence to suggest that the brake pads and brake discs of vehicles with regenerative braking need replacing less frequently compared to conventional vehicles. SMMT provided data on these costs for current non-plug-in hybrids and their conventional equivalents. The total maintenance costs are displayed in Table 18 for ICE vehicles and vehicles with regenerative braking.

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[34] The group rating systems takes into account the damage caused in an accident, component parts costs, the repair times, the capital cost, the vehicle performance and the security features of the car.

Table 18 – Annual maintenance cost ranges for each vehicle class

Maintenance costs £ / vehicle / year	Vehicle class	Lower	Central	Upper
ICE	**A&B**	£526	£590	£649
	C&D	£569	£660	£794
	E&D	£641	£782	£937
Alternative Drivetrains	**A&B**	£401	£465	£524
	C&D	£444	£535	£669
	E&D	£516	£657	£812

6.6 Discount rates

Discounting is the process which accounts for the fact that a sum of money saved or spent in the future has less value than the same sum saved or spent today. This means that when comparing costs and benefits occurring in different years (such as in a TCO calculation), future costs must be discounted relative to current costs. Discount rates can have a large effect on the TCO even over a four year period, with high discount rates reducing the perceived benefit of running cost savings in the future. The recent McKinsey report (Powertrains for Europe) used a 0% discount rate when assessing TCOs. Though transparent, this approach overestimates the benefits of vehicles with high upfront costs and low running costs as in reality consumers pay little attention to savings that will occur far into the future.

Private consumers are often observed to have high discount rates (>20%), reflecting the cost of finance of capital purchases, opportunity costs and the risk that the product may not deliver the claimed ongoing savings. This is seen in the domestic energy efficiency market, where consumers choose not to install measures with payback periods beyond 2-3 years. Conversely, governments use much lower discount rates to assess costs and benefits of projects and policies, as they consider a much longer time horizon. The UK government uses a 3.5% discount rate in these ‘social’ cost benefit analyses.

Businesses tend to use discount rates between these extremes, with a typical value of 10% per year. Such a rate would be used by fleet manager when assessing new vehicle additions to their fleet.

We use a discount rate of 10% per year (consistent with typical rates used for business decision making) in the following analysis. The effect of discount rates on the TCOs is tested in a scenario (Section 6.6) to highlight the effect of higher and lower discount rates on the TCO, with the higher and lower values of 3.5%[35] and 20% respectively.

6.7 VED (Vehicle Exercise Duty)

Taxes and charges such as VED and scrappage are not used in the analysis. Only VAT and fuel duty are included in the TCO calculation, to allow a transparent calculation of the ‘pure’ economics of each powertrain type before the effects of differential taxation and incentives. The use of VED and annual tax to support alternative vehicles is considered in Section 7.4.2 .

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[35] This is the UK Government’s green book discount rate used for Government cost benefit analyses.

6.8 Summary of contributions to the Total Cost of Ownership

The figure below shows the relative contribution of each component of the TCO to the overall cost of each vehicle in 2025. Note that for the conventional ICE vehicle, the selling price (net of the resale price) makes up c.65% of the TCO, while for plug-in vehicle vehicles the price makes up nearly 80%, reflecting higher purchase prices and very low fuel costs.

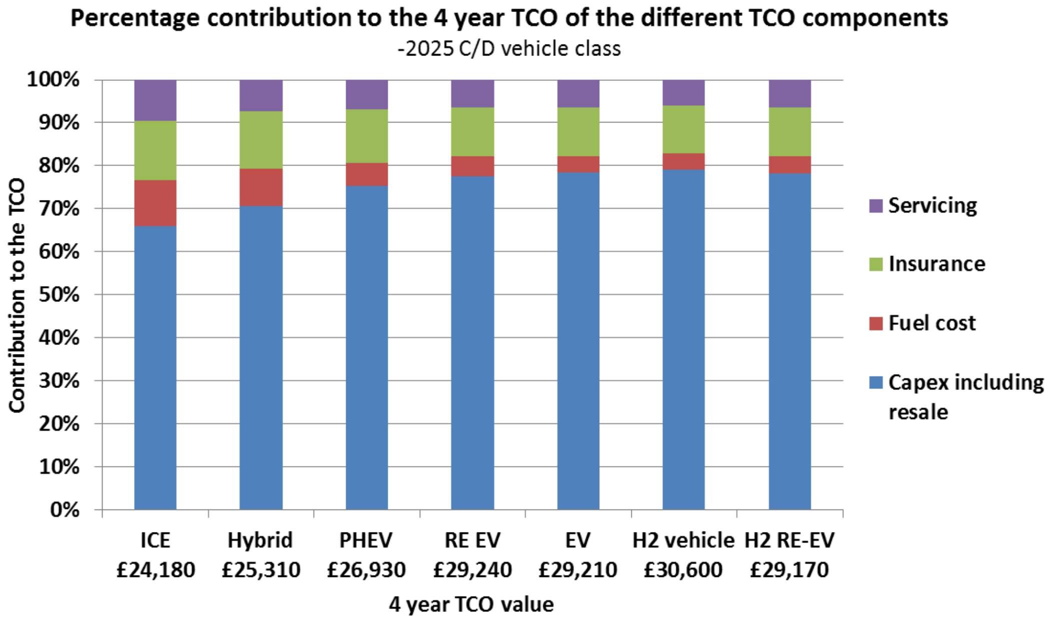

Figure 14 – Contribution to the four year TCO of the different TCO components for the C&D vehicle segment in 2025

The increased Capex of the alternative vehicles in 2025 is the most important factor affecting the TCO, this was the same as in 2010. Although the ongoing costs are significantly lower for alternative vehicles this is more than offset by their increased Capex.

Key Points Summary

The four year TCO inputs are separated into five components;

- **Capex including resale** – the capital cost to the consumer (manufacturing cost plus margin and VAT) minus the discounted resale value of the vehicle in year four.
- **Fuel costs** – calculated from the annual fuel use and fuel price projections from DECC and the McKinsey report on 'A portfolio of power-trains for Europe'.
- **Insurance (market trend) –** the historical annual increase in insurance cost over the past 16 years is 6% in real terms. An increase is assumed to continue, the range used is 0%–6%
- **Insurance (powertrain specific) –** the central projection is that there will be no powertrain specific costs. The range in powertrain specific costs use the upper and lower bounds of the insurance cost of the ICE vehicle class from What Car?.
- **Maintenance cost –** maintenance costs are £120 per year lower for vehicles with regenerative braking. The range in maintenance costs are taken from the range in the three year servicing costs from What Car? for each vehicle class.
- **2010 TCOs –** the PHEV has a TCO differential to the ICE vehicle of £6,800 and the EV a TCO differential of £20,000.

The discount rate used for all calculation is 10%.

7 Results

In this chapter, we present the results of the TCO analysis for the three reporting years of 2020, 2025 and 2030. We use Monte Carlo simulations to calculate the distributions of costs for each of the powertrains to capture explicitly the uncertainty in the projections and to highlight where costs for different powertrains overlap. To place these future projections into context, we begin by showing the differences in TCOs for vehicles in 2010.

7.1 TCO results for 2010

Figure 15 shows the total costs of ownership over four years for the C/D segment in 2010. The hybrid vehicles and pure electric vehicle are shown alongside the conventional ICE. Both the hydrogen vehicle and the hydrogen RE-EV are not shown as these vehicles are not available for purchase by the general public. However, based on the current cost of the fuel cell and hydrogen storage (as well as hydrogen fuel), the TCOs of these vehicles are estimated to be £121,800 and £81,500 respectively.

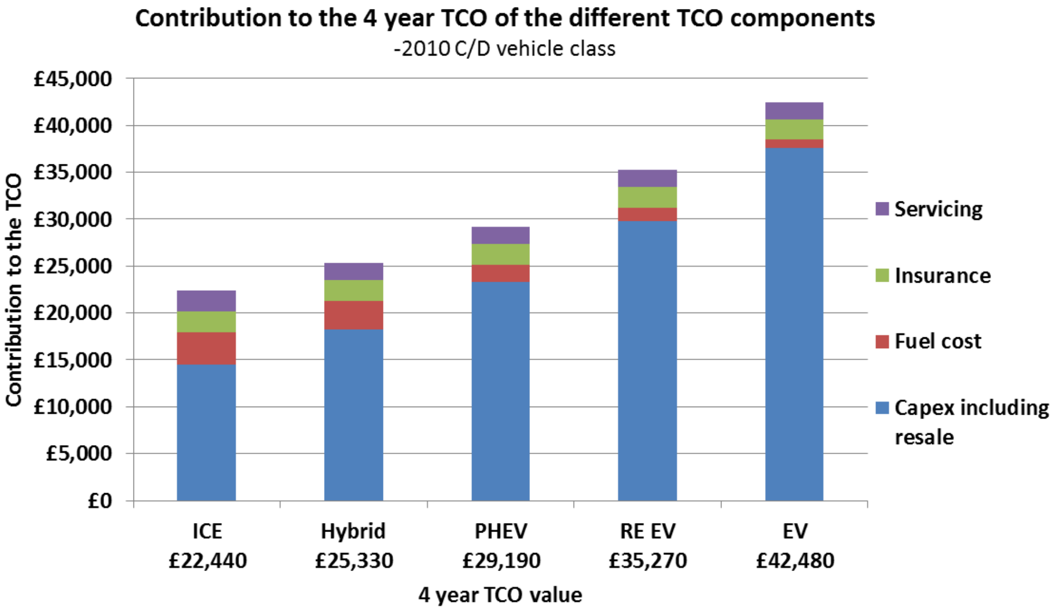

Figure 15 – contribution to the TCO of the separate TCO components in 2010 for all of the non-hydrogen C&D class vehicles

The conventional vehicle remains the most cost-effective vehicle in 2010 when assessed under a four year TCO. The non-plug-in hybrid is closest to matching the conventional vehicle, with an ‘on-cost’ of £2,900. There is a minimum of a £6,800 cost differential between the ICE and any plug in vehicle, due to the high capital costs of the batteries in current models. The TCO premium for the pure EV is £20,000 in 2010, before accounting for the £5,000 grant available from OLEV. Note that this assumes standard industry margins are applied to the production costs of the plug-in vehicles. In reality the selling prices of several current models are significantly below the costs shown here.

The results in 2010 show that even though plug-in vehicles make substantial savings in annual fuel costs, these are more than outweighed by increased capital costs. In the results below, we show how changes in the capital cost reduce this premium in the TCO.

7.2 Monte Carlo Results

This section explores the results of the Monte Carlo simulations. The Monte Carlo analysis shows the probability distributions of the four year TCOs of the different vehicle types. The distributions are constructed by drawing values at random for each of the distributions in the model, for example battery costs and fuel costs. The TCO is then calculated and recorded for each of these draws. By calculating the TCO over a very large number of draws (500,000), it is possible to generate an overall distribution of the TCO for each vehicle, showing the most likely value as well as the confidence limits.

7.2.1 Comparison across all vehicle segments in 2020

The ICE and hybrid vehicles have the lowest TCOs in 2020, as they did in 2010. Figure 16 shows that the distributions of the TCOs for the Base ICE and non-plug-in hybrid cars are narrow as there is less uncertainty over the costs associated with ICE and simple hybrid vehicles.

The PHEV’s TCO is c. £3k over the Base ICE while the RE-EV and EV have a c. £5k premium. These values are substantially lower than in 2010, where the premium was £6,800 for the PHEV and £20,000 for the pure electric vehicle, suggesting that low carbon vehicles can make strong progress in bridging the current TCO differential in the next ten years. The hydrogen RE-EV has a similar TCO to the pure EV, though the larger fuel cell stack required in the less-hybridised fuel cell car leads to an additional TCO of £3,000 relative to the EV. It should be noted that the H_2 car provides much a greater range than the EV, so the former provides greater functionality providing that sufficient refuelling infrastructure exists.

These reductions in ownership costs are dominated by changes in the capital costs rather than relative changes in ongoing costs. The premium of £5k for the RE-EV and pure EV matches closely the subsidy of up to £5k for alternative vehicle technologies currently available from OLEV. In other words, the current subsidy would still be required in 2020 for EVs and RE-EVs if they are to become comparable to ICE vehicles over a four year TCO.

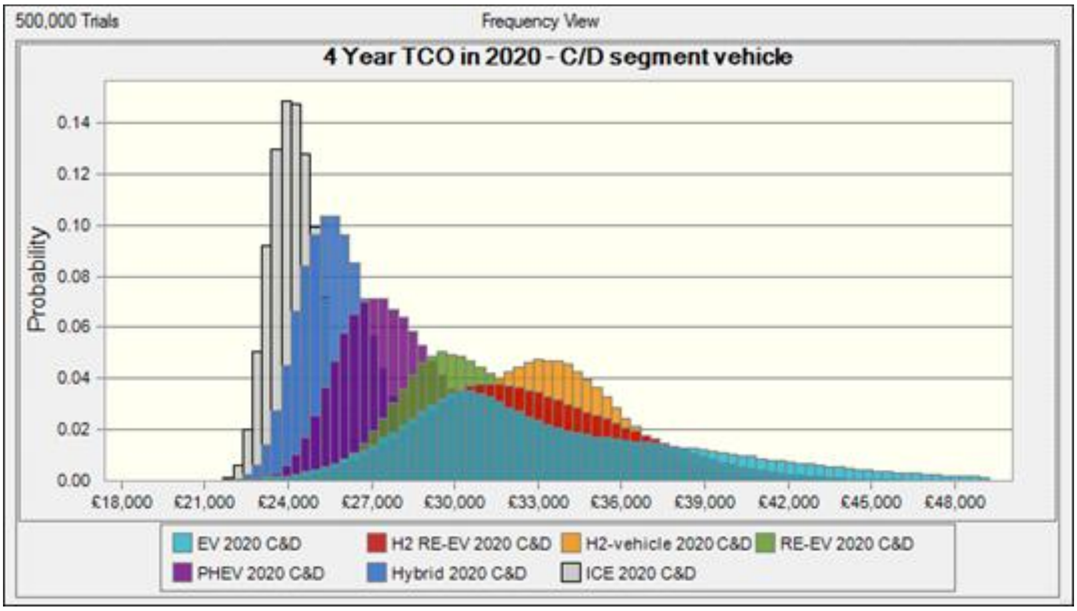

Figure 16 – Four year TCO in 2020 for the C&D class vehicle segment, Monte Carlo analysis of 500,000 runs

The long 'tails' for EVs in Figure 16 and Figure 17 is mainly due to the large uncertainty of the battery costs in 2020. The left-hand tail shows that there is a very low probability that the TCO of plug-in vehicles (including the pure EV) will be equal to the conventional car in 2020. On the other hand, there is a higher probability that the costs of the pure EV will exceed £36,000, if predicted battery cost reductions are not achieved.

The graph in Figure 17 clearly shows how the uncertainty in the component costs is reflected in the overall TCO in the various vehicles types. Vehicles with the largest batteries have the largest range of TCOs as batteries have the largest cost ranges, followed by hydrogen vehicles and ending with more mature technologies (Base ICE and conventional hybrid) where components other than capital costs have the largest effect on the TCO (see Section 7.3).

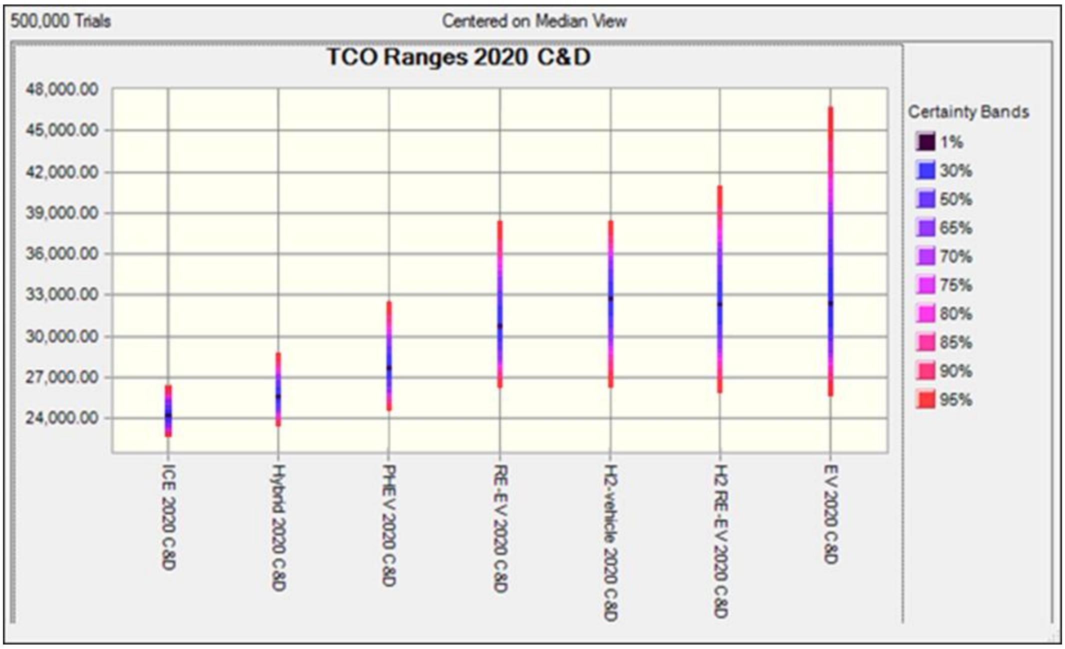

Figure 17 – Probability range spread of the different possible four year TCO values in 2020 for the C&D class vehicle segment for all the vehicle types, based on a Monte Carlo analysis of 500,000 runs

There is little difference in the probability distributions between vehicle segments (A&B, C&D and E&H as shown in Figure 16 and Figure 18) with one notable exception; the performance of RE-EVs, especially the change in position of the hydrogen RE-EV. Both the hydrogen and ICE RE-EV are systematically more expensive than the pure EV in small vehicles, but have very similar costs in the E&H segment, as shown in Figure 18. This reflects the relative costs of batteries versus other powertrain components. In the small vehicle, the low electricity consumption means that there is no benefit of reducing the battery capacity and fitting an internal combustion engine and generator (i.e. turning a pure EV into a RE-EV), as the additional powertrain components outweigh the battery cost. For large vehicles, the converse is true, and it is more cost-effective to fit a more complex powertrain and smaller battery than using a large battery to meet the range requirements.

As the merit order and distributions are similar for all the vehicle classes the focus for the rest of the analysis is on the C&D (medium class) vehicles, with any significant differences between vehicle classes highlighted. Further comparisons between vehicle classes are performed in Section 7.5

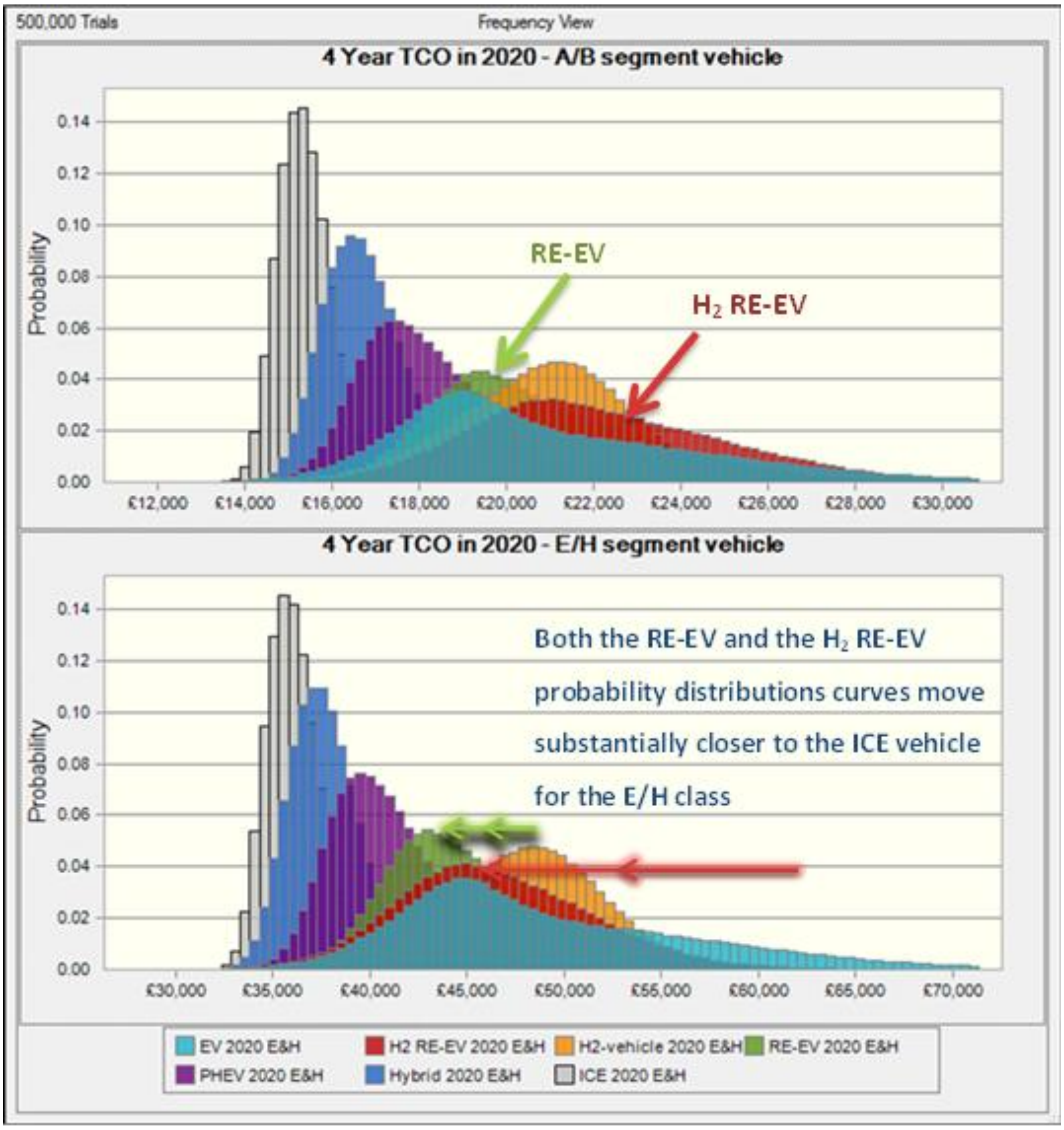

Figure 18 – Four year TCO in 2020 for the A&B and E&H class vehicle segments, Monte Carlo analysis of 500,000 runs

7.2.2 C/D results in 2025 and 2030

2025

By 2025 the EV's TCO becomes lower than the RE-EV (as shown by the green and teal lines of Figure 19). There is still a premium of just under £4k for EVs (relative to the Base ICE vehicle) which is slightly lower than for the RE-EV. As the battery costs decrease both the EV and RE-EV's capital cost reduces, but the RE-EVs costs are affected less strongly because of the other powertrain components, whose costs stay relatively static over time.

