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Low carbon cars in the 2020s: Consumer impacts and EU policy implications

Final report

for

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Contents

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Abbreviations

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ACEA	European Automobile Manufacturers' Association
BEUC	The European Consumer Organisation
BEV	Battery electric vehicle
EDF	Électricité de France S.A.
EE	Element Energy
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric vehicle
FCV	Fuel cell vehicle
HEV	(Full) Hybrid electric vehicle, non-plug in
ICE	Internal combustion engine
IEA	International Energy Agency
IKA	Institut für Kraftfahrzeuge
LDV	Light duty vehicle
LED	Light emitting diode
NEDC	New European Driving Cycle
NGO	Non-governmental organisation
OEM	Original equipment manufacturer
PHEV	Plug-in hybrid electric vehicle
SMMT	The Society of Motor Manufacturers & Traders (UK)
TCO	Total cost of ownership
TNO	Netherlands Organisation for Applied Scientific Research
ULEV	Ultra-low emission vehicle
VAT	Value added tax
WEO	World Energy Outlook (IEA)
WLTP	Worldwide harmonized Light vehicles Test Procedure

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1   Executive Summary

Improved fuel efficiency of light duty vehicles (cars and trucks) in the last decade has made an important contribution to reducing the EU's CO_2 emissions, and has had wider benefits to vehicle users and society such as lower fuel costs, improved local air quality (particularly in the case of hybrid and electrified powertrains), and reduced reliance on imported oil. The CO_2 standards Regulation (EC) No 443/2009, first introduced in 2009, required average new car emissions to be no higher than 130 gCO_2/km (measured on the NEDC standardised test) in 2015 and has set a target of 95 gCO_2/km (NEDC) in 2021. This has led to a considerable decline in the NEDC type-approval emissions of new cars, with the 2015 average standing at 119 gCO_2/km, having met the 130 gOC_2/km target nearly 3 years early. Despite adding to the cost of the vehicles, the reduced fuel consumption from this regulation has resulted in a negative cost of CO_2 saving, shown to be on average -€46.4/tonne CO_2 in 2013.[4] This has led a fall in the total costs of ownership for car drivers in the EU.

In order to accommodate car OEMs' 5-7 year development cycles, attention is now turning to the decarbonisation pathway for the 2020s, which will likely include a new CO_2 target for 2025. The European Commission has put in place ambitious climate goals, such as a 30% reduction in non-Emissions Trading Scheme sector emissions between 2005 and 2030, and an 80% reduction in overall emissions in 2050 from 1990 levels. To be met, these will require further improvement to the efficiency of conventional vehicles, as well as widespread deployment of ultra-low carbon technology, such as plug-in vehicles and hydrogen fuel cells.

Accordingly, now is a suitable time to assess the future cost impacts of low and ultra-low emission vehicles on private and fleet vehicle users, in particular whether improved fuel efficiency continues to offset the higher capital cost, and the competitiveness of ultra-low emission vehicles on a total cost of ownership basis. Element Energy was commissioned by BEUC to carry out such an analysis, co-ordinating a 'Roundtable on Sustainable Mobility' including representatives from consumer organisations, lease companies and NGOs to agree data inputs for a comprehensive study on the TCO of cars likely to be sold in the future in Europe.

This report first forecasts changes to the costs and efficiency of conventional petrol and diesel cars, such as internal combustion engine vehicles (ICEs) and full hybrids (HEVs), as well as ultra-low and zero emission powertrains, such as plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and H_2 fuel cell vehicles (FCVs). This is based on the latest evidence for future technology deployment, component costs, running costs (e.g. fuel costs, depreciation, maintenance and insurance), accounting for fuel consumption in real world driving.