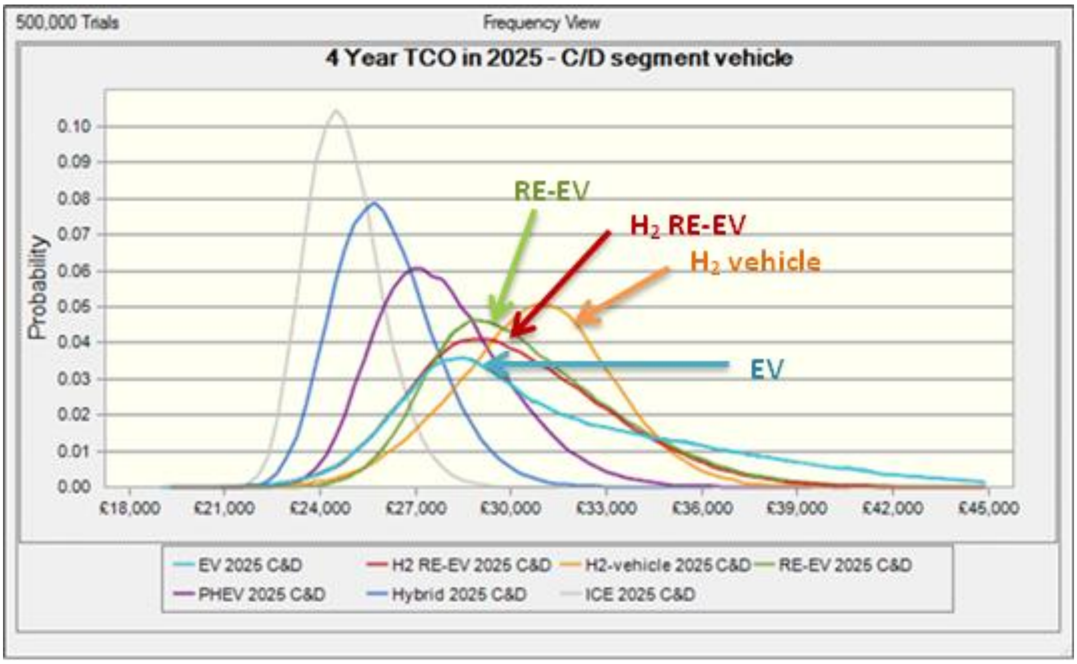

Figure 19 – Four year TCO in 2025 for the C&D class vehicle segment, Monte Carlo analysis of 500,000 runs

The hydrogen RE-EV becomes comparable to the petrol/diesel RE-EV as the drivetrain of the hydrogen RE-EV is significantly simpler and the cost of the hydrogen fuel cell is assumed to have decreased substantially by 2025.

The pure hydrogen vehicle is still c.£2,000 more expensive than the other vehicles types due to the large fuel cell stack and the use of hydrogen as a fuel. Compared to the hydrogen vehicle the hydrogen RE-EV has a smaller fuel cell stack and can use low cost electricity instead of hydrogen for a large proportion of journeys, these factors combined reduced the hydrogen RE-EV's TCO significantly below that of the pure hydrogen vehicle.

The spread of TCOs for the pure EV is the largest of all powertrains, highlighted in Figure 20. This is driven by uncertainty over battery costs. Although the most likely TCO value (mode) is £28,400 the distribution is skewed, which pushes the mean TCO up to £31,500.

The 5% and 95% bounds are £25,500 and £40,900, with a 22% probability that the TCO is above £36,000.

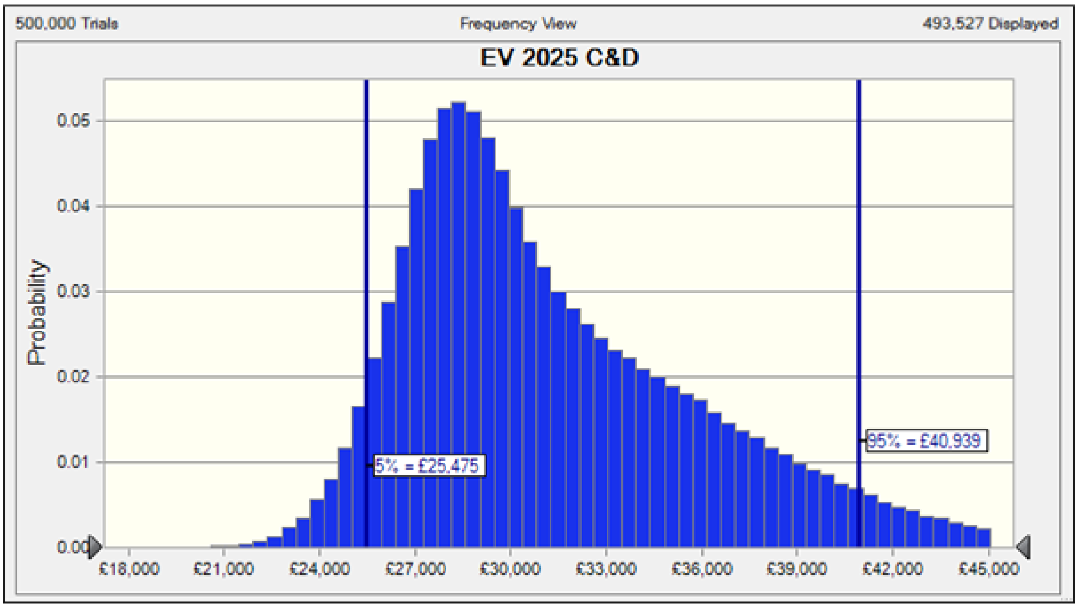

Figure 20 – Range of the four year TCO of an EV C&D class vehicle in 2025, based on the possible range of input variable the 5% and 95% confidence intervals are highlighted.

2030

A number of powertrains, including PHEVs, the EV and H_2 RE-EV, have TCOs within £2-3k of the Base ICE in 2030. The PHEVs now have a similar TCO to EVs (within £500), which implies that the additional costs due to having two powertrains (the ICE and electric powertrain) in the PHEV offset the savings from requiring a smaller battery. This additional cost of drivetrain complexity is further substantiated by the hydrogen vehicle and the ICE RE-EVs becoming cost equivalent as the ICE RE-EV's additional drivetrain complexity add the same cost as the fuel cell of the hydrogen vehicle.

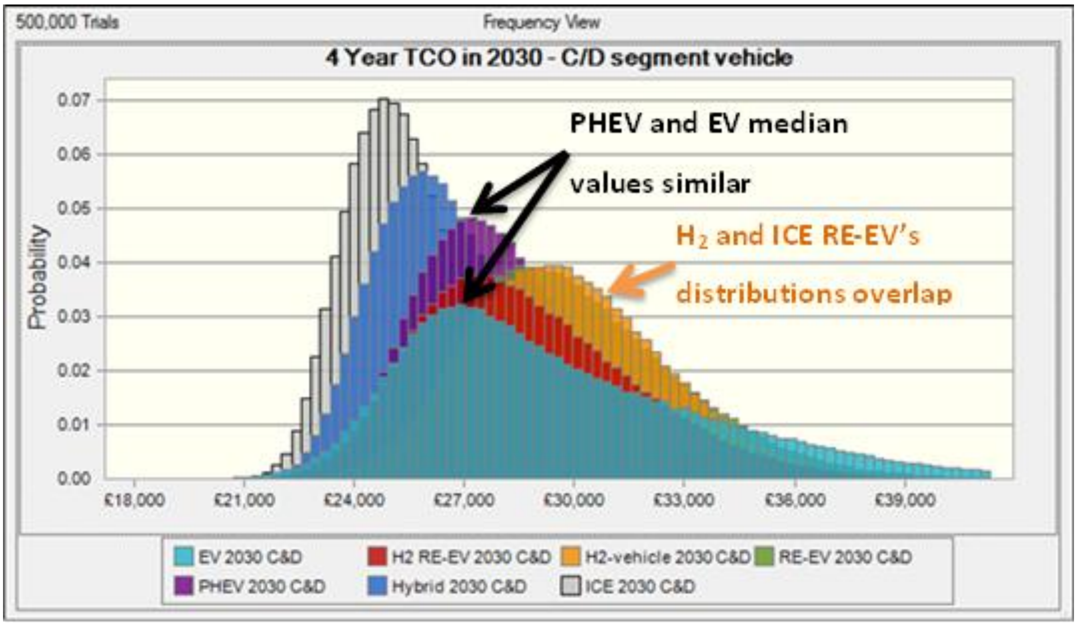

Figure 21 – Four year TCO in 2030 for the C&D class vehicle segment, Monte Carlo analysis of 500,000 runs

7.3 Sensitivity analysis: Central scenario

The results shown above combine the components of the TCO to calculate an overall distribution in ownership costs for each powertrain. It is also useful to examine the sensitivity of the TCO to changes in individual components. This sensitivity analysis is performed by setting the value of each TCO component to the upper and lower bounds (set out in Section 6), while holding all other components constant at their 'central' values. These upper and lower bounds represent the 95% confidence limit (2.5% and 97.5%) of the input variables' distribution boundaries used in the Monte Carlo analysis.

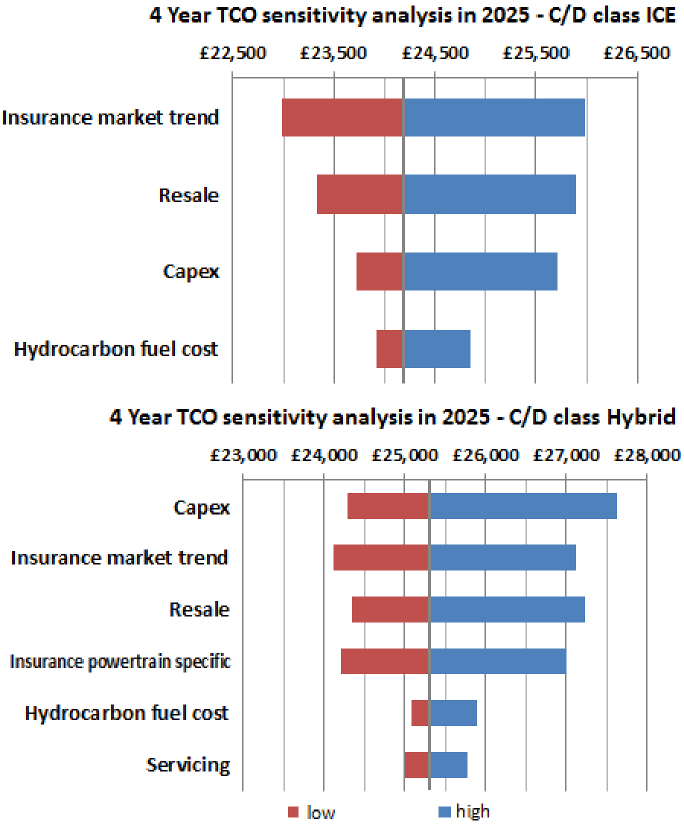

Figure 22 – Sensitivity analysis to the TCO components for a Base ICE and hybrid C/D class vehicles in 2025, the sensitivities used are the 95% confidence intervals for the input fields expressed in section 6

Figure 22 shows the sensitivity analysis for the conventional ICE and hybrid vehicles. For each component, the TCO at the upper and lower bound are shown either side of the central estimate (£24,200 for the conventional ICE).The figure highlights that the market trend for insurance[36] is one of the most powerful influences on the TCO, as the difference between the low and high limits is £3k for the C&D vehicle segment.

In comparison, the difference between the Low and 'High High' fuel price scenarios from DECC (see Section 6.2) implies a difference in fuel cost of only £945 over four years for the ICE. Under the central fuel price scenario, the fuel efficiency improvements in a 2025 ICE lead to a 26% reduction in fuel costs in real terms. Therefore for the conventional ICE vehicles the effect of fuel cost becomes less important to the TCO through time. Components other than fuel costs, such as insurance, resale and servicing comprise an increasingly large part of the annual running costs.

As expected, the vehicle purchase price (Capex) and resale values become more important for low carbon vehicles since they contribute up to 80% of the total cost of ownership. The effect of insurance becomes increasingly strong and is split into two sections (as discussed in Section 6.4): the 'market trend' affecting all vehicles; and premium/benefit for novel powertrains.

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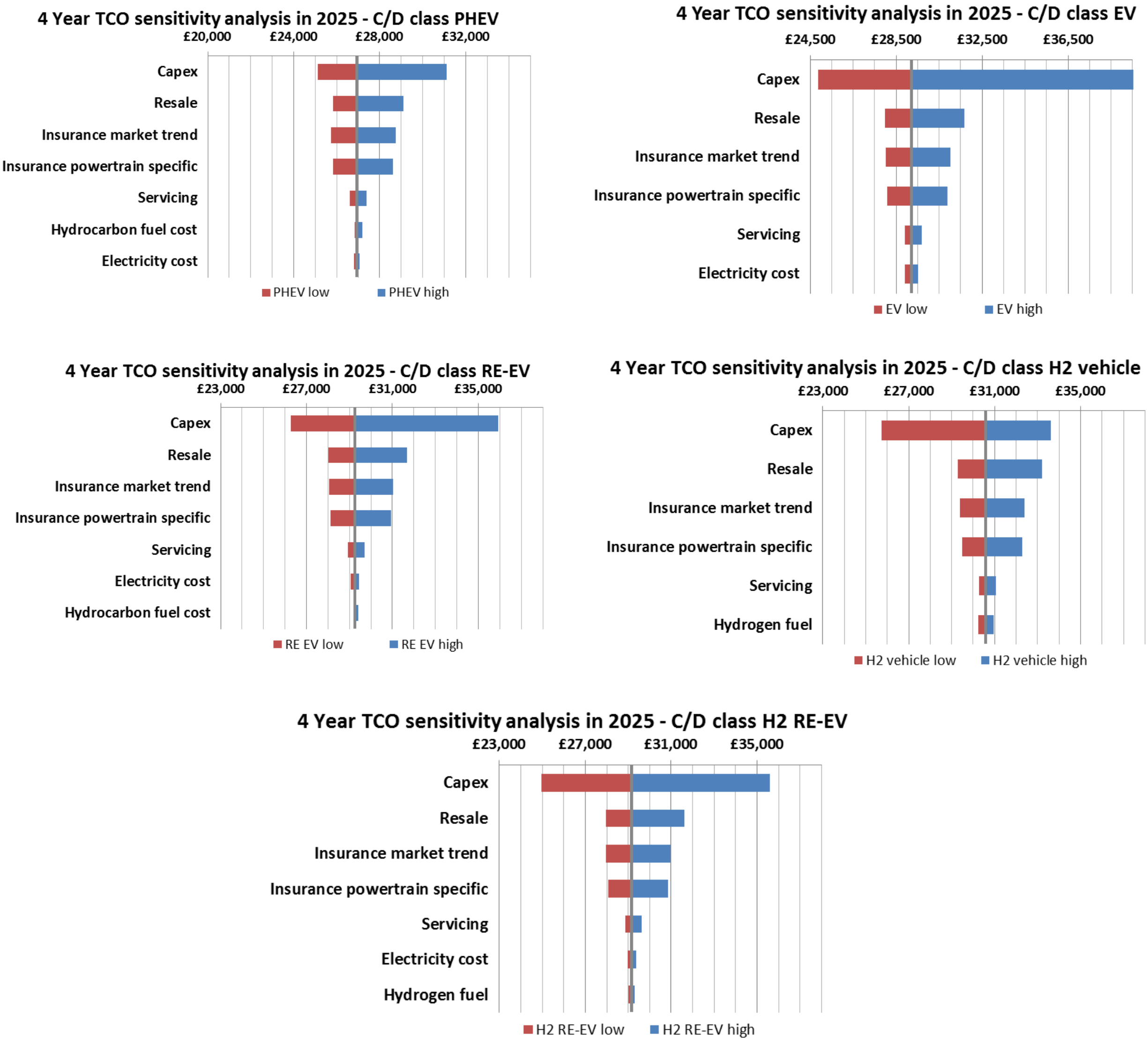
[36] The central projection for insurance cost increases is 3% annual growth (in real terms), applied to all powertrains, with high and low values of 6% year on year growth and zero growth. See Section 6.4.

For all the alternative vehicles beyond hybrids the variation in fuel costs have little effect on the TCO. Fuel costs are always the least sensitive component of the TCO for all alternative vehicles, as seen in Figure 23 and Figure 24.


4 Year TCO sensitivity analysis in 2025 - C/D class PHEV

4 Year TCO sensitivity analysis in 2025 - C/D class EV

4 Year TCO sensitivity analysis in 2025 - C/D class RE-EV

4 Year TCO sensitivity analysis in 2025 - C/D class H2 vehicle

4 Year TCO sensitivity analysis in 2025 - C/D class H2 RE-EV

Figure 23 – Sensitivity analysis to the TCO components for C/D class low carbon vehicles in 2025, the sensitivities used are the 95% confidence intervals for the input fields expressed in Section 3.3

It is interesting to note that the order of the sensitivities (from most to lease sensitive) does not change for the plug-in or hydrogen vehicles. Capex dominates, followed by resale and insurance, with servicing and fuel costs having the least effect on the range of TCOs.

All of the graphs in Figure 23 are shown over a £15,000 range, allowing the relative sensitivities to be directly compared. This is also shown in absolute terms in Figure 24. This allows for a quantitative comparison of the TCO component sensitivities of the different vehicles.

These graphs indicate that the combined effects of insurance[37] play a large role in the uncertainty of the TCO for all the vehicle types. Indeed, insurance sensitivities are higher

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[37] Market trend and powertrain specific costs.

than the effect of a 15% range in resale values. This is partly due to the effect of discounting (at 10%) as the resale value occurs in year four while the insurance costs are incurred at the beginning of each year.

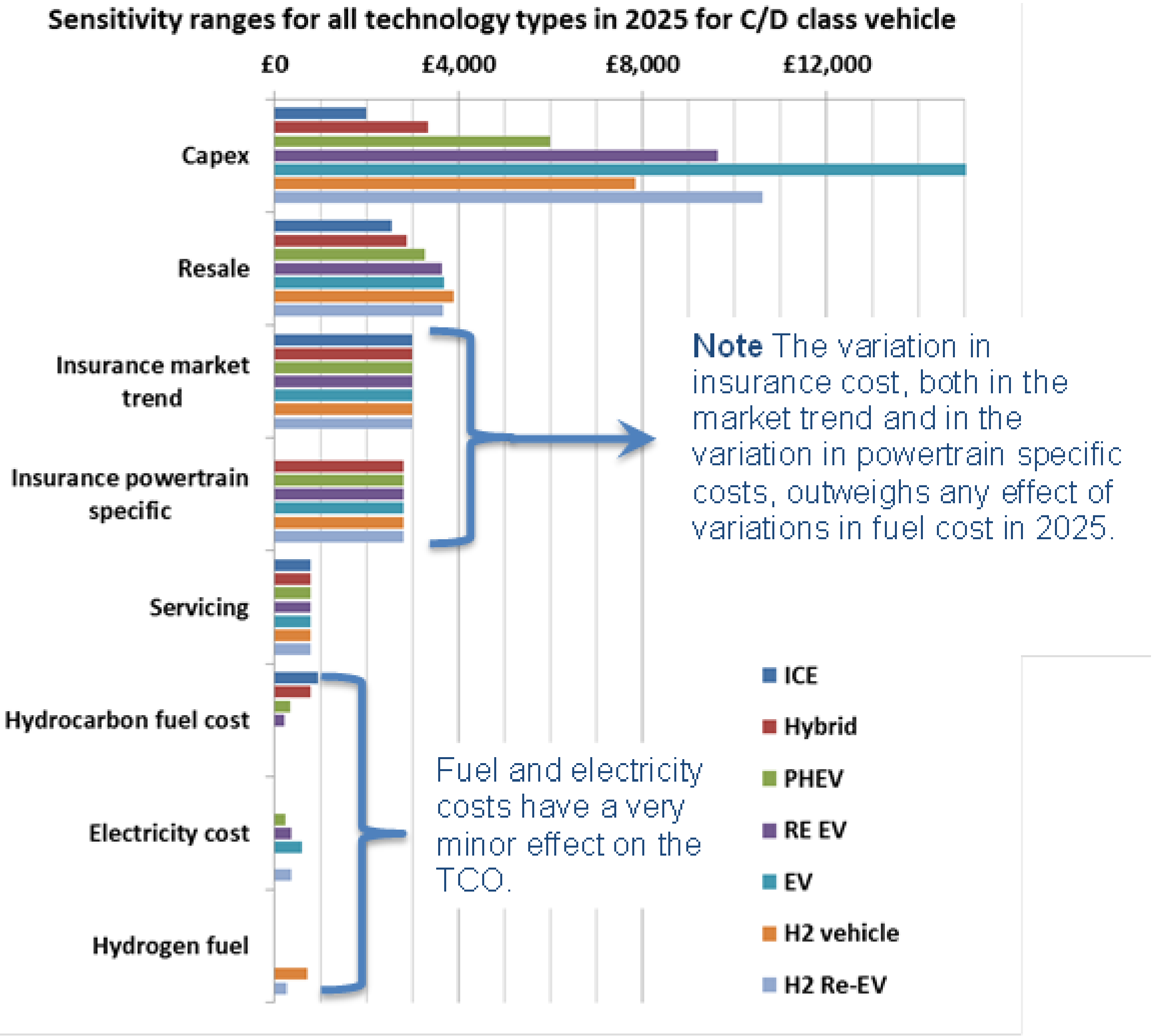

Figure 24 – Comparison of the TCO sensitivity ranges on the TCO values for all vehicle technologies, this graph shows the absolute values from the ranges displayed in Figure 22 and Figure 23 (C/D class vehicle in 2025) See section 6 for the sensitivity inputs.

7.4 "Value shortfall" for alternative vehicles in the Central TCO

The results presented above suggest that alternative vehicles are likely to remain more expensive than ICE vehicles on a TCO basis over the next twenty years unless they provided with ongoing support (or penalties are applied to conventional cars). The support required for alternative vehicles to achieve parity with ICE vehicles (on a TCO basis in 2025) is shown in Figure 25.

This value shortfall in the TCO could be remedied though different methods and policies. Some possible methods are discussed in this section along with the values required to equate alternative vehicle TCOs. It is likely that a combination of measures will be necessary.

Note that this analysis does not include current incentives for low carbon vehicles, such as banded VED and company car tax. VAT on the vehicle purchase price and fuel tax and VAT on fuel are included. The impact of VED on the TCOs of low carbon vehicles is considered below.

7.4.1 Capital Support

The shortfall in the alternative vehicle TCOs ranges from £1,100–£6,400 per vehicle in 2025 for the C&D class. This translates directly into the level of support required to equate alternative vehicles' TCOs to the ICE vehicle (not including any tax incentives that differentiate between vehicles such as VED).

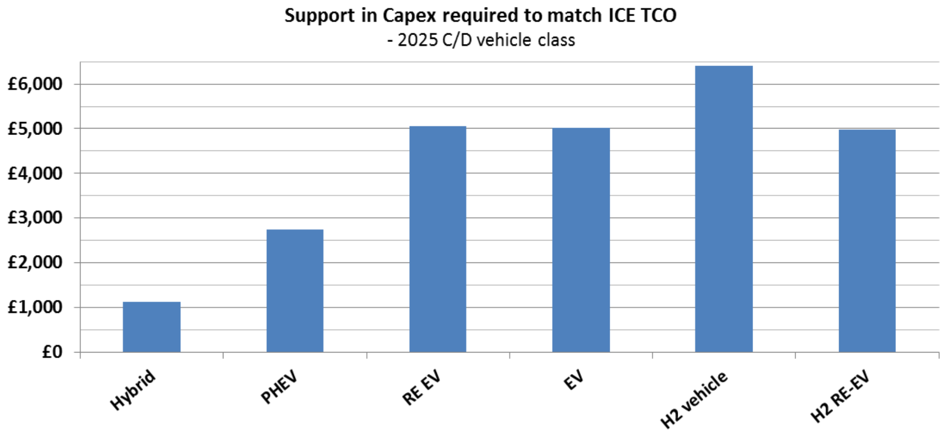

Figure 25 – Required support for alternative vehicles to make the four year TCO comparable to conventional ICE vehicles. Results are shown for the C&D segment only in 2025.

7.4.2 Taxation

The use of differentials in taxation policy between vehicles may allow the government to help equalise the TCOs of alternative vehicles. Many taxes and charges are already banded based on vehicle CO_2 emissions, such as VED (both in the showroom tax and annual charge), company car tax, congestion charging and residential parking fees. These could continue to provide incentives for consumers to purchase low carbon vehicles, though the banding must be reviewed periodically to ensure that only the best-in-class vehicles receive the greatest support. In other words, existing thresholds for taxation or congestion charging must be lowered over time to prevent greatly increased numbers of models from meeting the requirements due to incremental improvements. However, while congestion charging exemption could provide sufficient support to drivers of plug-in or hydrogen cars, it clearly does not affect the economic offer for drivers who do not drive into congestion charging areas. For these consumers, other incentives would be required to make the vehicles attractive relative to the incumbent.

The reduction in capital costs required to equate the vehicle TCOs can be converted to a percentage tax rebate. These are shown in Table 19 along with the required annual cost differential in vehicle tax required to equate the four year TCOs. These values take into consideration the discount rate of 10%.

Table 19 – Vehicle subsidies and changes is VAT to equate alternative vehicle TCOs to the Base ICE TCO. Results are shown for the C&D segment only in 2025.

Vehicle type	Hybrid	PHEV	RE-EV	EV	H_2	H_2 RE-EV
Change in capital required (£)	£1,130	£2,750	£5,060	£5,020	£6,410	£4,980
Percentage change in capital (tax rebate or support)	4.4%	9.5%	15.6%	15.4%	18.5%	15.3%
Annualised value shortfall (£/yr)	£360	£870	£1,600	£1,590	£2,020	£1,570

For vehicles other than the non-plug-in hybrid and the PHEV, the implied subsidy is equivalent to more than halving the rate of VAT payable on the vehicles. Even for the PHEV, if the government were to provide the equivalent of a £2,000 rebated to encourage the purchase of PHEVs, this would reduce revenues by £4bn per year based on 2 million annual vehicle sales. A more revenue-neutral approach could involve the VED ‘showroom tax’ of £1,000 being applied to all conventional vehicles and provided to buyers of low carbon vehicles as a rebate. A VED ‘showroom tax’ of £1,000 is very close to the current maximum value of first year VED (£950) in 2010/2011, though this currently applies only to vehicles emitting more than 255g/km.

Instead of making changes to the capital cost, the value shortfall in the TCO could be met through different pricing structures for annual tax (e.g. VED). Table 19 shows that for any plug in vehicle the annual difference in tax needs to be £870 for the PHEV. As the current VED price structure has a maximum cost differential of £460[38] the structure of VED would have to be overhauled to allow VED to be used to equate alternative vehicles’ TCOs. Currently for the new sales average vehicle the VED is £130[39] which can be reduced to zero by buying a fuel efficient vehicle – this value would need to increase seven fold to provide a sufficient incentive for the PHEV.

As VED alone is unlikely to equalise the TCO it is relevant to consider other current taxations and incentives with possible future taxes. The London congestion charge and free parking for electric vehicles have stimulated the EV market in London. These benefits can equate to annual savings of a £2,025[40] for the congestion charge and £2,250[41] from free vehicle parking. For those making frequent trips into the congestion zone alternative vehicles are likely to have a lower TCO than the Base ICE car.

Note that the current value shortfall in 2010 is approximately £20,000 (for a C&D class EV); this includes the standard vehicle margins. It is likely that the OEMs’ margins on EVs in 2010 are considerably lower than those used in this study, the Nissan leaf is currently

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[38] http://www.direct.gov.uk/en/Motoring/OwningAVehicle/HowToTaxYourVehicle/DG_10012524
[39] 144gCO_2/km.
[40] Based on a congestion charge of £9/day used 225 days a year (45 working weeks).
[41] Based on a parking charge of £10/day used 225 day a year.

sold for approximately £15,000 more than the equivalent vehicle in its class. Including the current government vehicle subsidy of £5,000 this still leaves a value shortfall of £10,000 for the Leaf and £15,000 from this study. As plug-in alternative vehicles are exempt from the congestion charge and there are free parking provisions in London a saving of up to £15,000 over four years is possible over ICE vehicles, this allows currently sold alternative to match the TCOs of conventional cars in London (but in no other UK city).

7.5 Capital support for all vehicles classes

As mentioned in section 7.2.1 there is little difference between vehicle classes in term of the merit order of the vehicle technologies. There are expected differences in the vehicle TCOs and the required support required to equate the alternative vehicle TCOs to the Base ICE vehicle. Figure 26 demonstrates that for all the alternative vehicles types the required support increase as the vehicle size (class) increases. This is expected as the larger vehicles require larger batteries and fuel cells.

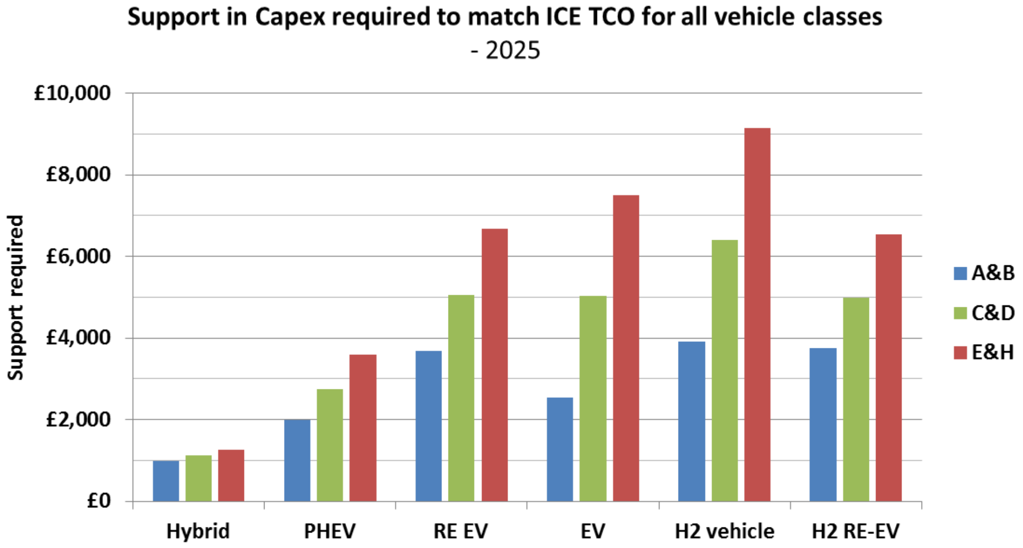

Figure 26 - Required support for alternative vehicles to make the four year TCO comparable to conventional ICE vehicles.

Modifying this support to a percentage of the TCO of the vehicles allows an objective comparison of all the vehicles classes simultaneously. Figure 27 demonstrates that the support required as a percentage of the TCO changes little over the vehicle classes for each of the alternative vehicle types. The range across vehicle classes is at maximum 4%, interestingly the way in which the support required as a percentage of the TCO changes across vehicles classes is different for the alternative vehicle types. For the hybrid and all plug in vehicles the support required as a percentage of the TCO decreases as the size of the vehicle increase and the Hydrogen vehicle relatively fairly constant. Pure EVs conversely increase the support required as a percentage of the TCO as the vehicle size is increased.

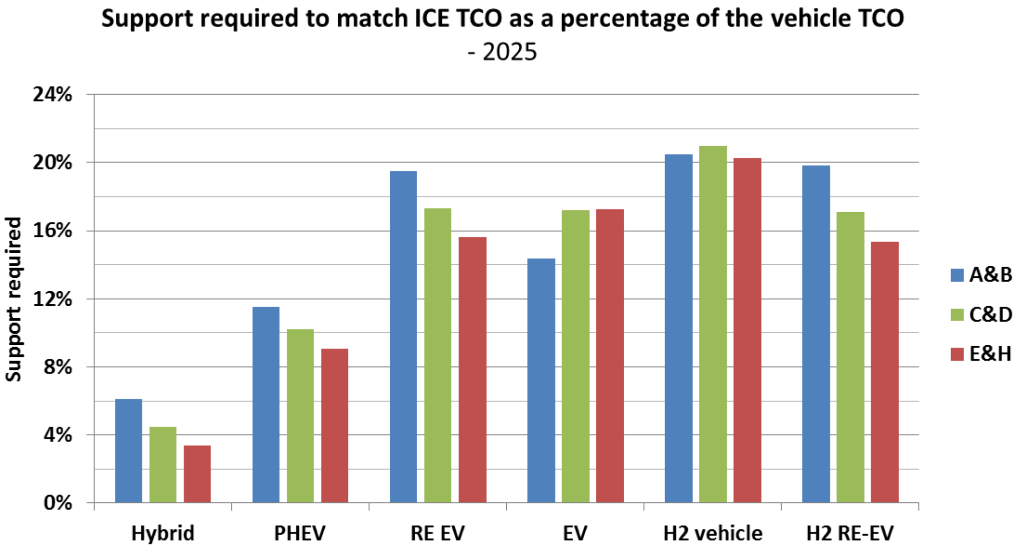

Figure 27 - Support required for alternative vehicles to make their TCO comparable to the ICE vehicles as a percentage of the TCO of the alternative vehicle.

This accounts for the changing of the ‘merit order’ of the EV and hydrogen RE-EV in the larger vehicles as previously discussed in Section 7.2.1 . This graph also highlights potentially why many of the current alternative vehicles are hybrids and not plug-in vehicles and why these vehicles are in the larger vehicle classes.

8 Disruptive scenarios

The Monte Carlo analysis shows the range of possible futures given incremental changes to the vehicles performances and component costs. The following scenarios are intended to illustrate the effects of step changes to the components of the TCO for conventional and low carbon vehicles. They are intended to show target driven futures and the effect of disruptive macroeconomic changes, rather than predictions of what may occur or be achievable. The following scenarios are considered:

1. Step changes in battery and fuel cell costs to \$100/kWh and \$30/kW respectively
2. Fuel shock scenarios where hydrocarbon fuel is increased to £3/l, electricity to £40p/kWh and hydrogen to £8/kg
3. The effect of discount rates where rates of 3.5%, 10% and 20% are considered
4. TCO lifetime, where the TCO period is increased from 4 years to 10 years

8.1 Battery and fuel cell cost reductions

During the Monte Carlo setup the lower bound for the fuel cell and battery costs represent the likely lower bounds for costs from industry consultation and a review of literature. This scenario goes beyond what most experts consider as a lower bound for the incremental change in battery and fuel cell costs and performance.

This scenario uses the DoE targets for battery packs and fuel cell stacks. It is important to note that these targets are based on allowing battery and fuel cell vehicles to compete with a Base ICE vehicle. These targets will require step changes in battery and fuel cell technologies to achieve the required cost and performance targets.

The cost and performance inputs are shown in Table 20.

Table 20 Battery pack and fuel cell system cost and performance targets specified by the US DoE[42,43]

Parameter Battery pack	Central	US ABC long-term goal
Specific Power (W/kg) – 30s	c. 200	400
Specific energy (Wh/kg)	<150	200
Cycle Life (80% DOD)	As current	1,000
Cost (\$/kWh)	\$400 in 2025, \$300 in 2030	\$100/kWh

Parameter Fuel Cell system	DoE Long term goal
Cost (\$/kW)	\$30/kW

Under these cost assumptions, EVs become competitive with conventional cars over a four year TCO as highlighted in Figure 28. Both hydrogen fuelled vehicles also come within £1,340 of the Base ICE’s TCO. When the battery and fuel cell costs are reduced to such a degree, the economics favour single energy sources over more complex hybrid powertrains. The PHEV and RE-EV now have the highest TCO as they have multiple drivetrains and therefore added components. These additional component costs are not sufficiently offset by the reduction in battery capacity or fuel cell size (and hence cost).

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[42] http://www.uscar.org/commands/files_download.php?files_id=27
[43] http://www.hydrogen.energy.gov/pdfs/review09/program_overview_2009_amr.pdf

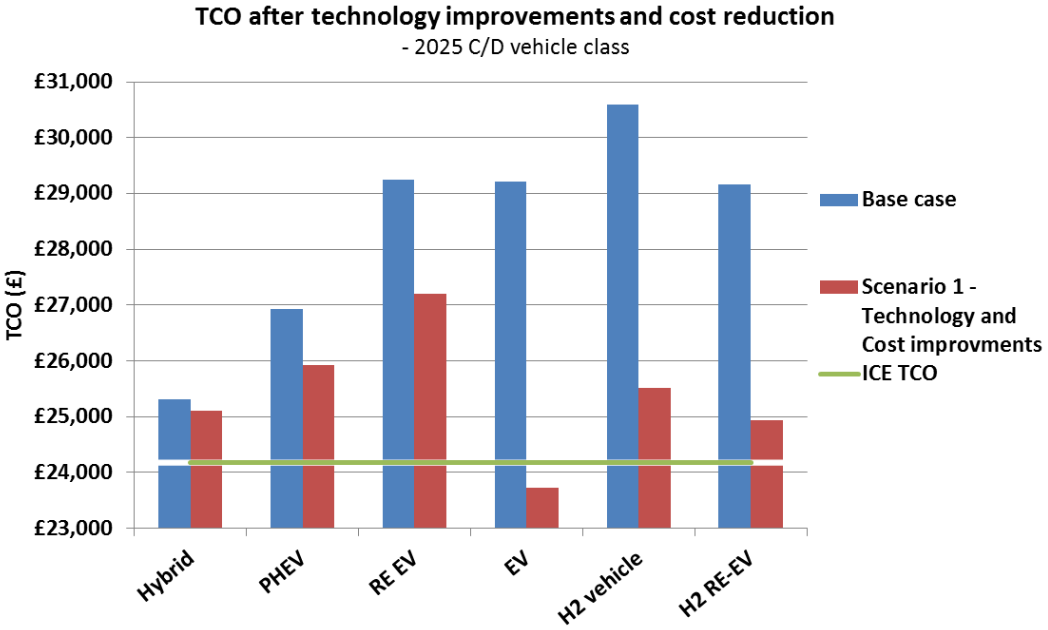

Figure 28 – TCO before and after the implementation of drastic cost reductions in battery and fuel cell costs and the improvement in battery energy density. Results are shown for the C&D segment only in 2025. All costs and performance changes are target driven by the DoE long term targets.

8.2 Fuel prices

The following scenario is designed to test the effect of fuel cost 'shocks' to on the TCO. The inputs here are designed to demonstrate the strength of the effect that extreme fuel prices have on the TCOs.

Table 21 – values and explanations of the fuel shock scenario inputs

Fuel average costs (2025–2029)	Central	Fuel shock	Supporting information/ Context
Hydrocarbon (£/L)	£1.28	£3	Resulting from oil price shocks, due to supply shortages, geopolitical factors etc.
Electricity (p/kWh)	20p	40p	A tripling of the high fuel price in 2011. This could arise due to expensive infrastructure and storage requirements resulting from a large proportion of renewable generation on the grid, lack of low cost CCS/nuclear and high cost of low carbon generation incentives such as the Feed-in Tariff.
Hydrogen (£/kg)	£4.61	£8	This could reflect the lack of cost reductions with increasing volumes, lack of volume sales, increased production costs (from increases in primary feedstock costs) and possible taxation on hydrogen as a road fuel

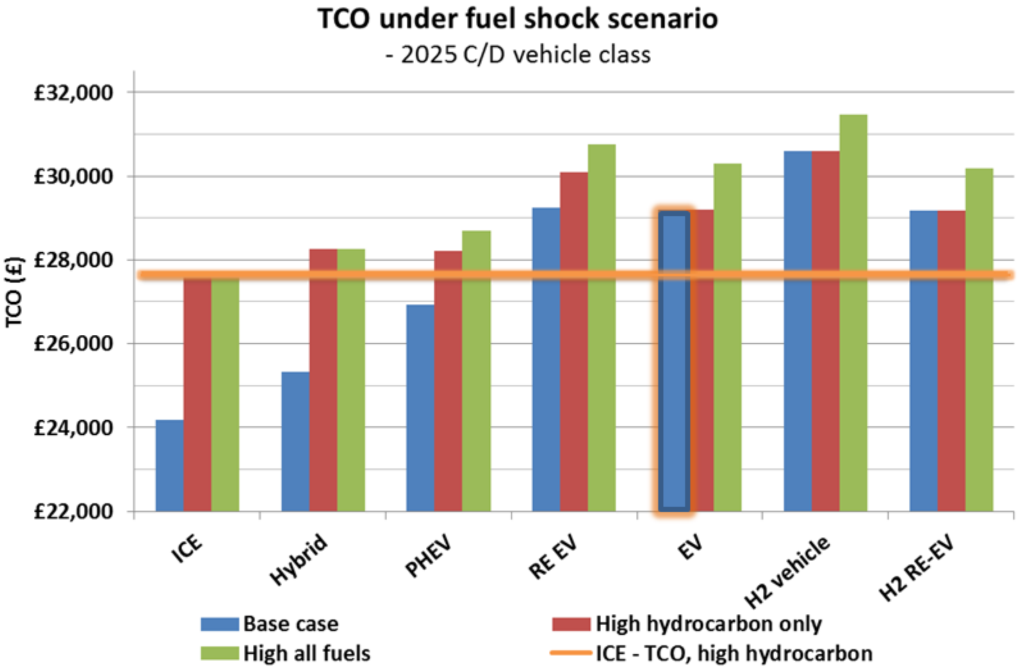

Figure 29 – TCO under fuel shock scenario highlighting the ICE TCO with a fuel cost of £3/l. Results are shown for the C&D segment only in 2025.

If the hydrocarbon fuel price increases to £3/l and the electricity and hydrogen prices were to remain at the levels in the central scenario the cost premium of £5,000 for EVs and hydrogen RE-EVs decreases to £1,500. This shows that although there would be significant fuel cost saving these would not be enough to cover the additional capital cost of alternative vehicles.

It is interesting to note in Figure 29 that tripling the electricity price has a relatively small effect on the TCO of the EV, even when the EV is travelling 15,000km annually. This is due to the relatively small contribution of fuel costs to the overall TCO for pure battery electric vehicles (see Figure 22).

8.3 Discount rates

Discount rates can have a large effect on the relative merits of the different vehicles' TCOs. The 10% discount rate that has been used throughout (and explained in Section 6.6) is used in the central scenario. The lower bound used is the standard government discount rate of 3.5%. This 3.5% discount rate is already higher than a zero rate used in many other studies on total costs of ownership. The upper discount rate of 20% was chosen to represent a commonly utilised discount rate to represent a consumer's approach to future costs.

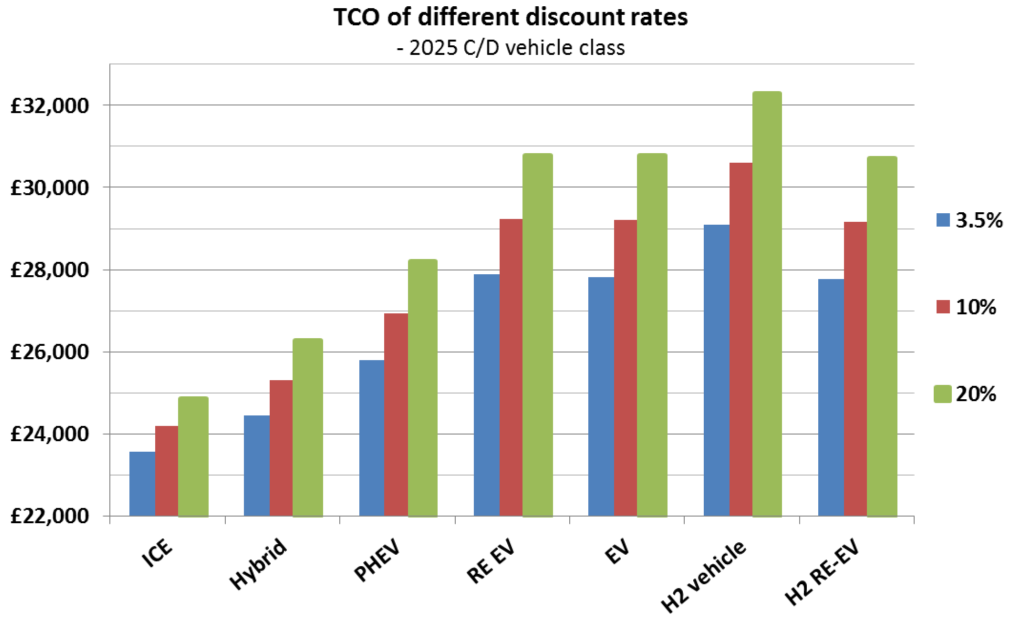

Figure 30 – Four year TCO values under different discount rates, 3.5%, 10% and 20%. Results are shown for the C&D segment only in 2025.