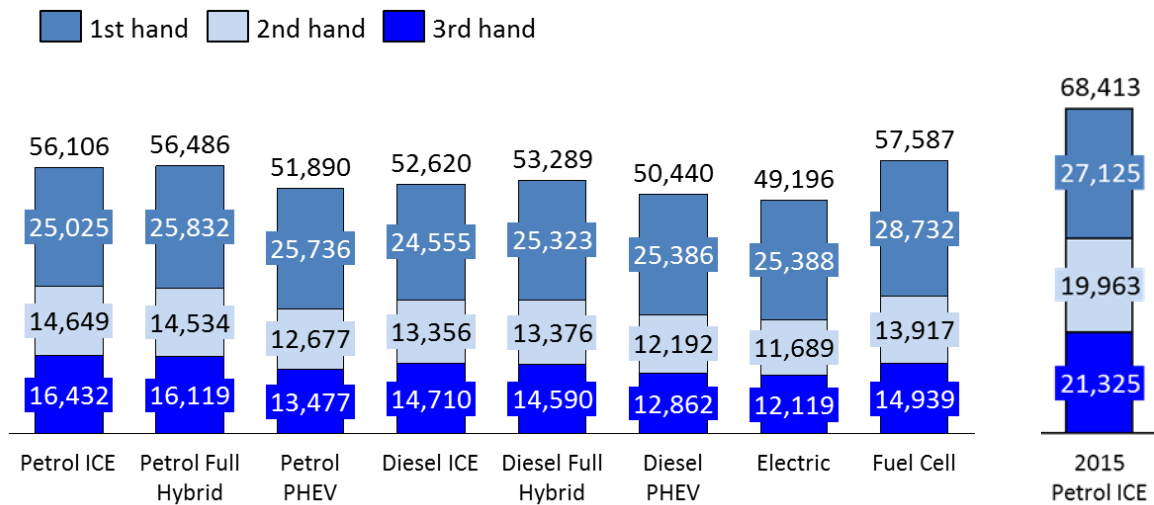## Example Forecasts for NEDC and Real World Emissions
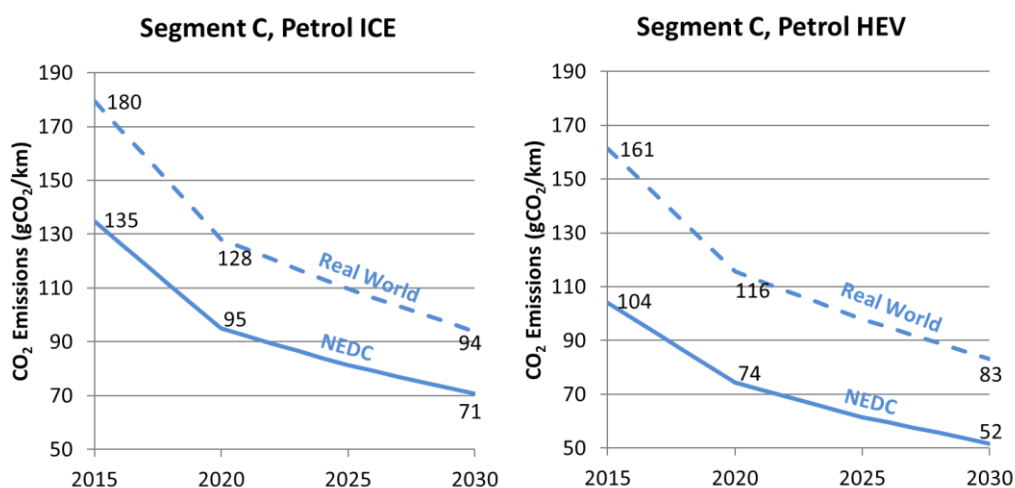
From these forecasts, the Total Costs of Ownership (TCOs) for different powertrains are calculated for first, second and third owners during the vehicle lifetime over the period 2015-30. The result is a strong convergence in the unsubsidised ownership costs of plug-in electric powertrains with conventional ICEs and HEVs, even on a 4-year (first owner) basis. For context, the range of 4-year TCOs for conventional and plug-in cars is inside the cost of several of the most popular optional extras, such as parking sensors and satellite navigation, which are of the order €500-€1,000. Crucially, all powertrains (except H_2 fuel cells) on average have lower ownership costs in 2030 compared with petrol ICEs in 2015, despite a backdrop of rising fuel and electricity prices. BEVs, in particular, reach near TCO parity with diesel ICEs, the cheapest powertrain, for the first owner in 2030. Over the life of the vehicle, the TCO of ultra-low emission vehicles falls significantly below conventional vehicles, even after the costs of home charging points is included.