Increasing the discount rate increases the TCO of all vehicles. This is because it reduces the perceived value of the car at resale and hence the 'net' purchase price rises. This effect outweighs the reduction in perceived fuel and insurance costs. High discount rates also increase the range over which the TCOs are distributed. It is interesting to note that even a 3.5% discount rate is not sufficient to equalise the four year TCO between the conventional car and the PHEV. This value shortfall is shown for the three discount rate assumptions in Table 22.

Table 22 – Subsidy and shortfall for different discount rates, C&D class in 2025

Discount rate	ICE TCO	PHEV TCO	Shortfall
3.5%	£23,600	£25,800	£2,200
10%	£24,200	£26,900	£2,700
20%	£24,900	£28,200	£3,300

8.4 Ten year TCO

As the ongoing costs of alternative vehicles are lower than the Base ICE vehicle it would be expected that the longer the TCO period the more comparable ICE and alternative vehicles would be on a TCO basis. However, changing the period over which the TCO is calculated has little impact on the relative attractiveness of conventional and low carbon vehicles.

A 10 year TCO was chosen to represent an average expected lifetime and mileage of a vehicle (150,000km). No additional servicing requirements were introduced above tyre and brake replacements and annual servicing. There is no consideration for reduction in battery performance or provision for battery replacement. The effect of battery replacement on a ten year TCO is discussed in Section 8.4.1.

The Monte Carlo run of the 10 year TCO looks very similar to the four year TCO in terms of its distributions and order of vehicles. Figure 31 below shows both the four year and 10 year TCOs. The same range is used on both figures (£21,000) allowing the distribution to be directly compared side by side.

The TCO distribution over ten years are broader than over four years, this is not unexpected as there is a greater uncertainty over longer timescales. The PHEV and hybrid vehicles' TCOs move marginally closer to the ICE vehicle's distribution. However all the other vehicles do not become more comparable to the ICE vehicle for a ten year TCO compared to four years.

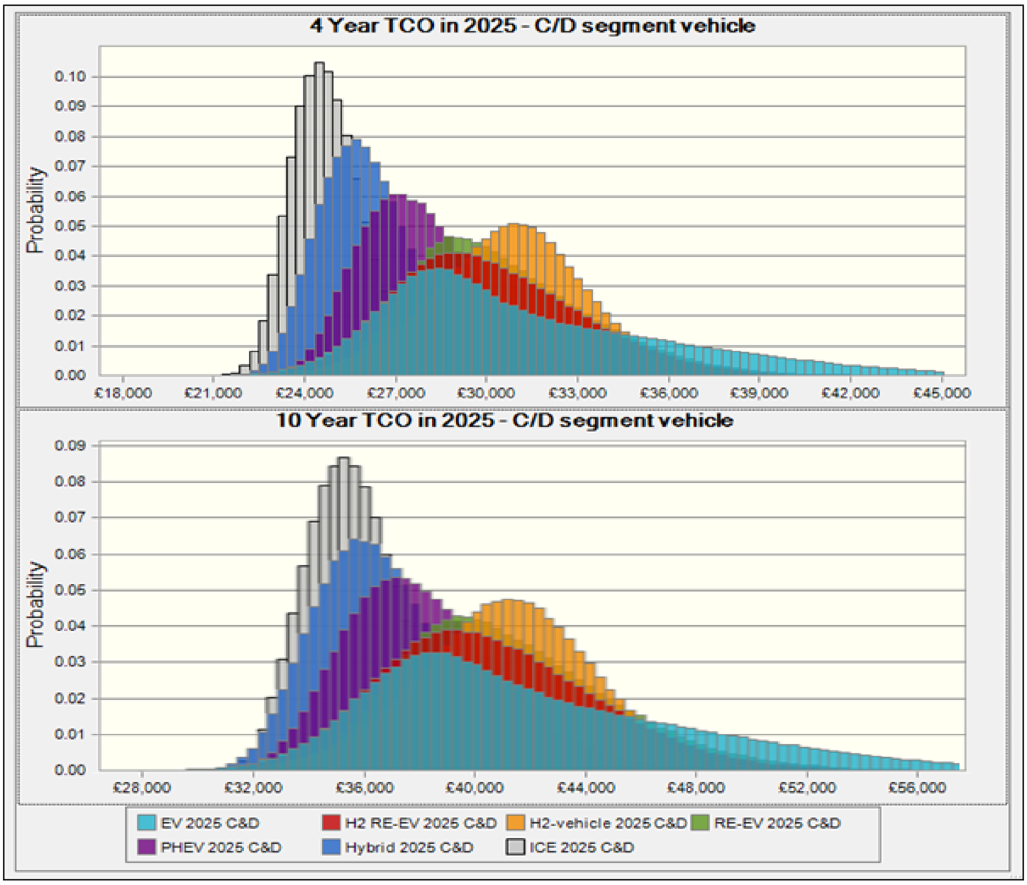

Figure 31 – 10 year TCO in 2025 for the C&D class vehicle segment, Monte Carlo analysis of 500,000 runs

As expected the contribution of the ongoing costs as a fraction of the overall TCO is larger over ten years than over four years (Figure 32) but the effect is relatively limited. The capital cost including resale has a larger absolute value over ten years than over four (Figure 33). This is the result of a combination of to two factors: discounting and vehicle depreciation.

In the TCO calculation the capital cost of the vehicle is being partially offset by the discounted resale value of the vehicle. As the discount rate is 10% any resale value left in year 10 is heavily discounted (by a factor of 0.42), whereas in the four year TCO calculation the resale value is only discounted by a factor of 0.75. This means that the capital costs is offset by the resale of the vehicle by a much lesser degree in the ten year TCO calculation than the four year calculation. Hence the absolute value of Capex including resale is much higher in a ten year TCO than a four year TCO as shown in Figure 33.

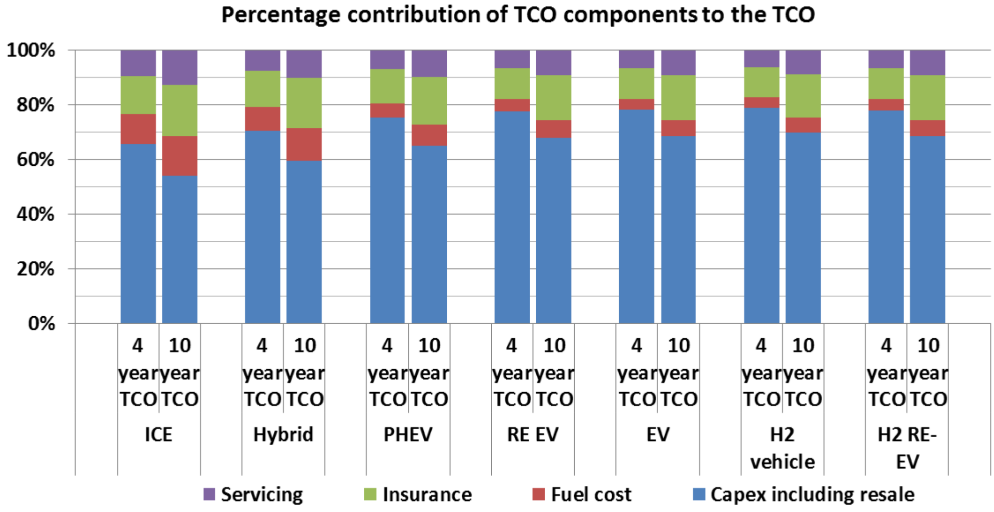

Figure 32 – Comparison of contributions to the TCO for four year and ten year TCOs. Results are shown for the C&D segment only in 2025.

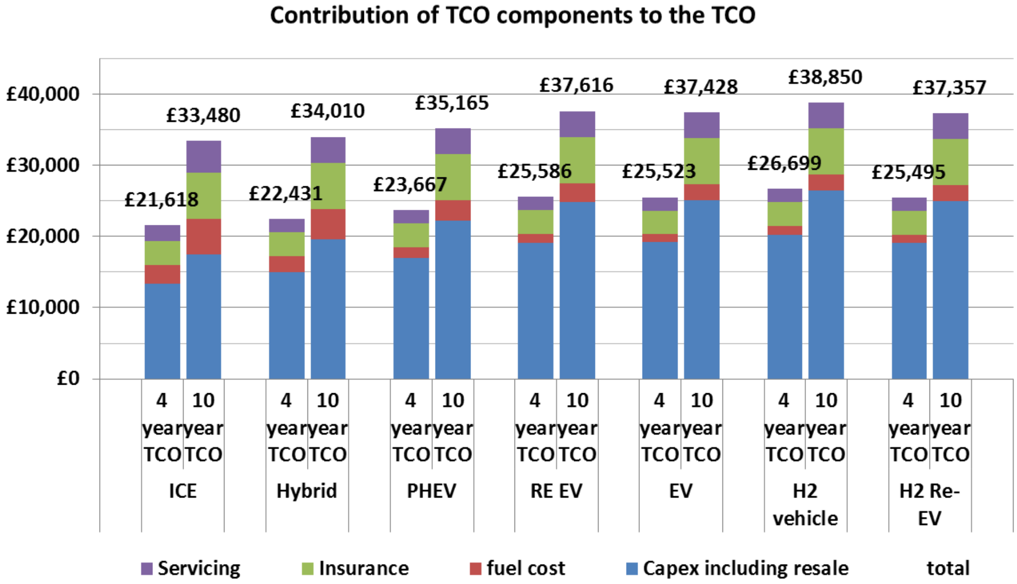

Figure 33 – Contribution of different TCO components to the TCO for four year and 10 year TCO timescales. Results are shown for the C&D segment only in 2025.

The surprising effect of increasing the TCO to ten years is visible when we compare the required support to equate the TCOs to the ICE vehicle over four and ten years. Figure 34 shows that the required support changes very little by changing the period over which the TCO is calculated, this is especially true for the vehicles with a high capital cost. This shows that the capital cost including resale value of the vehicle is only marginally offset by a reduction in ongoing costs. The PHEV shows the greatest reduction in required subsidy as the greatest fuel cost reductions are gained for the least additional capital cost (see Section 9).

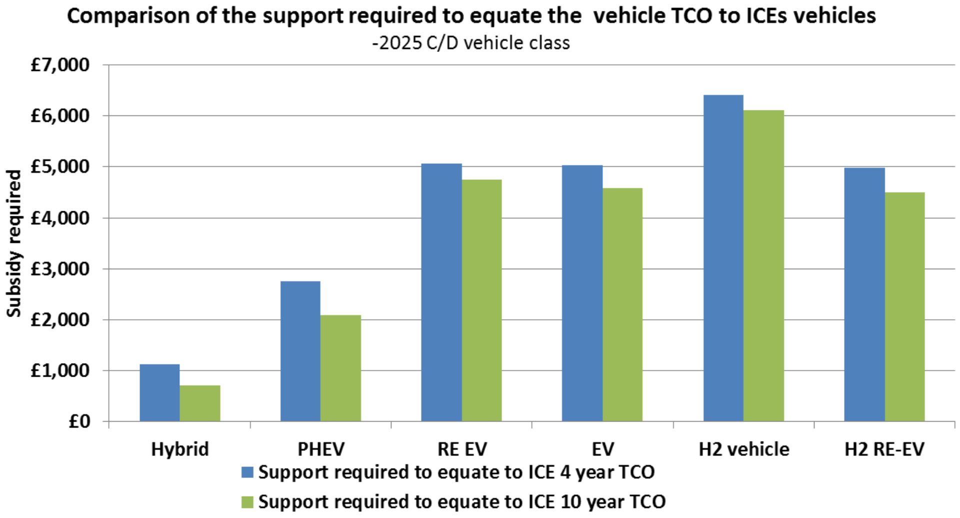

Figure 34 – Support in year one required to equate alternative vehicle technologies to ICE vehicles over the TCO periods of four and ten years. Results are shown for the C&D segment only in 2025.

Figure 35 shows that the annual support required to equalise the TCOs of low carbon cars to that of the Base ICE is significantly lower for a 10 year TCO. For example, the amortised support for the PHEV drops from £690 to £210 per year. This simply reflects the fact that a similar level of total support can be given over a longer period in smaller annual amounts.

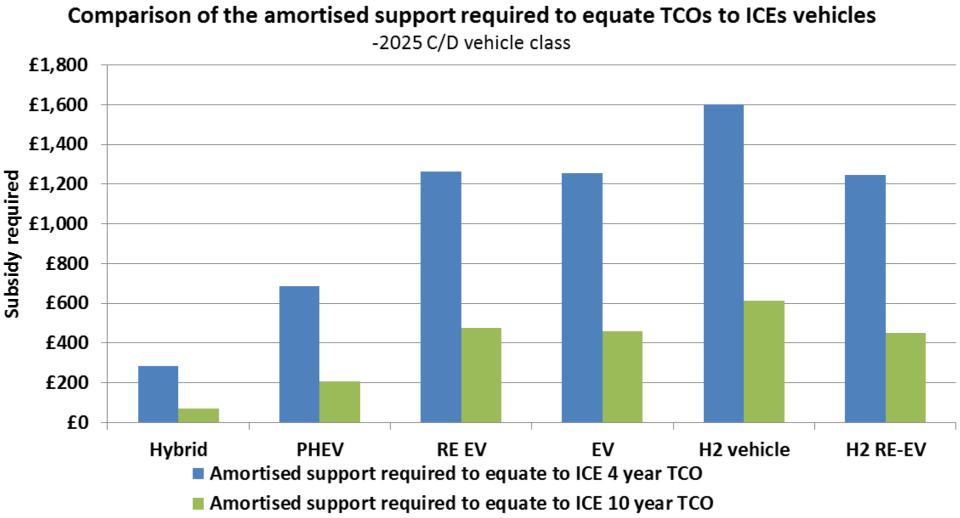

Figure 35 – Amortised support required to equate alternative vehicle's TCO to the ICE vehicle over the TCO periods of four and ten years. Results are shown for the C&D segment only in 2025.

8.4.1 Battery replacement effects on 10 year TCO

If battery replacement is included in the 10 year TCO in year 5[44] (2030) for all technologies where the battery is an integral part of the drive train, i.e. RE-EVs and EVs, then the TCOs of the vehicles change significantly. All of these vehicles' TCOs increase by between £1,700 and £5,000 for the C&D class vehicles (this includes five years of discounting and battery costs at 2030 values).

Including replacement batteries in the 10 year TCO further worsens the vehicles' TCOs relative to the ICE vehicle. Adding this can double the required subsidy for EVs and increase by 30% the required support for each of the vehicles with batteries, as shown in Figure 36.

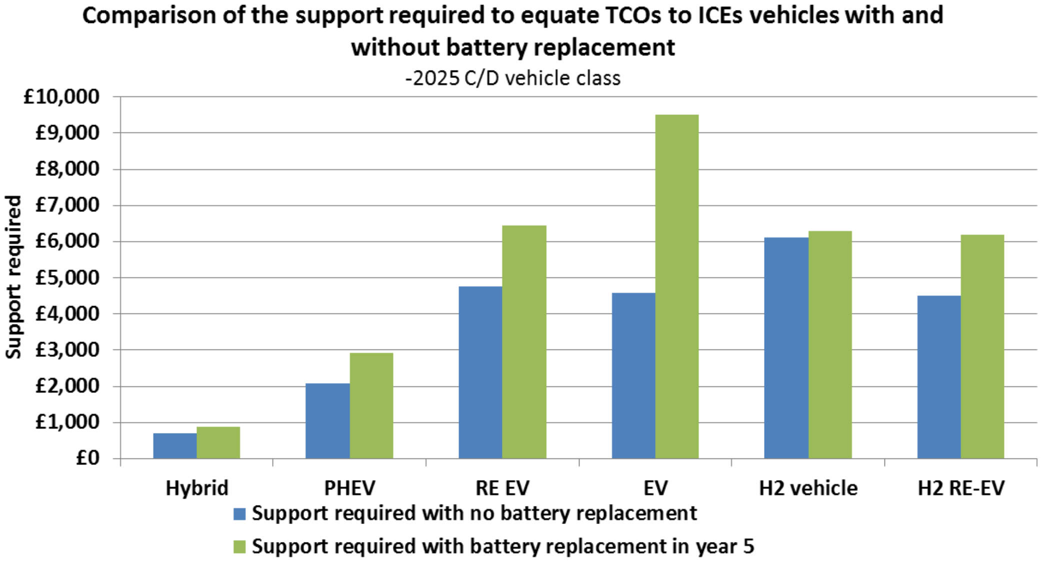

Figure 36 - Support required to equate alternative vehicle technologies to ICE vehicles over a TCO period of ten years, with and without battery replacement. Results are shown for the C&D segment only in 2025.

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[44] Consistent with the Nissan Leaf battery warranty

8.5 Vehicle utilisation

Results from analysis presented above are based on simplifying assumptions on vehicle users that assume a single driving pattern for all consumers. This assumption allows all vehicles to be compared equally over the same annual driving distance and vehicle usage patterns (Section 4.3).

In reality different people use vehicles in different ways. This includes different driving patterns and annual mileage. Through manipulation of the NTS data it is possible to model the effect of driving patterns on the performance of plug-in vehicles.

Method

The NTS give detailed information on the number of journeys taken (number of starts), the distances of these journeys and who is taking the journeys. As each user undertakes a different number of journeys and different lengths of journeys it is possible to create different driving profiles for different vehicle users. These driving profiles can be used to generate distribution curves for total annual mileage (Figure 37, left) and the proportion of annual mileage travelled by journeys of a particular length (Figure 37, right). These new distribution curves are used to calculate the annual fuel use of the vehicles for each of the fuel types.

The easiest way to disaggregate users based on their vehicle is to use company cars and non-company cars as a metric, which is recorded in the National Travel Survey. It has been assumed that all respondents using a company car as their primary vehicle completed their travel diaries for that vehicle, as this is not explicitly recorded in the NTS.

This disaggregation allows different annual mileages to be calculated using the NTS data and the disaggregation of trip length by vehicle type as shown in Figure 37.

The average annual distances driven by “business” cars and “non-business” cars are 22,600 km and 12,800 km respectively.

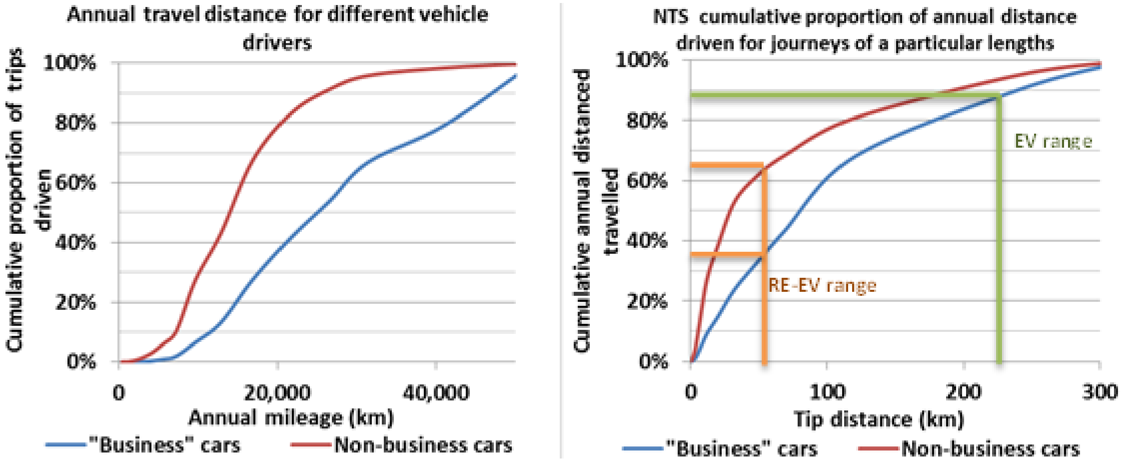

Figure 37 – Annual travel distances by driver type (cumulative) and cumulative proportion of annual distance travelled by trip distance for different vehicle types. Original data from the NTS.

Using these new inputs for annual distance travelled and journey statistics we then calculate the proportion of trips and distance that could be covered by a plug-in vehicle with a set electric range. For example, for non-business users 65% of annual distance occurs in trips less than the range of a RE-EV (60km), while for business users that figure is only 35%.

8.5.1 TCO results for company car drivers

Figure 38 shows the TCO differential for all vehicles relative to the conventional ICE for the business and non-business travel patterns. For all the alternative vehicles the subsidy required to equate the TCOs to the ICE is less for the "business" vehicles than for the "non-business" vehicles. This is due to the "business" vehicles travelling considerably further than the "non-business" vehicles. This is an important result. In other words, even though the proportion of trips completed in electric mode is lower for business users in the PHEV and RE-EV, the annual fuel savings are still higher than for non-business users because their absolute usage is higher.

This result assumes that company car drivers are able to recharge their vehicles at the end of each trip, rather than simply charging at home at the end of the working day. If vehicles are only charged at the end of return trips, the annual distance covered using electricity will be significantly lower with an associated reduction in fuel and CO_2 savings.

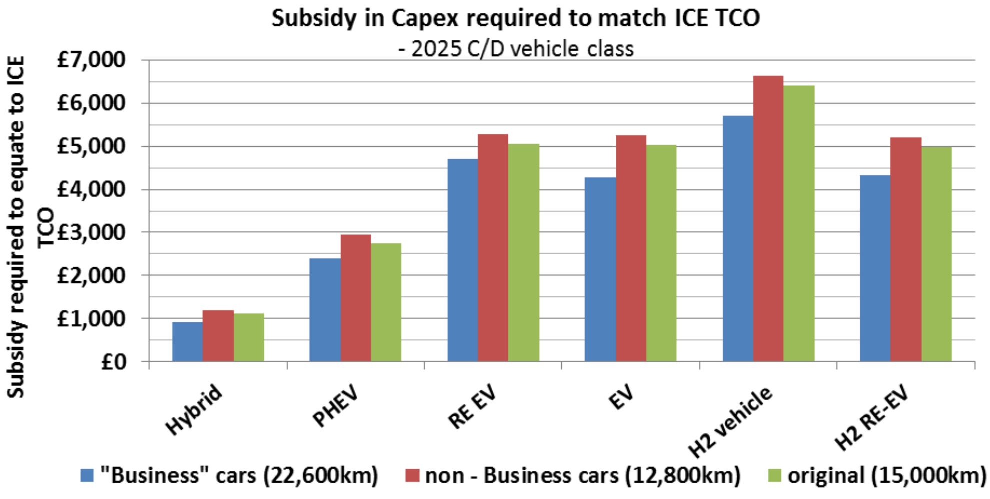

Figure 38 – TCO differential relative to the Base ICE under different driving patterns. Results are shown for 2025 C&D class vehicles only.

8.5.2 CO_2 emissions for company car drivers

Tailpipe emissions were recalculated based on the new travel patterns, taking into account the different fraction of the annual driving distance completed in electric mode. These values are shown in Figure 39. The emissions for the Base ICEs and non-plug-in hybrids are identical for business and non-business users as we have not taken account of differences in fuel efficiency for urban and extra-urban driving. However, the PHEV and RE-EV show a significant difference. PHEV tailpipe emissions rise from $37gCO_2$/km for non-business users to $48gCO_2$/km (a rise of 30%), reflecting the increased

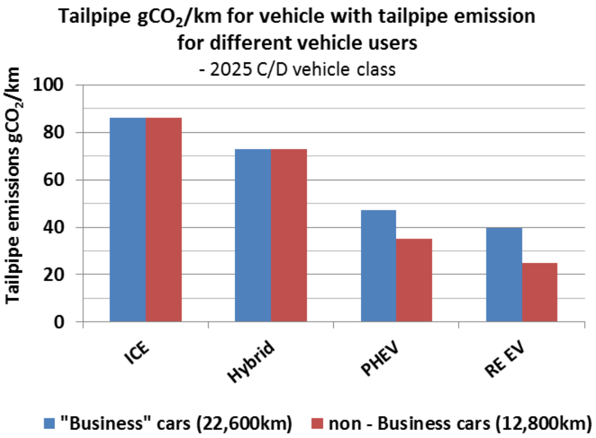

Figure 39 – Tailpipe gCO_2/km figures for different user groups based on different journey statistics

reliance on liquid fuels for the longer distance trips. RE-EVs show a similar trend, with emissions rising from 22gCO_2/km in 2025 to 40gCO_2/km.

Figure 40 shows the effect of driving patterns on a cost-effectiveness metric (in terms of £/gCO_2/km). The main conclusion is that EVs become more cost-effective than PHEVs for business users, since they deliver substantial fuel cost savings over the higher annual driving distance. At first glance this appears an anomalous result, as in reality a pure EV could not complete 100% of business trips with a range of only 220km. However, Figure 37 shows that an EV with a range of 220km (the assumed value for the C/D vehicle in 2025) is able to complete up to 88% of the annual driving distance of business users if recharging facilities are available at the end of the long trips. This suggests that such an EV could be highly suitable for an average business user, particularly in a vehicle fleet where ICE vehicles were available as substitutes for the very longest trips.

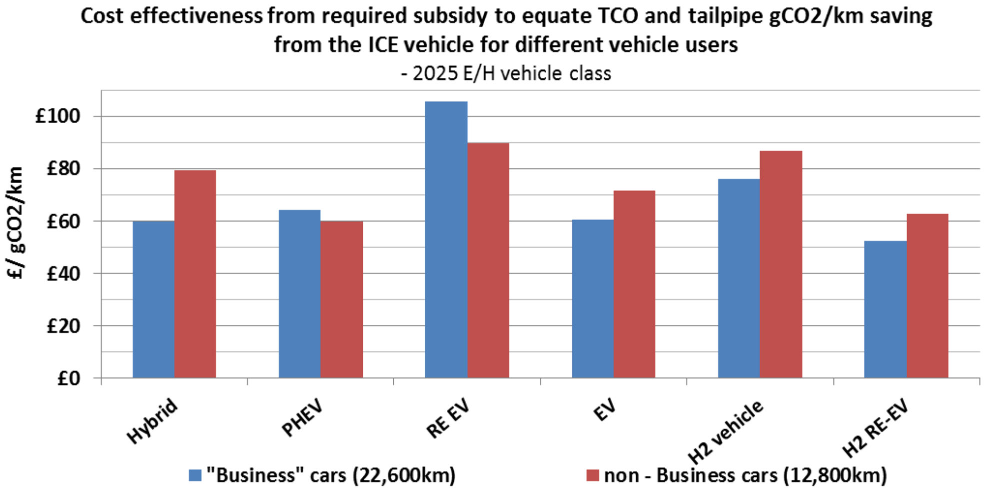

Figure 40 - The relative cost effectiveness of the subsidy required to equate the four year TCO to the ICE TCO relative to the gCO_2/km improvement over the ICE vehicle, for all alternative vehicles, for different driving types. Results are shown for the E&H segment only in 2025.

Note that RE-EV (and to a lesser extent the PHEV), have a lower 'cost-effectiveness' for business cars than non-business cars, in terms of the amount of support required to reduce emissions by 1g/km. This is because although the TCO is more favourable for business users due to higher annual driving distances, the real-world emissions per km are significantly higher than for non-business users because of the increased use of liquid fuels rather than electricity. However, it should be noted that this effect would not be captured by current emissions testing methodologies (e.g. the New European Drive Cycle), as it would not reflect the higher CO_2 emissions for longer average trip lengths.

In summary, the high mileage of business users leads to low carbon (plug-in or electric) vehicles having total costs of ownership closer to the Base ICE compared with private motorists. However, this group is also likely to have higher emissions per km unless sufficient infrastructure is available to ensure that the vehicles are used in electric mode for the highest proportion of their total driving distance.

8.6 Leasing models

8.6.1 Battery leasing for EVs

The analysis above has shown that the total costs of ownership of battery electric vehicles remain higher than a conventional car between 2010 and 2030. The cost of the battery itself is the biggest contributor to this cost premium. For example, at the 'central' battery cost assumptions in this study, the battery for a C/D segment car in 2025 is still over £7,000. The cost of batteries, combined with uncertainty over their performance over a typical vehicle lifetime of 10-12 years, has lead several OEMs to offer battery leasing rather than outright ownership. Under the model proposed by Renault, consumers would purchase an electric car for the same upfront cost as a petrol/diesel equivalent, and this price would not include the battery. The battery would then be leased for a monthly fee, and the arrangement would allow battery swaps at Better Place swapping facilities.

Better Place in conjunction with Renault charges €199 – €249 (£178 – £222) for battery leasing[45] for the Renault Fluence ZE. This is equivalent to c.£10,000 over 4 years of ownership, which leads to considerably higher total costs of ownership than a conventional car, even when lower fuel bills are taken into account. In other words, with batteries at current prices, neither outright purchase nor a battery leasing model allows electric vehicles to compete with ICEs on total costs of ownership.

It is possible to calculate the 'maximum' battery lease fees that could be charged in future by a vehicle manufacturer if an EV is to have a similar TCO to a conventional vehicle. This is shown in Figure 41. If only the capital and running costs of the ICE and EV are included (while excluding the battery cost), the TCO of a C/D segment EV in 2025 is £2,400 lower than an ICE. This means that the OEM could charge up to this amount over 4 years, equivalent to £50 per month, and the EV would still have lower total costs. However, this charge would be significantly lower than the charge required by the OEM to recoup the cost of the battery. The cost of a battery for a C/D segment vehicle is £7,300 in 2025; if the OEM wished to recover 50% of this cost over the first four years of car ownership, it would have to charge a total of £110 per month, or £60 more than the 'maximum' that consumers would pay if they insisted that the TCO is equal to that of an ICE car. Note that this assumes that the battery has no value at the end of its life (c.8 years). It is possible that automotive batteries will find a second life in stationary power/energy storage applications, but it remains to be seen whether this will be reflected in a resale value for end of life battery packs.

A key area of uncertainty in a battery lease model concerns the residual value of an EV without a battery. It is possible that such a vehicle would have a high residual value, as it requires much less maintenance than a 4 year old ICE due to fewer moving parts, and the new owner can simply sign a new battery lease agreement and use a new battery (or batteries in the case of a swapping scheme). Alternatively, consumers may be nervous about buying any second vehicle which commits them to a potentially expensive lease arrangement and cannot be used without it, and hence place a very low value on such a vehicle. If the market behaves in the former case, this could have a strongly positive influence on the total costs of ownership of an EV, as it would reduce vehicle depreciation which is one of the largest costs of vehicle ownership. If the residual value of such a vehicle was to be 20% higher than an equivalent ICE car after four years (equivalent to c.£2,000 on a car with a residual value of £10,000), the total costs of ownership for an EV would be within £500 of a conventional car by 2030. These market trends will become

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[45] This includes recharging in Better Place locations and battery swaps. See http://www.betterplace.com/ for details.

clear over the next three or four years as the first generation of EVs sold with battery leases reach the end of their contract periods.

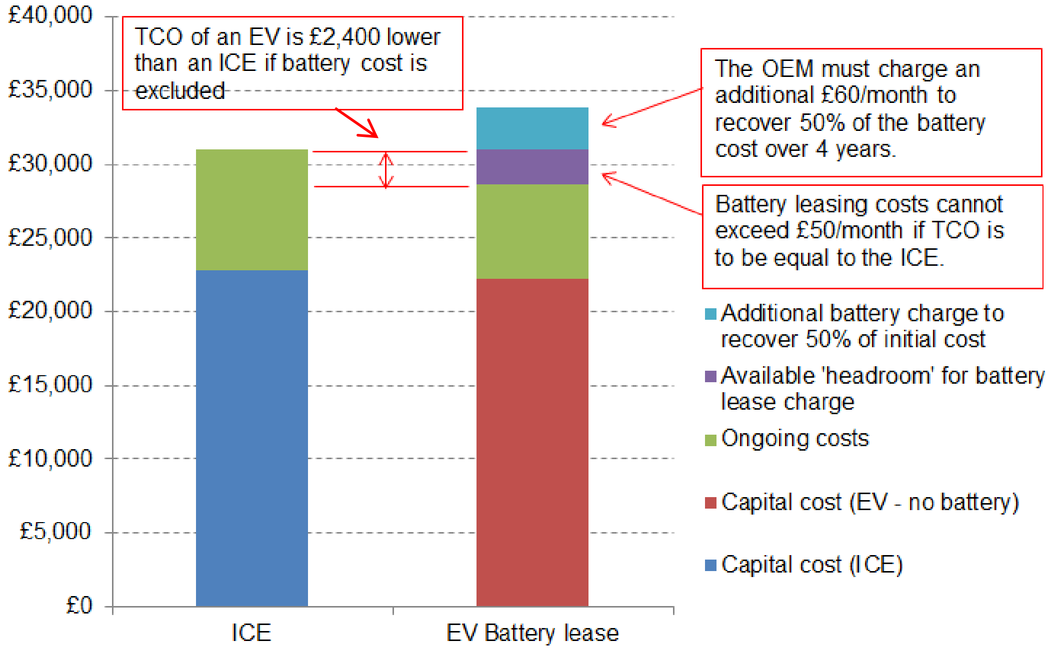

Figure 41 Comparison of EV and ICE costs under a battery leasing model

8.6.2 Vehicle leasing

Throughout this report, we have focused on the costs of car ownership for vehicles purchased outright and sold at the end of four years. However, many fleet and private users often lease their cars, preferring to pay a monthly fee rather than purchase the vehicle outright. The precise terms of leasing arrangements vary across leasing companies, for example whether they include servicing and maintenance, initial payments, or an option to buy the vehicle at the end of the lease for a guaranteed price. It is expected that broadly similar arrangements will be available for low carbon and conventional cars in future.

Assuming that lease companies will seek similar profit margins when leasing different powertrain types, the monthly fee charged to users will depend primarily on the capital cost of each car and its residual value after 4 years, since this difference must be recouped through the lease fees. The analysis carried out in Section 7.4 on the TCO of vehicles relative to the ICE vehicle show that there is always a cost premium on low carbon cars. This suggests the monthly fees charged for these vehicles will be higher than for conventional cars. In other words, if a car is more expensive to purchase, it is also likely to be more expensive to lease. This suggests that leasing models on their own will not be sufficient to allow low carbon cars to compete with the incumbent on a total cost of ownership basis.

Vehicle leasing could play an important role in reducing the capital cost barrier of low carbon vehicles, by allowing consumers to repay this through higher monthly payments. This is particularly beneficial to users who do not have access to savings or low cost finance with which to purchase a vehicle outright. In addition, leasing companies may be able to offer lower insurance and servicing costs than would be available to private buyers. Though this benefit applies to all powertrains (including conventional cars), it may be more important for low carbon powertrains where guaranteed insurance and servicing costs reduce perceived risks for consumers.

The ability to reduce risk for vehicle users could be the largest benefit of leasing for low carbon cars. Uncertainty over the costs and ownership experience of novel technologies is often a significant barrier to purchase. This uncertainty falls into two broad categories:

- Perceived technology risk concerns the vehicle not performing as expected. This could include lower fuel bill savings or electric range in the real world than claimed by manufacturers, or through technology failure such as breakdowns or excessive battery degradation. Leasing models lower the perceived risk by placing the onus on the lease company to provide a working vehicle throughout the lease period.
- Cost uncertainty, both of the vehicle resale value and other ownership costs such as servicing and insurance. Uncertainty over the resale value of novel powertrains (particularly pure electric vehicles) is considerable, as there are no historical data on the long term performance and reliability of plug-in vehicles.

These uncertainties reduce the number of consumers willing to purchase an alternative vehicle[46]. Vehicle leasing has the potential to remove a large part of the technology cost uncertainty and part of the performance uncertainty of alternative vehicles by moving the risk from the consumers to the vehicle leasing company. As the market for plug-in vehicles develops, it is likely that existing lease companies will offer these vehicles alongside conventional cars, and stakeholders should monitor whether consumers show a stronger preference for leasing rather than owning low carbon cars, allowing leasing offers to be tailored to offer the optimal combination of cost and risk reduction to prospective customers.

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[46] LowCVP conference presentation 2011, John Batterbee ETI

9 Costs of CO_2 abatement

Reducing fleet average gCO_2/km is an important factor for vehicle manufactures and OEMs face penalties if they fail to meet targets for average vehicle carbon emissions. It is therefore important for them to calculate the most cost effective way of reducing their sales weighted vehicle emissions.

CO_2 targets can be measured in three main ways; tank to wheel (tailpipe emissions); 'well to wheel'[47]; and life cycle emissions. All of these are considered in the following section.

Using the previously calculated support levels required to equalise the alternative vehicles' TCOs to the conventional vehicle, it is possible to calculate the costs per gram of CO_2 per km saved.

It is important to note that these cost effectiveness calculations use the subsidy required to equate the TCO and do not take into account any additional infrastructure costs that may be required as part of the technology.

9.1 Tailpipe and vehicle use emissions

Our analysis of the different vehicle types outputs the amount of fuel used annually, by fuel type, for each of vehicle technologies. Using the relative carbon intensities of the fuels of each fuel type it is possible to calculated the expected gCO_2/km for each vehicle type. This can be separated into tailpipe emissions and the emissions resulting from the production and delivery of that fuel.

Projections of grid CO_2 intensity were used to calculate emissions from electricity production. The emissions factors from hydrogen production are taken from Concawe[48], with a production mix of 25% steam methane reforming, 25% steam methane reforming with CCS and 50% from electrolysis using renewables (including nuclear). This hydrogen generation mix gives a hydrogen emissions factor of 5.7 $kg.CO_2/kg.H_2$ in 2025.

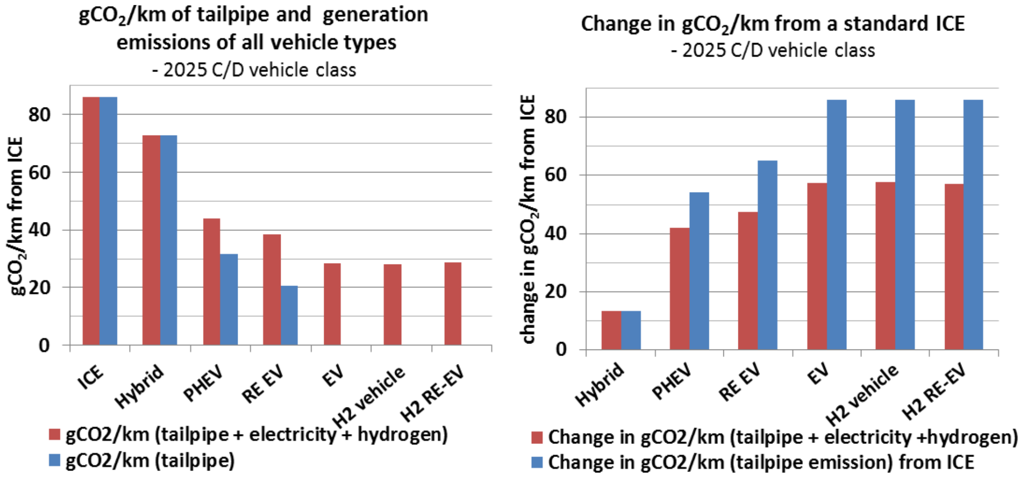

Figure 42 – Vehicle fuel (generation and vehicle emissions) gCO_2/km emissions and gCO_2/km saving from a standard ICE, tailpipe and from vehicle fuel (generation and vehicle) emissions from different vehicle types for C&D class vehicles in 2025.

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[47] Both from primary fuel emissions and primary fuel generation or alternatively to include embodied carbon content of the fuel. 'well to wheel' as defined here includes primary generation only (power plant emissions and direct fuel emissions)

[48] "Well-to-Wheels" Appendix 2 *Concawe* 2008

The gCO_2/km of each of the vehicle types is shown in Figure 42. As expected the gCO_2/km figures drop for tailpipe emission as more electricity and hydrogen is used. Converting these gCO_2/km figures into savings from the ICE vehicle (Figure 42) allows a comparison of the cost effectiveness of the different technologies using the subsidy required to equate the vehicle TCOs (see Figure 25 or Figure 34). This cost effectiveness is shown in Figure 43

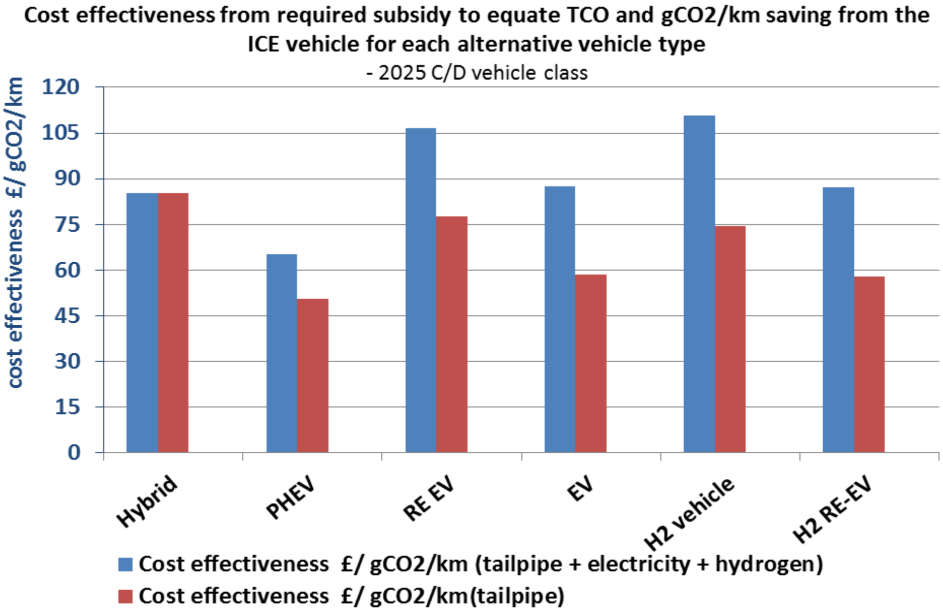

Figure 43 –The relative cost effectiveness of the subsidy required to equate the four year TCO to the ICE TCO relative to the gCO_2/km improvement over the ICE vehicle, for all alternative vehicles. Results are shown for the C&D segment only in 2025.

The cost effectiveness graphs show that for both tailpipe and fuel generation emissions the most cost effective solution for reducing vehicle emissions is the PHEV. This is unsurprising as the PHEV’s range is designed to do the largest distance possible in electric mode with the lowest possible additional capital cost. However, while PHEVs are highly cost effective (in terms of support required), they are unable to offer complete decarbonisation of passenger cars. In other words, if tailpipe emissions from new cars are required to drop below c.30gCO_2/km then only RE-EVs, EVs and hydrogen cars are able to meet this very low target. The cost effectiveness of all powertrains in the three segments is shown in Figure 44.

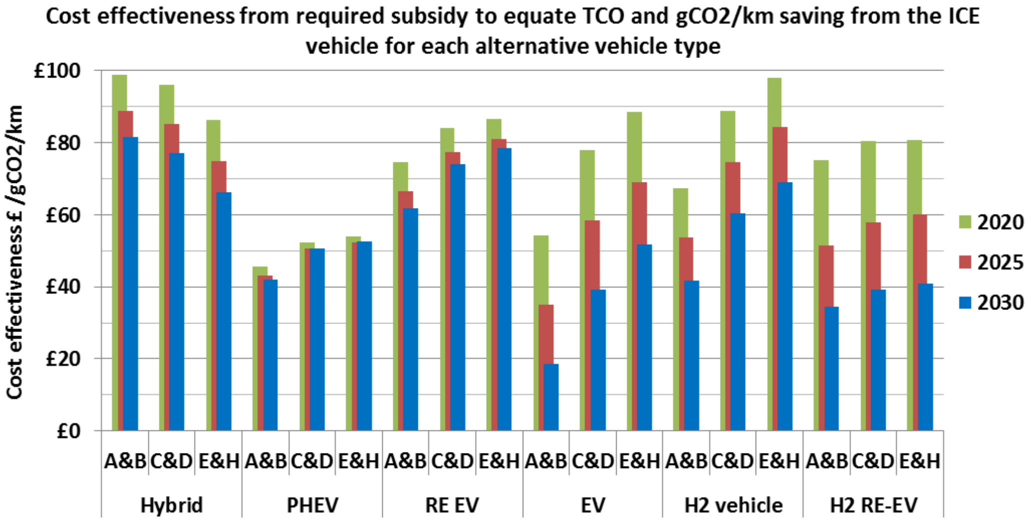

Figure 44 – The relative cost effectiveness of the subsidy required to equate the four year TCO to the ICE TCO relative to the gCO_2/km improvement over the ICE vehicle, for all alternative vehicles.