Change in 4-year TCO, average all segments, 2015-30
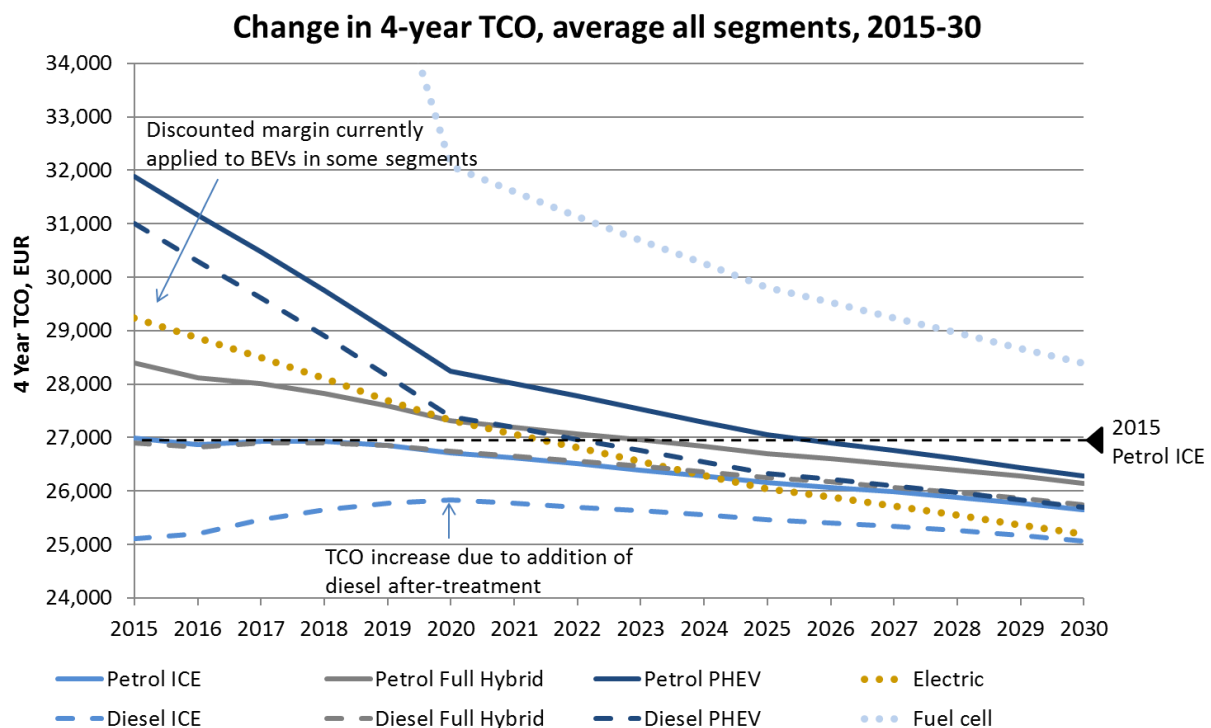
Plug-in electric vehicles show highly competitive ownership costs over the vehicle lifetime compared with conventional ICEs. Since the majority of depreciation cost is levied on the first owner, second and third owners face similar purchase prices across all powertrains, but can continue to take advantage of the lower running costs of plug-in electric cars. BEVs and PHEVs show the cheapest ownership costs of all for second and third owners resulting in, for example, whole life ownership costs of Segment C BEVs being €6,900 cheaper than petrol ICEs and €3,400 than diesel ICEs by 2025. The study also considers the cost of battery replacements for plug-in vehicles during their lives which, if full replacements are necessary, increase the TCOs for these vehicles. This additional cost may be mitigated through partial replacements, extending the operating lifetime of vehicles with new batteries or residual value of used batteries that can be used in other sectors such as home energy storage.