9.2 Life cycle emissions

There is a continuing drive within the vehicle manufacturing industry to monitor and publish vehicle life cycle emissions. Several manufacturers, such as Mercedes, Toyota and Volkswagen, publish life cycle assessments of new models to demonstrate progress made over previous models or competitors' vehicles. These sources have been used to calculate illustrative values for lifecycle emissions of vehicles in this study. For a full description of the methodology used to calculate the different lifecycle emissions please refer to Appendix F.

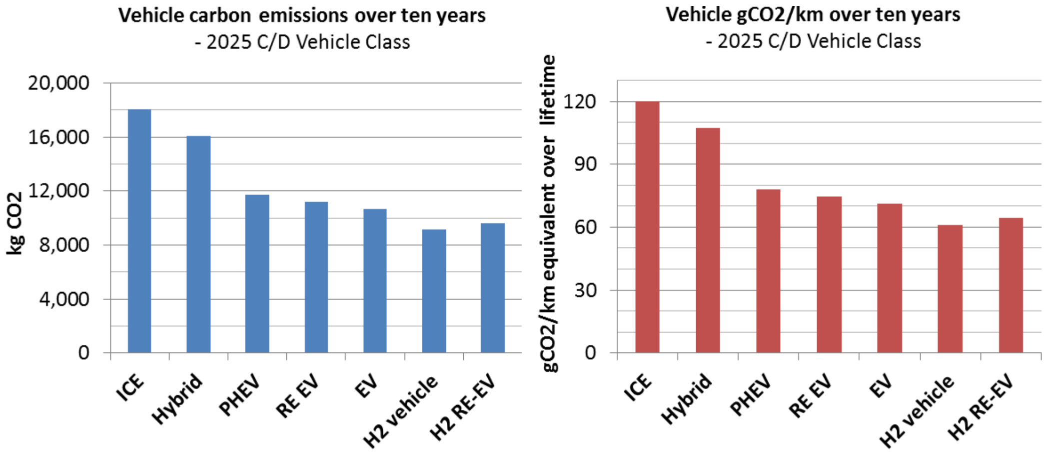

Figure 45 – Lifecycle emissions and gCO_2/km (calculated over ten years to remain consistent with the TCO) including production and demolition for the C&D vehicle segment for all vehicle types in 2025.

The emissions over ten years for tailpipe (direct), well to wheel and "cradle to grave" are shown in Figure 45. These values can be converted into a gCO_2/km based on the distance travelled by the vehicle over the TCO lifetime.

As cars become more fuel efficient in the future, production and scrappage emissions make an increasingly large contribution to total lifecycle emissions. If a C&D class car has an embodied emissions of 4.8 tonnes CO_2eq (a 20% reduction on 2010 figures) and the vehicle travels 150,000 km during its lifetime (ten years based on the current annual driving distance assumption) then embodied emissions contribute a further 32gCO_2/km to the vehicle's stated tailpipe emissions. This effectively increases the stated ICE vehicle emissions (gCO_2/km) in 2025 by 35%.

A breakdown of the lifetime CO_2 emissions are shown in Figure 46. As the electricity grid has partially decarbonised by 2025 the embodied (production) emissions of EV account for over half of the total lifetime emissions of the vehicle. As more alternative vehicle come to market and the electricity grid decarbonises, the production emissions become increasingly important and become an ever larger fraction of vehicle's lifecycle emissions. These results are similar to Ricardo's recent report on lifecycle emissions of low carbon vehicles for the LowCVP[49].

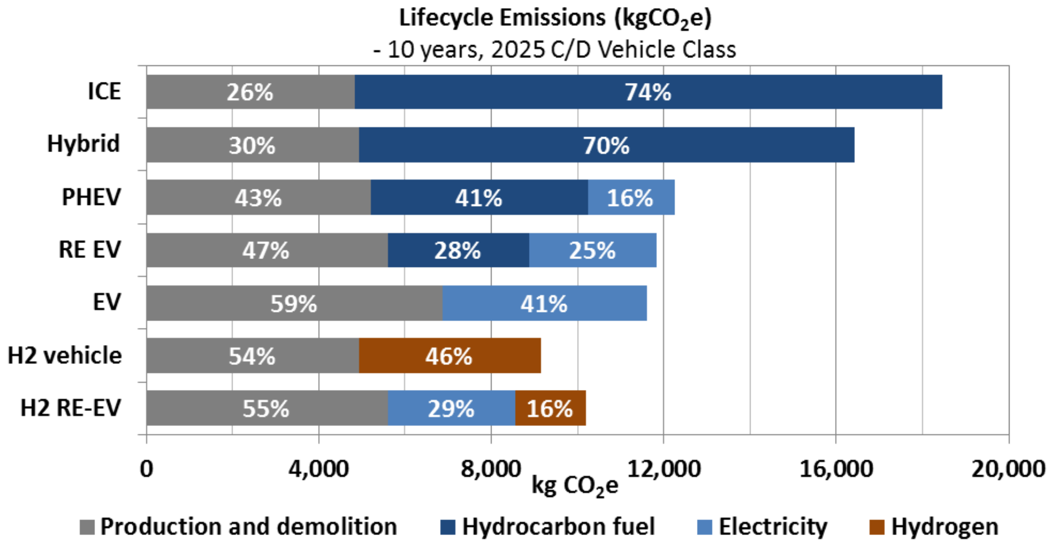

Figure 46 – Breakdown of lifecycle emissions by production and fuel for the C&D vehicle segment in 2025

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[49] Press release available at http://www.lowcvp.org.uk/assets/pressreleases/LowCVP_Lifecycle_Study_June2011.pdf

9.3 Whole life cost of CO_2

Using the required subsidy to equalise the alternative vehicle TCO to ICE TCO and the difference in gCO_2/km of the lifecycle emissions the whole life cost of carbon can be calculated for the vehicle. Figure 47 shows that the gCO_2/km is highly dependent on the lifetime of the vehicles. Over a full ten year (150,000km) lifetime, the cost per gCO_2/km saved is lowest in the PHEV. The pure EV costs nearly twice as much per gCO_2/km saved due to the CO_2 embodied in the battery. This is an important consideration, and suggests that while tailpipe emissions is a highly suitable metric for non-CO_2 pollutants and urban air quality concerns, moving to a life cycle analysis is necessary to correctly capture the impacts of electric powertrains.

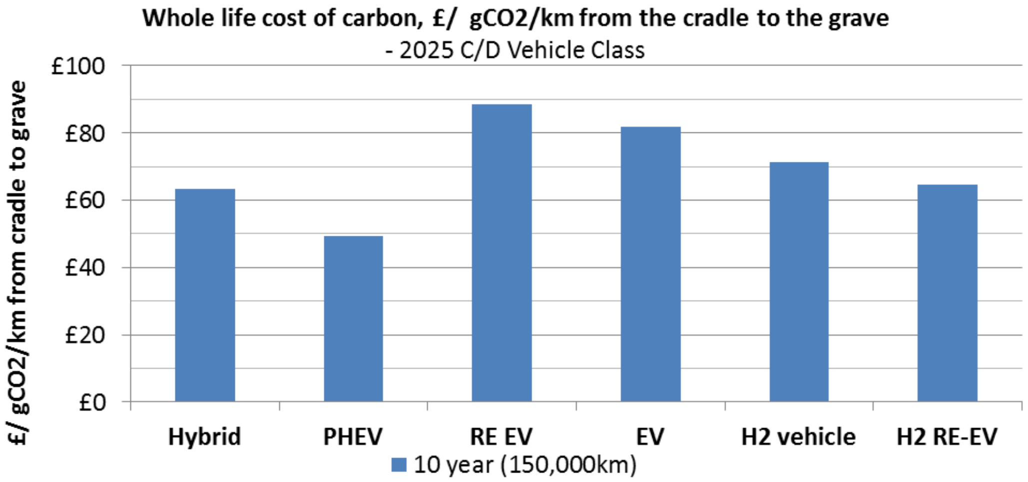

Figure 47 – Carbon abatement vehicle cost effectiveness, from the vehicle subsidy required to equalise the TCOs for all powertrains and the relative carbon savings associated with each vehicle type (four year duration only)

10 Conclusions

Conclusions

Low and ultra-low carbon vehicles are expected to play an important role in the passenger car market between 2010 and 2030. Our analysis confirms the excellent CO_2 saving potential of these vehicles, as well as the potential for substantial improvements in conventional internal combustion engine cars. Our results also show that despite significant reductions in battery and fuel cell costs, plug-in and H_2 are expected to remain more expensive than conventional cars when assessed on a total cost of ownership basis. This suggests that strong and consistent policy support and incentives will be required to meet aggressive targets for plug-in vehicle roll-out, such as the Committee on Climate Change's 'Medium Scenario', which envisages that 60% of the new car fleet in 2030 will be plug-in hybrids or pure electric vehicles[50]. Without incentives for low carbon car buyers, or substantial increases (more than a doubling) of fuel prices relative to current levels, consumers are likely to favour improved conventional cars over more expensive advanced powertrains. Improved conventional cars (and non-plug-in hybrids) appear capable of meeting medium term CO_2 targets (such as the EU fleet average target of 95g/km in 2020), but ultra-low carbon cars must reach widespread deployment if longer term goals to 2030 and beyond are to be achieved.

Headlines

1. The TCO of alternative vehicles in relation to conventional ICE vehicles narrows substantially over the coming decade. It narrows further from 2020-2030 in most scenarios.
2. Although the TCO of alternative vehicles reduces substantially conventional ICE vehicles continue to have a lower TCO.
3. If the government wishes to increase the uptake of alternative vehicles it will need to support alternative vehicles with a mechanism to allow the alternative vehicles to be at least comparable to ICE vehicles on a TCO basis.
4. As the conventional ICE vehicles increases in efficiency the effect of changes in fuel cost become less important as fuel costs contribute to a lower proportion of the TCO. The implication of this is that capital costs will become a higher proportion of total ownership costs which reduces the appeal of ultra-low carbon cars.
5. Other factors such as insurance have an increasingly large effect on the TCO of vehicles if current trends continue. Differentials in insurance or maintenance costs between conventional and low carbon cars must be minimised if drivers are to benefit from the significantly lower fuel costs of new technologies.

Vehicle Costs

- Conventional cars provide the lowest total costs of ownership of all powertrains in 2010, before incentives are taken into account.
    - The current capital cost premium for plug-in vehicles of over £10,000 (for the C&D class) far outweighs the benefits of lower ongoing costs.
    - This continues through to 2030 with the increase in ICE vehicle efficiency offsetting the increase in the ICE vehicle capital costs. This allows the

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[50] Committee on Climate Change: The Fourth Carbon Budget. Page 161.

TCO of ICE vehicles to remain relatively constant with only a slight increase with time.

- By 2020, we expect low carbon vehicles to make substantial progress in bridging the current differential in the TCOs. There is however still a cost premium for alternative vehicles in 2030. The premium for the pure EV drops from £20,000 in 2010 to £3,000 in 2030, while the PHEV falls from £6,800 to £2,400.

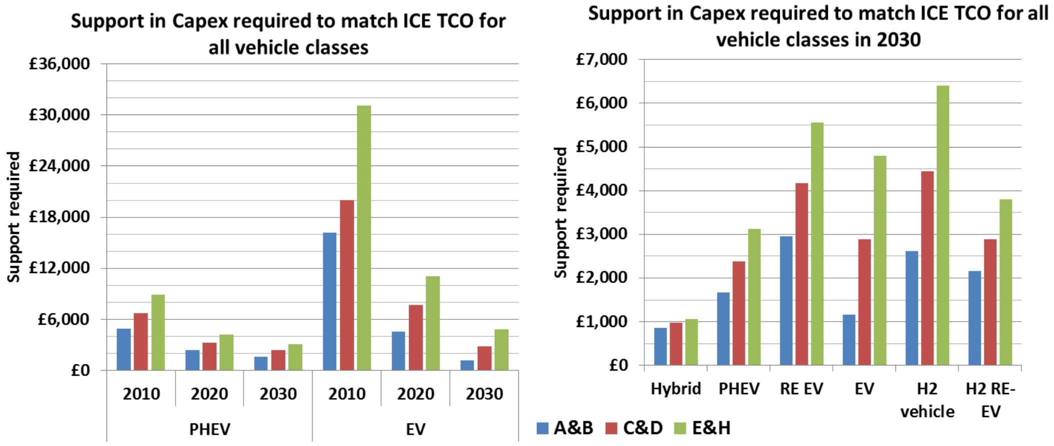

Figure 48 – Support required to equate alternative vehicle TCOs to the ICE TCO.

- As battery costs decrease through time, the TCO of the pure EV falls below that of the RE-EV by 2025 and the PHEV by 2030 for the A&B class. The C&D and E&H pure EV's TCO drops below the RE-EV's by 2030. As the extra battery capacity required for the EV becomes cheaper the additional complexity of a hybrid powertrain adds additional costs to the RE-EV and PHEV.

- We assume that the range of the pure EV is 240km in 2030, which is still substantially below that of a RE-EV or conventional vehicle. If the EV was required to have the same range as a RE-EV or ICE vehicle (>500km) the battery would have to be doubled in capacity adding significant cost, making the EV the most expensive alternative vehicle.

- Battery costs are required to drop below £68/kWh for EVs with a 240km range to be comparable to the ICE vehicle on a TCO basis in 2025. This is significantly lower than what most experts believe is possible with existing technology.

- The predicted improvements in conventional internal combustion vehicles over the next 20 years significantly reduce the contribution of fuel costs to the total costs of ownership. Expected improvements in the ICE vehicle's fuel efficiency deliver large fuel bill savings in these vehicles, in turn reducing the potential benefit of using an alternative fuel or powertrain. The fuel contribution to the TCO changes from 16% in 2010 (for the C&D class ICE vehicle) to 9% by 2030.

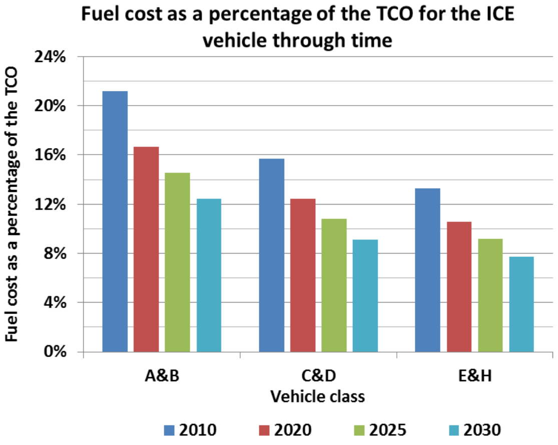

Figure 49 – Fuel cost of through time of the ICE vehicle as a percentage of the ICE vehicle's TCO

- Delivering the improvements in conventional ICE vehicles will require several major changes in the current market trends in new ICE vehicles. For example we assume the reversal of the current market trend in increasing vehicle mass, and a shift in focus by OEMs to fuel efficiency over increasing performance. These improvements in the ICE vehicle with time mean that the alternative vehicles are being compared against a continually improving baseline.

- Pure (non-hybridised) hydrogen vehicles remain the most expensive vehicle option in the central scenario. The fuel cell cost for the hydrogen vehicle remains high, as it is sized to meet the peak load of the vehicle (109kW for a C&D vehicle).

- Hydrogen RE-EVs are more attractive in larger vehicle segments and have an equal or lower TCO compared with liquid-fuelled RE-EVs after 2025 for vehicle classes C&D and above. A fully hybridised H_2 vehicle offers the ability to a lower cost fuel (electricity) while delivering the same overall range and functionality of a conventional car with zero tailpipe emissions.

- Business users with high annual driving distances potentially gain the most from vehicles with low running costs per km such as plug-in vehicles. However, since these vehicles deliver their running cost benefits only when using electricity as an energy source, sufficient infrastructure would need to be available to allow charging at the end of individual trips (rather than charging only at home at the end of the working day). Due to their high range, hydrogen cars may offer more cost-effective ultra-low carbon motoring for these high mileage drivers.

Emissions

- The tailpipe emissions of conventional non-hybridised ICE vehicles are expected to fall from the current value of 138g/km in 2010 to a potential 74g/km in 2030 for the medium sized (C&D) vehicle. Assuming no changes in current market shares for each car segment and the future provision for biofuel (10% by energy) the fleet average tailpipe emissions from the base ICE vehicles changes from 144gCO_2/km[51] in 2010 to 71gCO_2/km in 2030.

- It is possible for the base ICE vehicles to deliver the required efficiency savings for the EU new sales fleet average emissions of 95gCO_2/km in 2020. Assuming the current market shares for each vehicle segment remain constant, fleet average vehicle emissions from base ICE vehicles alone would be 95.7gCO_2/km in 2020, including the future provision for biofuels (10% by energy). This doesn't include emissions reductions from sales of non-plug-in hybrids.

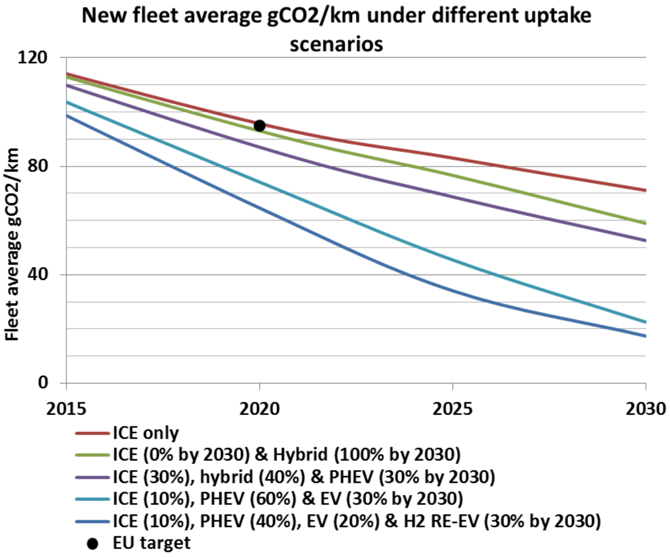

Figure 50 – Fleet average CO_2/km through time for different uptakes of alternative vehicles. This assumes the current market shares for each vehicle segment remain constant through time.

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[51] SMMT New Car CO_2 report 2011

- Further progress in decarbonising passenger cars after 2020 will require the deployment of non-plug-in and plug-in hybrid vehicles, as base ICE vehicles alone can reduce the fleet average emission by only a further 14gCO_2/km[52]. The most cost-effective solution to reduce vehicle emissions further is the PHEV with an electric range of approximately 30km. A new car fleet comprised entirely of PHEVs would have emissions of c.30gCO_2/km by 2030.

- The PHEV continues to outperform the RE-EV (with a 60km range) in terms of cost-effectiveness to 2030, since the cost of providing extra electric range outweighs further reductions in emissions and fuel bills. However, this conclusion is dependent on the real world range electric range (and hence fuel bill savings) offered by these vehicles in under different driving patterns. The hydrogen RE-EV and EV become the most cost effective vehicle technology in the C&D class vehicle in 2030.

- If future vehicle emissions targets move below c.20g/km (tailpipe emissions only), PHEV and RE-EVs cannot deliver this level of reduction (without a substantial increase in biofuel) even with predicted efficiency improvements in internal combustion engines. Only pure electric and hydrogen vehicles can offer such low tailpipe emissions.

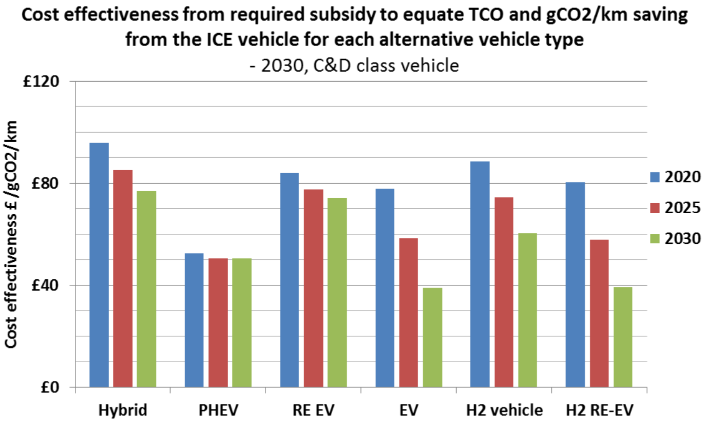

Figure 51 – The relative cost effectiveness of the subsidy required to equate the alternative vehicle's four year TCO to the ICE TCO relative to the gCO_2/km improvement over the ICE vehicle

Policy implications

- No one vehicle type is expected to dominate the market for alternative vehicles. A portfolio of different technologies is likely to emerge in the market. All of the alternative vehicles have a premium in their TCOs over the ICE vehicle and will require some form of support to equalise their TCOs.

- Current incentives available to all drivers (e.g. differential VED bands) are not sufficient to close the TCO gap between low carbon and conventional cars.

- For drivers who benefit from Congestion Charging and free parking by driving low emission vehicles, the value of these incentives (up to £10,000 over four years) is sufficient to equalise the TCO across all powertrains except the hydrogen fuel cell vehicle by 2020.

- By 2025, the differential in the TCOs requires £870 of incentives per year to break even with the conventional car for the PHEV, and £1590 for the pure EV.

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[52] Assuming no change in vehicle sales distributions and no increase in biofuels beyond 10%

Vehicle type	Hybrid	PHEV	RE-EV	EV	H_2	H_2 RE-EV
Support required to equate to the ICE TCO in 2025 (£)	£1,130	£2,750	£5,060	£5,020	£6,410	£4,980
Annualised support required (£/yr)	£360	£870	£1,600	£1,590	£2,020	£1,570

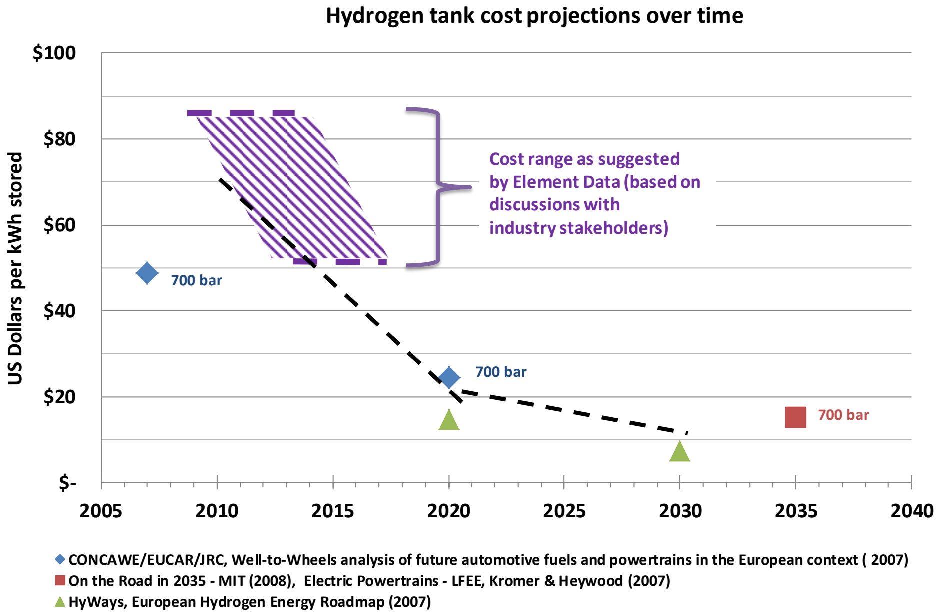
- The relative cost-effectiveness of the PHEV means that any policy to support plug-in vehicles will lead consumers to favour these vehicles over pure electric ones, unless differential support or exemptions are in place.

- Our analysis suggests that large fuel price shocks (up to £3/l in 2025) are required to equalise the TCOs of battery electric and conventional cars. This is because fuel prices account for only a small portion of the TCO by that year due to efficiency improvements in all powertrains.

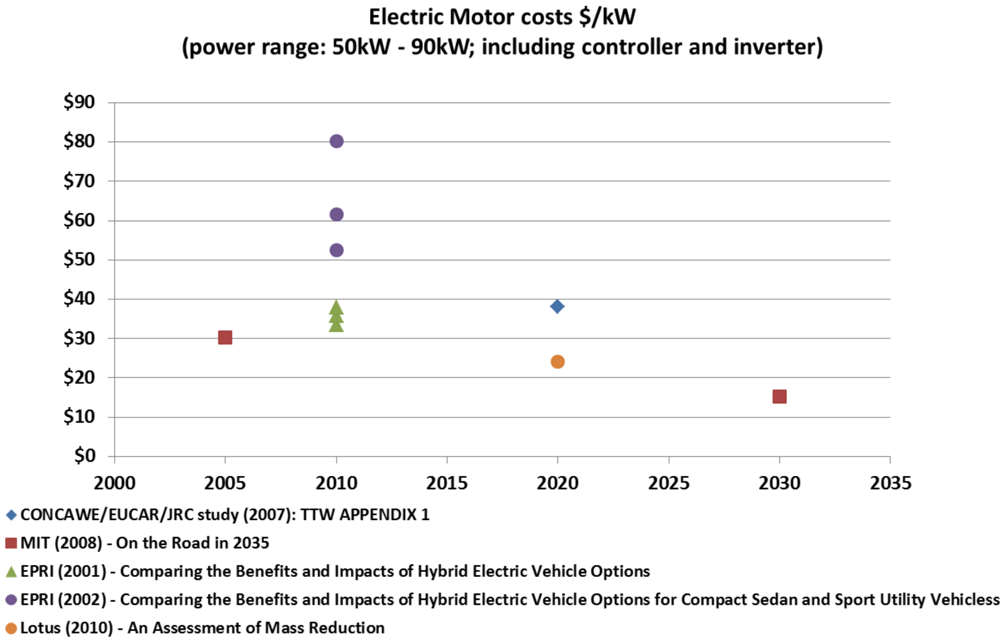
Appendix

Appendix A – Vehicle assumptions and references

Hydrogen tank costs and references



Electric motor costs and references



Additional drive train component costs and references

Component	2020	2025	2030	Reference
Additional wiring costs[1]	£133	£133	£133	MIT (2008), Lotus (2010), Deutsche Bank
Regenerative braking costs[2]	£207	£207	£207	King Review (2007), Lotus (2010)
Battery pack hardware, tray and cooling (thermal management)[3]	£661	£661	£661	EPRI (2001)
Exhaust costs[4]	£471	£471	£471	CONCAWE/EUCAR/JTI (2007)
Stop start additional cost[5]	£235	£215	£215	King Review(2007), CONCAWE/EUCAR/JTI (2007)
Additional Transmission cost[6]	£168	£168	£168	MIT (2008)
Battery charger cost	£279	£253	£227	EPRI (2001), MIT (2008), Deutsche Bank, Electrification Coalition (2009, 2010)

Notes

1 Additional costs for heavy duty wiring for hybrid and electric vehicles

2 Additional cost for regenerative braking for hybrid/electric vehicles

3 Costs for mounting battery in vehicle and thermal management

4 Additional exhaust costs for meeting future Euro particulate limits (relative to current exhaust systems)

5 Additional cost for a belt starter generator for stop-start vehicles

6 Additional transmission costs for hybrid vehicles for vehicles built from 2020-2035

Appendix B – Future vehicle characteristics

2010	ICE			Hybrid			PHEV			RE EV			EV			H2 vehicle			H2 RE-EV		
	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H
Range in pure EV mode (km)	x	x	x	2	2	2	20	20	20	60	60	60	150	160	200	2	2	2	60	60	60
Battery capacity (kWh)	x	x	x	1.2	1.4	1.8	3.8	4.4	5.6	12.0	14.1	17.5	23.7	29.5	46.0	1.4	1.6	1.9	14.8	16.2	18.9
Approximate Total vehicle weight (kg)	1037	1407	1844	1049	1421	1862	1074	1451	1900	1157	1548	2019	1273	1701	2304	1051	1423	1863	1184	1569	2033
Hydrogen range (km)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	400	400	400	400	400	400
Hydrogen storage capacity (kWh)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	117	131	156	129	142	165
Percentage of distance travelled in EV mode	0%	0%	0%	0%	0%	0%	31%	31%	31%	62%	62%	62%	100%	100%	100%	0%	0%	0%	62%	62%	62%
Percentage of distance travelled in ICE mode	100%	100%	100%	100%	100%	100%	69%	69%	69%	38%	38%	38%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Percentage of distance travelled in H2 mode	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	38%	38%	38%
Tailpipe emissions in year including biofuel(gCO_2/km)	118	140	178	104	123	157	54	64	82	30	35	45	0	0	0	0	0	0	0	0	0

2020	ICE			Hybrid			PHEV			RE EV			EV			H2 vehicle			H2 RE-EV		
	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H
Range in pure EV mode (km)	x	x	x	2	2	2	30	30	30	60	60	60	150	200	230	2	2	2	60	60	60
Battery capacity (kWh)	x	x	x	1.0	1.2	1.5	4.8	5.6	7.0	9.8	11.4	14.2	17.6	28.0	39.7	1.1	1.3	1.5	10.8	12.2	14.7
Approximate Total vehicle weight (kg)	953	1285	1672	961	1294	1683	989	1328	1725	1028	1373	1781	1088	1500	1977	961	1294	1683	1036	1379	1785
Hydrogen range (km)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	500	500	500	500	500	500
Hydrogen storage capacity (kWh)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	102	117	143	108	123	148
Percentage of distance travelled in EV mode	0%	0%	0%	0%	0%	0%	43%	43%	43%	62%	62%	62%	100%	100%	100%	0%	0%	0%	62%	62%	62%
Percentage of distance travelled in ICE mode	100%	100%	100%	100%	100%	100%	57%	57%	57%	38%	38%	38%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Percentage of distance travelled in H2 mode	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	38%	38%	38%
Tailpipe emissions in year including biofuel (gCO_2/km)	84	99	125	72	85	108	32	37	47	21	24	31	0	0	0	0	0	0	0	0	0

2025	ICE			Hybrid			PHEV			RE EV			EV			H2 vehicle			H2 RE-EV		
	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H
Range in pure EV mode	x	x	x	2	2	2	30	30	30	60	60	60	150	220	260	2	2	2	60	60	60
Battery capacity (kWh)	x	x	x	0.9	1.1	1.3	4.2	5.0	6.2	8.7	10.1	12.6	15.4	27.1	39.7	0.9	1.1	1.3	8.7	10.1	12.6
Approximate Total vehicle weight (kg)	906	1222	1589	912	1229	1598	935	1255	1630	964	1289	1673	1009	1402	1853	912	1229	1598	964	1289	1673
Hydrogen range (km)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	500	500	500	500	500	500
Hydrogen storage capacity (kWh)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	84	98	124	87	102	127
Percentage of distance travelled in EV mode	0%	0%	0%	0%	0%	0%	43%	43%	43%	62%	62%	62%	100%	100%	100%	0%	0%	0%	62%	62%	62%
Percentage of distance travelled in ICE mode	100%	100%	100%	100%	100%	100%	57%	57%	57%	38%	38%	38%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Percentage of distance travelled in H2 mode	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	38%	38%	38%
Tailpipe emissions in year including biofuel (gCO_2/km)	73	86	109	62	73	92	27	32	40	18	21	26	0	0	0	0	0	0	0	0	0

2030	ICE			Hybrid			PHEV			RE EV			EV			H2 vehicle			H2 RE-EV		
	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H	A&B	C&D	E&H
Range in pure EV mode (km)	x	x	x	2	2	2	30	30	30	60	60	60	150	240	300	2	2	2	60	60	60
Battery capacity (kWh)	x	x	x	0.8	0.9	1.2	3.7	4.4	5.5	7.6	8.9	11.1	13.3	25.7	39.9	0.8	0.9	1.2	7.6	8.9	11.1
Approximate Total vehicle weight (kg)	859	1158	1505	864	1163	1512	881	1183	1537	904	1210	1570	938	1309	1740	864	1163	1512	904	1210	1570
Hydrogen range (km)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	500	500	500	500	500	500
Hydrogen storage capacity (kWh)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	74	87	109	76	89	111
Percentage of distance travelled in EV mode	0%	0%	0%	0%	0%	0%	43%	43%	43%	62%	62%	62%	100%	100%	100%	0%	0%	0%	62%	62%	62%
Percentage of distance travelled in ICE mode	100%	100%	100%	100%	100%	100%	57%	57%	57%	38%	38%	38%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Percentage of distance travelled in H2 mode	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	38%	38%	38%
Tailpipe emissions in year including biofuel (gCO_2/km)	63	74	93	52	61	77	23	27	33	15	17	22	0	0	0	0	0	0	0	0	0

Appendix C – TCO component breakdown

Capex - not including vat and margins

year		2010			2020			2025			2030		
		Upper (2.5% limit)	Central	Lower (97.5% limit)	Upper (2.5% limit)	Central	Lower (97.5% limit)	Upper (2.5% limit)	Central	Lower (97.5% limit)	Upper (2.5% limit)	Central	Lower (97.5% limit)
ICE	**A&B**	£7,610	£7,610	£7,610	£9,450	£8,640	£8,310	£9,930	£8,790	£8,400	£10,420	£8,960	£8,510
	C&D	£14,330	£14,330	£14,330	£16,600	£15,530	£15,150	£17,290	£15,780	£15,320	£17,980	£16,030	£15,490
	E&H	£23,210	£23,210	£23,210	£26,010	£24,590	£24,150	£26,930	£24,940	£24,390	£27,850	£25,280	£24,640
Hybrid	**A&B**	£12,380	£10,650	£9,750	£12,060	£10,570	£9,750	£12,280	£10,540	£9,750	£12,530	£10,570	£9,800
	C&D	£20,480	£18,050	£16,780	£19,640	£17,700	£16,660	£20,020	£17,730	£16,710	£20,410	£17,800	£16,790
	E&H	£31,070	£27,780	£26,030	£29,610	£27,060	£25,740	£30,140	£27,130	£25,830	£30,680	£27,250	£25,950
PHEV	**A&B**	£18,620	£14,290	£12,000	£16,010	£12,660	£10,990	£15,400	£12,170	£10,810	£14,910	£11,870	£10,680
	C&D	£29,040	£23,060	£19,880	£24,820	£20,610	£18,450	£24,220	£20,090	£18,280	£23,750	£19,790	£18,150
	E&H	£42,600	£34,510	£30,190	£36,470	£31,010	£28,210	£35,760	£30,400	£28,020	£35,230	£30,040	£27,880
RE EV	**A&B**	£30,030	£19,910	£14,610	£21,040	£15,130	£12,240	£19,230	£13,950	£11,750	£17,740	£13,190	£11,360
	C&D	£42,350	£29,540	£22,790	£31,120	£23,820	£20,090	£29,110	£22,490	£19,550	£27,460	£21,640	£19,110
	E&H	£59,040	£42,440	£33,680	£44,540	£35,200	£30,370	£42,120	£33,580	£29,710	£40,120	£32,540	£29,170
EV	**A&B**	£43,670	£26,250	£17,180	£24,370	£15,280	£11,490	£20,610	£13,000	£10,490	£17,560	£11,540	£9,690
	C&D	£59,440	£37,220	£25,620	£40,010	£25,600	£19,590	£35,700	£22,660	£18,360	£31,330	£20,490	£17,160
	E&H	£92,190	£57,810	£39,850	£58,890	£38,500	£30,000	£53,590	£34,670	£28,440	£48,390	£31,950	£26,900
H2 vehicle	**A&B**	£76,370	£66,930	£38,040	£18,560	£15,740	£11,710	£16,340	£14,290	£11,250	£16,100	£13,050	£10,950
	C&D	£126,060	£111,330	£62,710	£30,370	£25,980	£19,670	£26,940	£23,960	£19,150	£26,690	£22,130	£18,780
	E&H	£183,510	£162,690	£91,940	£45,120	£38,900	£30,000	£40,320	£36,210	£29,390	£40,000	£33,650	£28,900
H2 RE-EV	**A&B**	£64,470	£48,970	£29,670	£23,270	£16,750	£12,310	£19,210	£14,160	£11,170	£17,280	£12,540	£10,460
	C&D	£93,380	£74,010	£45,000	£33,670	£25,560	£19,630	£28,930	£22,570	£18,400	£26,740	£20,530	£17,560
	E&H	£128,920	£104,430	£64,140	£47,550	£37,220	£29,410	£41,880	£33,650	£28,020	£39,180	£30,990	£26,960

The central values in 2010 match well with market data (2010). The upper (2.5%) and lower (97.5%) limits vary widely due to many factors, mainly battery costs in 2010, these variations are explained in Section 5.

One year fuel costs

Year		2010	2020	2020	2020	2025	2025	2025	2030	2030	2030
Cost scenario		Central	Upper	Central	Lower	Upper	Central	Lower	Upper	Central	Lower
ICE	**A&B**	£820	£800	£630	£570	£700	£550	£500	£600	£480	£430
	C&D	£970	£950	£740	£680	£820	£650	£580	£700	£560	£500
	E&H	£1,240	£1,200	£930	£850	£1,040	£820	£740	£890	£710	£630
Hybrid	**A&B**	£720	£690	£540	£490	£590	£470	£420	£500	£400	£350
	C&D	£860	£810	£640	£580	£690	£550	£490	£580	£470	£410
	E&H	£1,090	£1,030	£800	£730	£880	£700	£620	£730	£590	£520
PHEV	**A&B**	£440	£410	£320	£290	£390	£310	£260	£340	£270	£220
	C&D	£520	£480	£380	£340	£450	£360	£300	£400	£320	£260
	E&H	£670	£610	£480	£430	£570	£450	£380	£500	£400	£330
RE EV	**A&B**	£330	£360	£280	£250	£360	£280	£230	£320	£250	£200
	C&D	£400	£420	£330	£290	£420	£330	£270	£380	£300	£240
	E&H	£510	£530	£420	£370	£530	£420	£340	£480	£380	£300
EV	**A&B**	£210	£250	£200	£170	£300	£240	£180	£290	£230	£160
	C&D	£250	£300	£240	£200	£360	£280	£210	£340	£270	£190
	E&H	£310	£380	£300	£250	£450	£350	£260	£430	£330	£240
H2 vehicle	**A&B**	£1,570	£470	£360	£250	£330	£250	£180	£270	£210	£140
	C&D	£1,760	£530	£410	£290	£390	£300	£210	£310	£240	£170
	E&H	£2,110	£650	£500	£350	£490	£380	£260	£400	£300	£210
H2 RE-EV	**A&B**	£790	£340	£270	£210	£320	£250	£180	£280	£220	£160
	C&D	£870	£400	£310	£240	£370	£290	£210	£330	£260	£180
	E&H	£1,030	£490	£380	£290	£470	£370	£260	£420	£330	£230

One year servicing costs

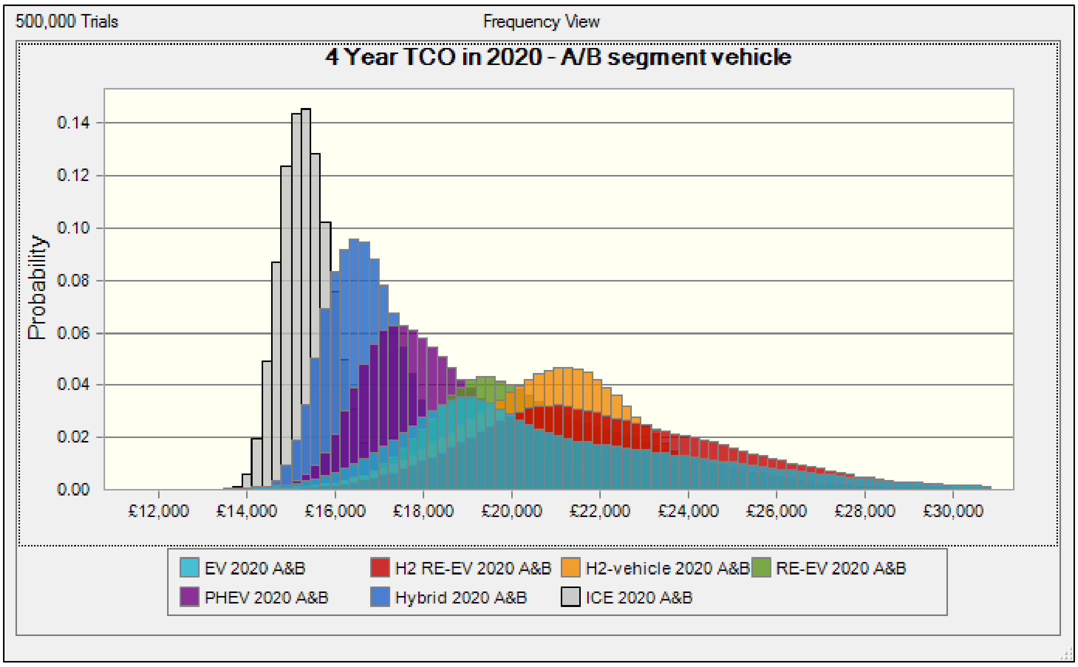
Cost scenario		Lower	Central	Upper
ICE	**A&B**	£530	£570	£640
	C&D	£590	£660	£780
	E&H	£650	£790	£940
Hybrid, PHEV, RE EV, EV, H2, H2 RE EV	**A&B**	£400	£440	£520
	C&D	£460	£530	£660
	E&H	£520	£670	£810