16-year whole life TCO for Segment C powertrains in 2025

Legend: ■ 1st hand ☐ 2nd hand ■ 3rd hand

	Petrol ICE	Petrol Full Hybrid	Petrol PHEV	Diesel ICE	Diesel Full Hybrid	Diesel PHEV	Electric	Fuel Cell	2015 Petrol ICE
Total	56,106	56,486	51,890	52,620	53,289	50,440	49,196	57,587	68,413
1st hand	25,025	25,832	25,736	24,555	25,323	25,386	25,388	28,732	27,125
2nd hand	14,649	14,534	12,677	13,356	13,376	12,192	11,689	13,917	19,963
3rd hand	16,432	16,119	13,477	14,710	14,590	12,862	12,119	14,939	21,325

Further analysis is carried out in this study to test the sensitivity of results to the input assumptions.

- The cost competitiveness of PHEVs is largely dependent on level of driving carried out under electric power, and therefore the frequency of charging. There is a strong financial incentive to maximise this, as halving the proportion of electrified kilometres from ~70% costs €1,000-1,500 more in fuel over a 4-year TCO for a medium-sized (Segment C) Petrol PHEVs and €600-900 for equivalent diesel PHEVs.
- The TCOs are fairly insensitive to the price of oil, largely due to the relatively high fuel taxes in Europe which dampen the impact on final fuel prices. For example, the study explores an alternative low oil price scenario where oil is 27% cheaper in 2030, but this leads to petrol and diesel prices being only 11% and 14% lower, respectively. Future efficiency improvements of petrol and diesel vehicles further reduce the impact of changes to the price of oil for the TCO. As a result of these fuel efficiency improvements, increasing the 2025 oil price from a baseline of $97 per barrel to its record historical monthly peak of $133 (July 2008) would only imply an additional ~€130 per year for a medium sized petrol or diesel car purchased in 2025.
- High mileage applications increase the benefit of lower running costs for BEVs and PHEVs. For example, increasing the annual mileage by 5,000km to 20,000km results in Segment C BEVs becoming cheaper than petrol ICEs on a 4-year TCO basis in 2025, and only €100 more than diesel ICEs.
- Accelerating the decrease in battery costs to match recent announcements by General Motors and Tesla would mean 4-year TCO parity between Segment C BEVs and petrol and diesel ICEs would be observed as early as 2020. Alternatively, OEMs could take advantage of the faster battery cost reduction by increasing the range of electric vehicles. The lower battery cost scenario is shown to be worth approximately 200 km of additional NEDC range (from 320 km to 520 km).

Internal combustion engines are expected to remain a major component of vehicle powertrains throughout the 2020s and so continued improvement in their efficiency is beneficial. However, from a consumer perspective, it is important to ensure that this continues to remain a cost-effective means of decarbonisation. Deployment of additional efficiency technology adds to the vehicle manufacturing cost, but historically this has previously been fully offset by the resulting fuel savings. To test whether this continues to hold true, alternative scenarios are explored in which technology deployment in conventional ICEs is held constant either at 2015 or 2020 levels, but costs of already deployed technology continue to fall at the baseline rate. Static fuel efficiency in future vehicles increases TCOs for first, second and third owners in the 2020s, suggesting that more efficient vehicles continue to benefit customers even as efficiency gains become harder and more costly to achieve. This highlights the

benefits of policies that continue to drive these efficiency improvements beyond the end of the current fleet CO_2 regulations.