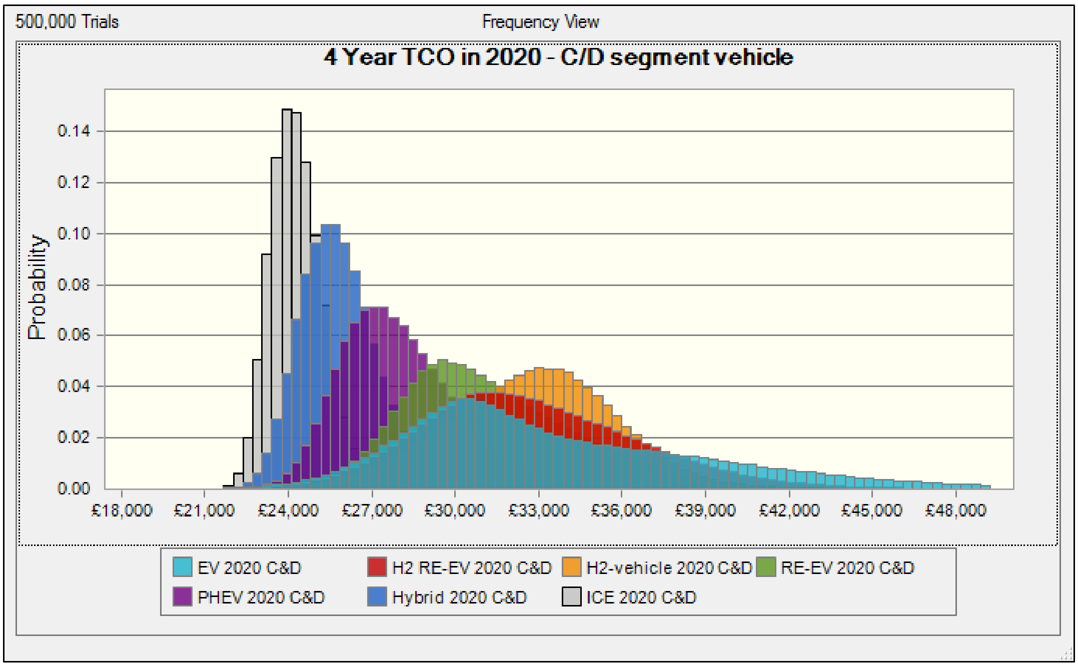
One year insurance costs

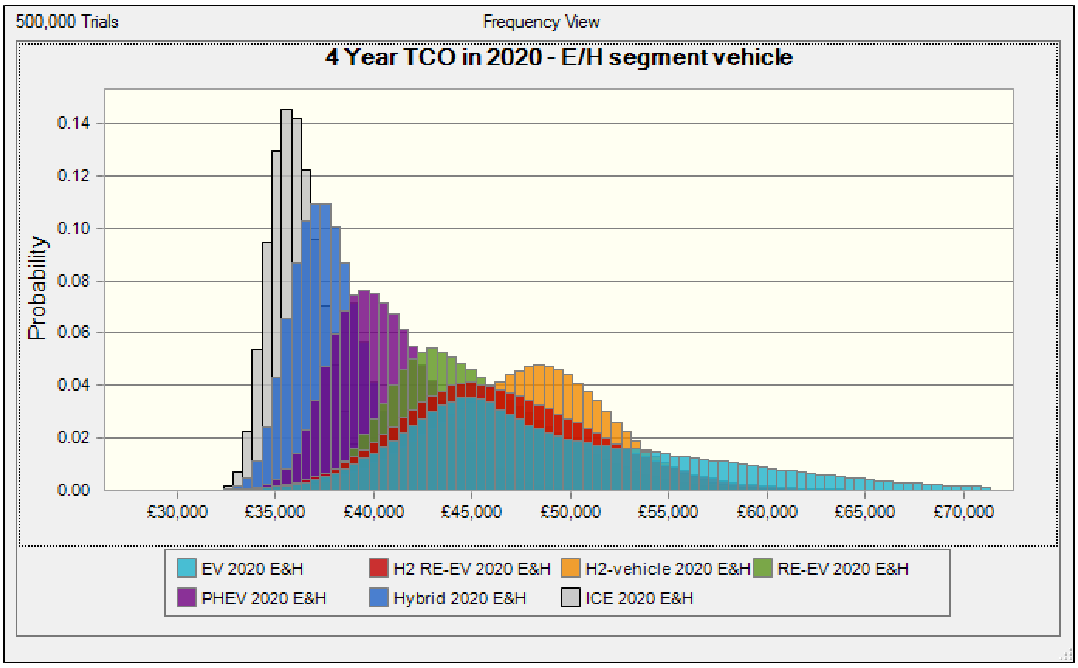
Year		2010			2020			2025			2030		
Cost scenario		Lower	Central	Upper	Lower	Central	Upper	Lower	Central	Upper	Lower	Central	Upper
ICE	**A&B**	£290	£380	£620	£380	£510	£680	£380	£590	£910	£380	£680	£1,210
	C&D	£410	£620	£930	£620	£830	£1,100	£620	£960	£1,480	£620	£1,110	£1,980
	E&H	£600	£880	£1,150	£880	£1,190	£1,580	£880	£1,380	£2,120	£880	£1,590	£2,830
Hybrid, PHEV, RE EV, EV, H2, H2 RE EV	**A&B**				£290	£510	£1,100	£290	£590	£1,480	£290	£680	£1,980
	C&D				£410	£830	£1,660	£410	£960	£2,220	£410	£1,110	£2,970
	E&H				£600	£1,190	£2,050	£600	£1,380	£2,740	£600	£1,590	£3,670

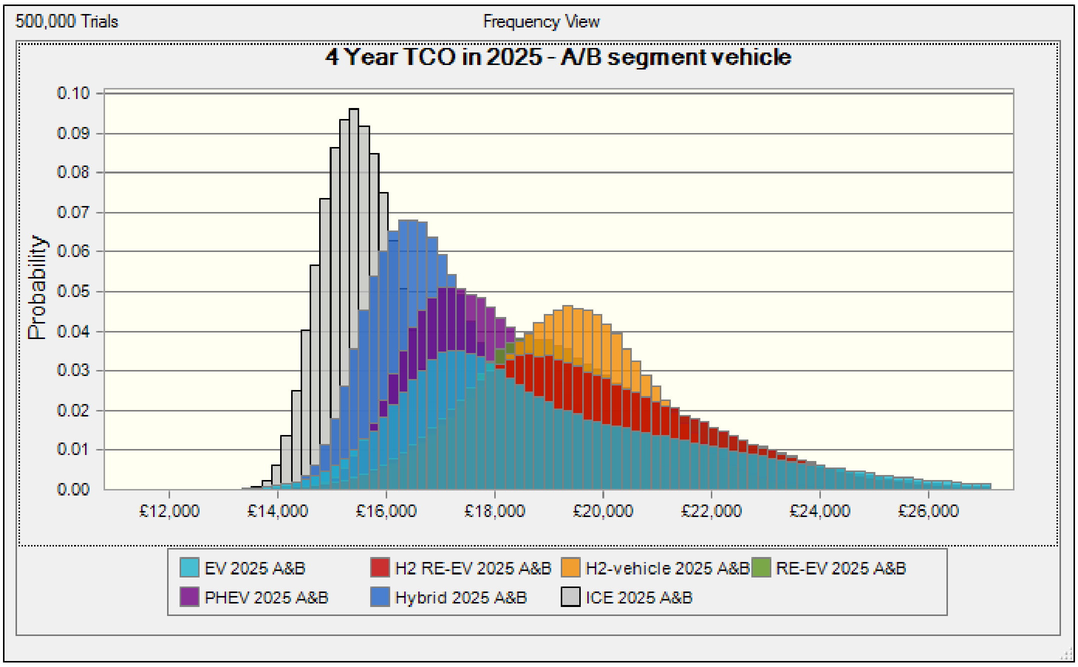
Appendix D – Additional TCO graphs and data

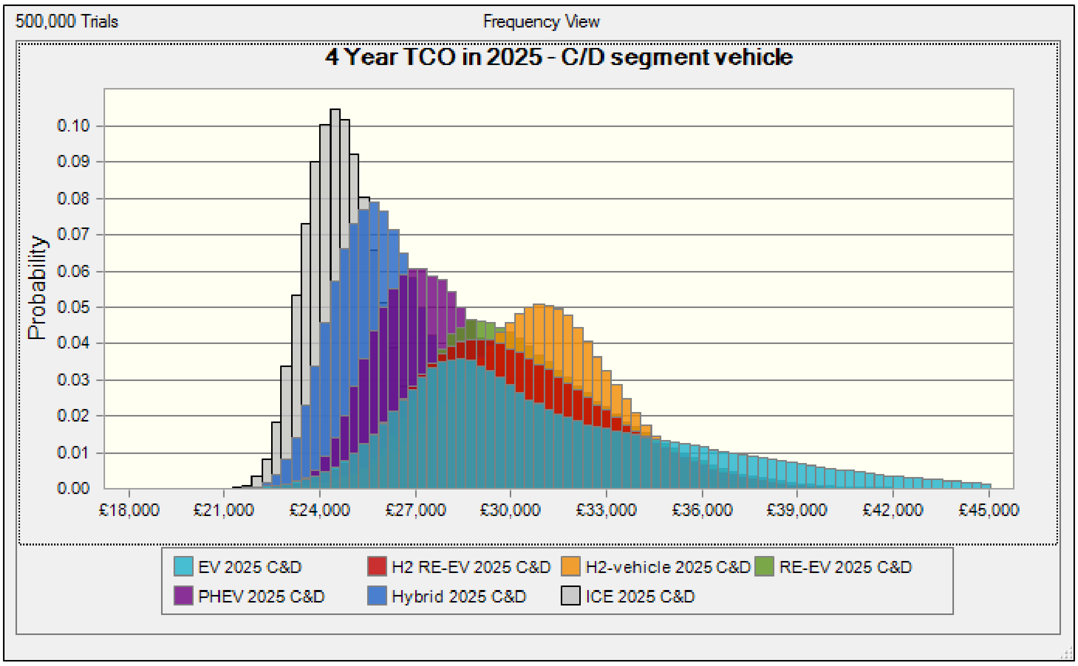
TCO graphs by year and vehicle segments

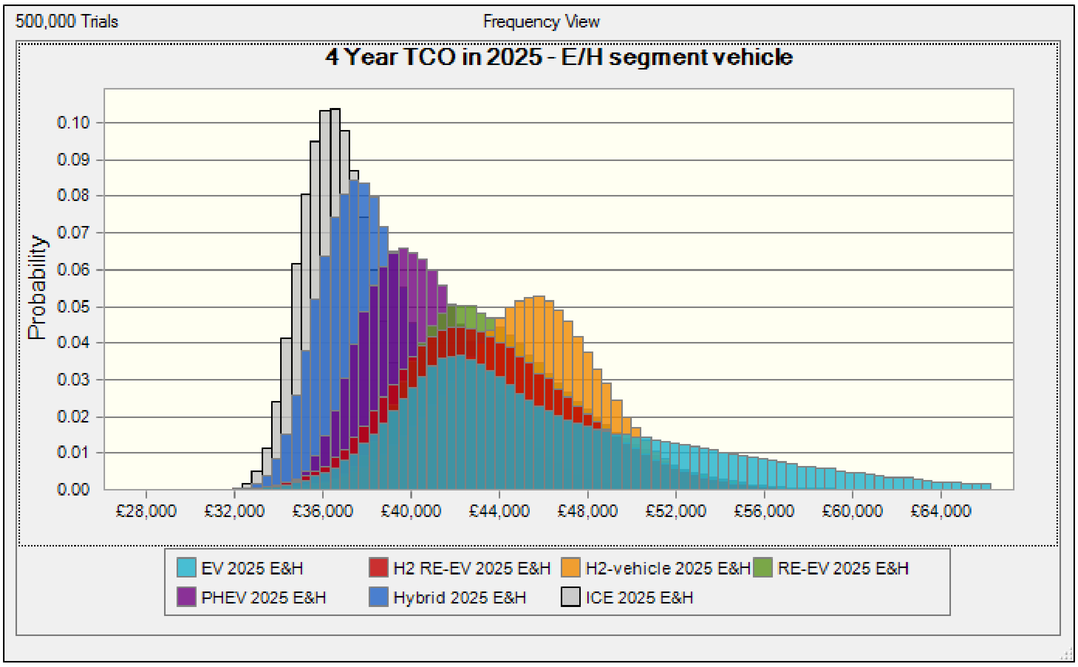


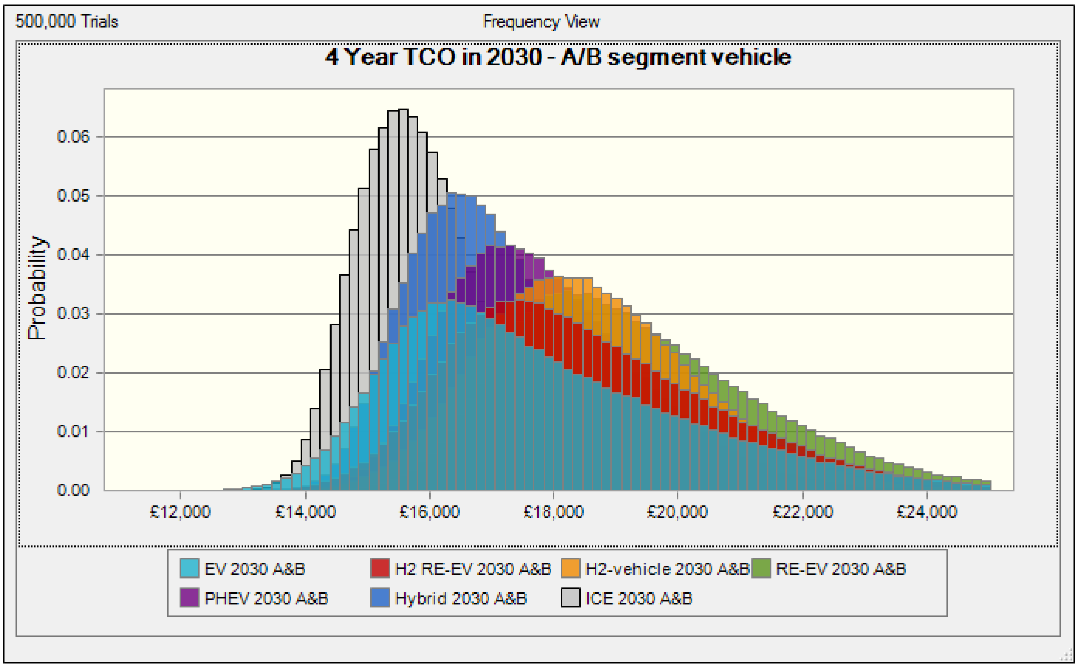


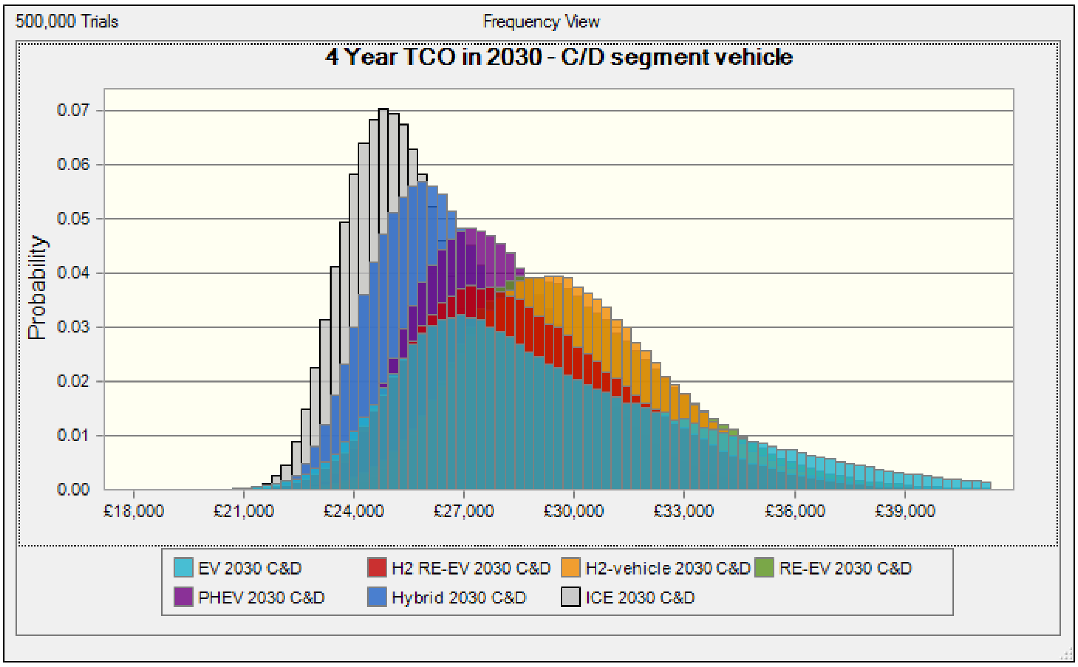

500,000 Trials
Frequency View
4 Year TCO in 2020 - E/H segment vehicle
Probability
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
£30,000
£35,000
£40,000
£45,000
£50,000
£55,000
£60,000
£65,000
£70,000
EV 2020 E&H
H2 RE-EV 2020 E&H
H2-vehicle 2020 E&H
RE-EV 2020 E&H
PHEV 2020 E&H
Hybrid 2020 E&H
ICE 2020 E&H

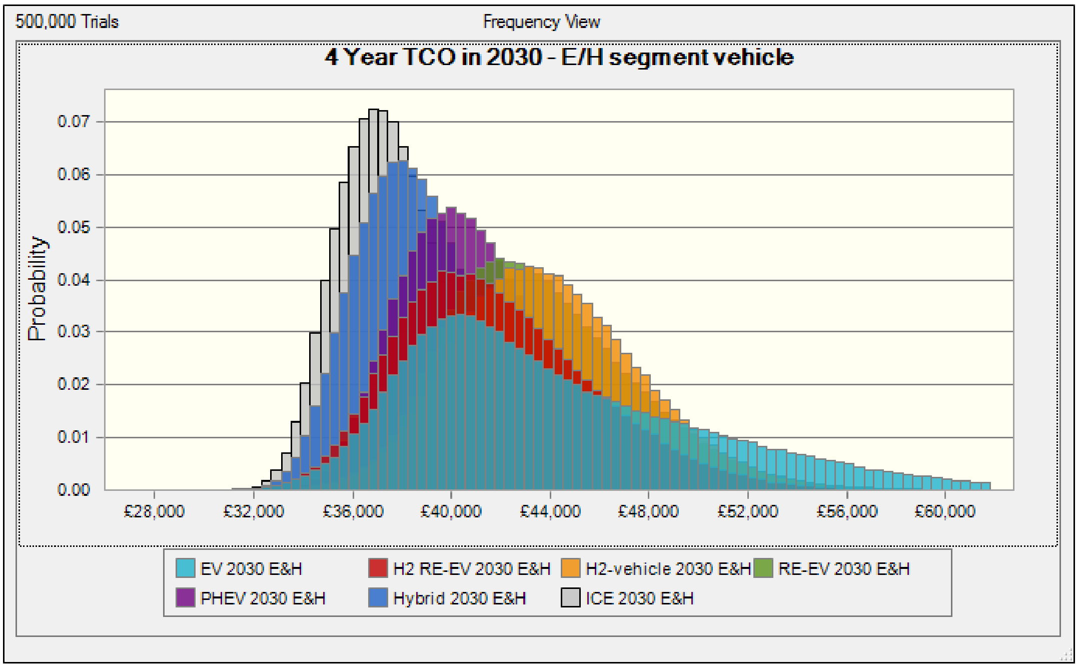

500,000 Trials
Frequency View
4 Year TCO in 2025 - A/B segment vehicle
Probability
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
£12,000
£14,000
£16,000
£18,000
£20,000
£22,000
£24,000
£26,000
EV 2025 A&B
H2 RE-EV 2025 A&B
H2-vehicle 2025 A&B
RE-EV 2025 A&B
PHEV 2025 A&B
Hybrid 2025 A&B
ICE 2025 A&B


500,000 Trials
Frequency View
4 Year TCO in 2025 - C/D segment vehicle
Probability
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
£18,000
£21,000
£24,000
£27,000
£30,000
£33,000
£36,000
£39,000
£42,000
£45,000
EV 2025 C&D
H2 RE-EV 2025 C&D
H2-vehicle 2025 C&D
RE-EV 2025 C&D
PHEV 2025 C&D
Hybrid 2025 C&D
ICE 2025 C&D


500,000 Trials
Frequency View
4 Year TCO in 2025 - E/H segment vehicle
Probability
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
£28,000
£32,000
£36,000
£40,000
£44,000
£48,000
£52,000
£56,000
£60,000
£64,000
EV 2025 E&H
H2 RE-EV 2025 E&H
H2-vehicle 2025 E&H
RE-EV 2025 E&H
PHEV 2025 E&H
Hybrid 2025 E&H
ICE 2025 E&H


500,000 Trials
Frequency View
4 Year TCO in 2030 - A/B segment vehicle
Probability
0.00
0.01
0.02
0.03
0.04
0.05
0.06
£12,000
£14,000
£16,000
£18,000
£20,000
£22,000
£24,000
EV 2030 A&B
H2 RE-EV 2030 A&B
H2-vehicle 2030 A&B
RE-EV 2030 A&B
PHEV 2030 A&B
Hybrid 2030 A&B
ICE 2030 A&B


500,000 Trials
Frequency View
4 Year TCO in 2030 - C/D segment vehicle
Probability
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
£18,000
£21,000
£24,000
£27,000
£30,000
£33,000
£36,000
£39,000
EV 2030 C&D
H2 RE-EV 2030 C&D
H2-vehicle 2030 C&D
RE-EV 2030 C&D
PHEV 2030 C&D
Hybrid 2030 C&D
ICE 2030 C&D


500,000 Trials
Frequency View
4 Year TCO in 2030 - E/H segment vehicle
Probability
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
£28,000
£32,000
£36,000
£40,000
£44,000
£48,000
£52,000
£56,000
£60,000
EV 2030 E&H
H2 RE-EV 2030 E&H
H2-vehicle 2030 E&H
RE-EV 2030 E&H
PHEV 2030 E&H
Hybrid 2030 E&H
ICE 2030 E&H

Appendix E – Lifecycle methodology

To calculate the life cycle emissions of the different vehicles the following analysis was carried out. To estimate the embodied emissions and recycling/demolition emissions of the different vehicles classes the environmental credentials of several existing vehicles[53] were used to get an average for the vehicle class. A reduction factor of 20% was applied to this to represent new manufacturing techniques and processes.

To evaluate how the different vehicle compare in embodied CO_2 it is assumed that the embodied emissions of the vehicles are the same apart from the addition of the battery, fuel cell and hydrogen tank embodied emissions as these different elements are likely to have the largest embodied emissions. This is a reasonable assumption based on previous reports of embodied emissions of existing and alternative vehicles[54].

Battery embodied emissions have been calculated by a variety of sources[54,55,56] we have taken an average of 75kgCO_2/kWh of battery capacity. Unfortunately neither fuel cell nor vehicle hydrogen tanks are yet produced in large enough quantities for anyone to have published the life cycle or embodied emissions of these components; they have therefore been excluded from the analysis.

Table 23 DECC central scenario for grid electricity generation mix by fuel type.

Generation type	TWh[57]	Comment
Coal (without CCS)	27	
Coal (with CCS)	22	Upstream only
Oil	3	Assumed hydrocarbon equivalent
Gas	157	
Nuclear	33	Carbon Free
Renewables	122	Carbon Free
Imports	13	Not included
Storage	4	Not included
Other	6	Not included

To calculate the additional emissions from the production of the hydrocarbon fuels the upstream CO_2 requirement for production is added to the carbon content of the fuel. Estimating the additional energy requirement for electricity generation is more complex. The predicted DECC electricity generation mix in 2025 (central scenario **Error! Reference source not found.**) was used, combined with the upstream and processing carbon emissions of the fuel types used in electricity generation (**Error! Reference source not found.**) to estimate the additional embodied CO_2 element of electricity.

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Table 24 processing and additional combustion emissions in CO_2e for different electricity generation fuels.

Generation type	Upstream CO_2 as a percentage of total combustion CO_2	No- CO_2 emissions from combustion inCO_2e as % of total combustion CO_2
Gas[58,59]	23.4%	0.1%
Coal[58,59]	4.4%	0.5%
Oil[60]	7.3%	

All forms of liquid hydrocarbon fuel have the emissions of 0.224tonnes of CO_2 per tonne of product, which translates to 0.176gCO_2/l of fuel[61].

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