Finally, analysis of the expected emissions of future powertrains provides a view on the level of uptake of ULEVs required to meet particular CO_2 levels. A level of 70-80 gCO_2/km (based on the forthcoming WLTP standardised test) in 2025 would require 10-22% ULEVs, although the exact share depends on the ratio of BEVs to PHEVs and electric range of PHEVs favoured by vehicle manufacturers. Since HEV emissions already lie close to this range, their market share shows little impact on overall average emissions. Correspondingly, a level 45-55 gCO_2/km (WLTP) in 2030 would require 30-45% ULEVs. These values are in-line with other studies on the likely market shares of ultra-low emission vehicles by 2025 and 2030[1], and recent announcements by car manufacturers on what could be achieved by 2025[2].

The analysis conducted in this study leads to the following conclusions:

- The continued overall cost savings from improved vehicle efficiency, along with increasingly cost-competitive BEVs and PHEVs, suggest that ambitious CO_2 targets can be set in the 2020s without disadvantaging the consumer.
- Further improvement to the efficiency of conventional ICEs can make a considerable contribution to reducing light duty transport sector emissions, with a negative cost of CO_2 saving. The payback period of additional technology deployed between 2015 and 2025 is predicted to be on average 0.7 - 1.7 years, and provide lifetime fuel savings of €4,410 - €9,360, depending on the fuel, segment and extent to which vehicle manufacturers improve already deployed technology. The technology deployed between 2020 and 2025 alone offers a payback of 2.0 - 4.3 years on average, saving €910 - €2,510 over the lifetime of the vehicle. This highlights the benefit of continued efficiency improvements into the 2020s.
- Plug-in electric cars show highly competitive TCOs when considered over the current average technical life of a European car, and BEVs reach near parity on average with diesel ICEs for the first owner in 2030, accounting for future increases in vehicle driving range. Low running costs will make BEVs and PHEVs attractive options for second and third owners and overall lifetime TCOs are significantly below those of conventional cars.
- Batteries stand as a key uncertainty in the cost competitiveness of plug-in cars, particularly BEVs. Baseline results in this study employ a conservative battery cost scenario, and OEM expectations suggest that a more aggressive cost reduction is possible. Conversely, the impact of higher battery costs on the TCO may be limited, as manufacturers are likely to make trade-offs between battery size (and vehicle range) and selling prices. Further work is required to understand the lifetime of EV batteries under real driving conditions, including the evolution of residual values as next generation vehicles are released with higher electric ranges.
- Whilst EVs are not forecast to disadvantage consumers from a cost of ownership perspective, future policies should recognise the need to overcome additional barriers for ULEV adoption. This includes availability of a widespread rapid charge network on major roads (or hydrogen refuelling stations for fuel cell vehicles), and providing charging solutions for drivers without access to off-street parking. Commitments to addressing these will be critical in increasing consumer acceptance, which in turn reduces risks for vehicle manufacturers to deploy novel powertrains across their model ranges.

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[1] Review of recent EV sales forecasts featured in Ricardo-AEA for RAC (2013) Powering Ahead - The Future of Low-Carbon Cars and Fuels

[2] Volkswagen aim to sell 20-25% electric cars by 2025; Nissan targeting 20% of European sales to be electric by 2020; 40% of Ford's available models to be electrified by 2020.

2 Introduction

Reducing emissions from new cars and vans has been an important component of continuing efforts to reduce greenhouse gas emissions from the European transport sector. In addition to reducing climate impacts, increasing the efficiency of new vehicles has numerous wider benefits, including lower fuel costs for users, improved local air quality (particularly in the case of hybrid and electrified powertrains), and lower oil imports with associated benefits for energy security and Europe's balance of payments. CO_2 emissions from light vehicles are currently regulated by two EC Regulations, which require average new car emissions to fall to 130g/km in 2015 and 95g/km in 2021 and van emissions to reach 175g/km in 2017 and 147g/km in 2020.[3] These regulations have been successful in driving down new vehicle emissions as measured on the NEDC test, though the increasing gap between test cycle and real-world emissions has compromised some of these savings. Average car emissions on the NEDC reached 119g/km in 2015, and van emissions fell to 169g/km in 2014 and achieved the 2017 target four years early.

The progress in efficiency to date has been achieved while providing lower total costs of ownership to users, as small increases in the purchase prices of more efficient vehicles have been easily offset by ongoing fuel savings. According to a European Commission evaluation of the new vehicle regulations, new vehicle emissions regulations are estimated to have generated net economic benefits of €7.3 billion[4]. The additional purchase cost of a new car in 2013 was €183 per car compared with a 2006 vehicle, which is offset by lifetime fuel savings of €1,336 for petrol cars and €981 for diesel cars. This implies a negative cost for CO_2 savings delivered by the car regulation of -€46.4/tonne, compared to estimates of +€32.4 to +38.7/tonne before the regulation was introduced. These benefits take into account the fact that the anticipated fuel savings from the regulations have been lower than expected, due to the increasing divergence between test cycle and real-world fuel consumption.

Against this backdrop, attention is now turning to the further reductions in vehicle emissions required in the 2020s in-line with the European Union's climate goals. Depending on the emission reductions targeted by future new vehicle standards or other mechanisms, a combination of advanced technologies such as vehicle mass reduction, engine efficiency improvements, use of micro and mild hybrid systems and further deployments of ultra-low and zero emission vehicles will be required.

As policy discussions continue within Europe about the level of ambition needed for new vehicle emissions in the 2020s and the mechanisms to be used to deliver them, it is timely to assess the future cost impacts of low and ultra-low emissions vehicles on private and fleet vehicle users, in particular whether the lower running costs of more efficient vehicles will continue to outweigh the higher upfront costs of advanced vehicles. This report by Element Energy was commissioned by BEUC (The European Consumer Organisation), to explore the total costs of ownership of cars sold in the 2020s. Specifically, the study aims were as follows:

- Synthesise the latest evidence on future costs and performance of new cars, covering incremental improvements to petrol and diesel cars as well as ultra-low and zero emission powertrains
- Develop a robust set of assumptions for the other components of vehicle ownership costs, such as depreciation rates, fuel costs, maintenance and insurance, and how these are likely to evolve in the future for each powertrain
- Calculate the Total Costs of Ownership for different powertrains in 2020, 2025 and 2030. This includes an assessment of how costs are likely to vary for first, second and third owners.

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[3] For cars: Regulation (EC) No 443/2009; for vans: Regulation (EU) No 510/2011
[4] European Commission (2015): Evaluation of Regulations 443/2009 and 510/2011 on CO2 emissions from light-duty vehicles

- Examine the sensitivity of the results to changes in input assumptions, e.g. energy prices, annual driving distances etc.
- Draw conclusions on the implications of the results for post-2020 policy mechanisms to drive decreases in new vehicle emissions

This study was carried out using a continuous peer review process, during which representatives from a number of different organisations working on automotive affairs were convened at five roundtable meetings (from here on we will refer to this as 'the Roundtable') to discuss the methodology, data sources and results. The information and views set out in this report are those of the author(s) and do not necessarily reflect the opinions of those individuals or their organisations involved during the peer review process. The authors of this study would like to acknowledge the participation of the following individuals and their organisations:

Leo Muyshondt (Test-Achats), Okorn Boštjan (Slovene Consumers' Association – ZPS), Ronald Vroman (Consumentenbond), Kolbe Gregor (VZBV), Lauranne Krid (FIA Region 1) Victor Brangeon (FIA Region 1), Chris Carroll (BEUC), Sylvia Maurer (BEUC), Chris Nobel (Cleaner Car Contracts), Koenraad Backers (Cleaner Car Contracts), Pete Harrison (European Climate Foundation), Greg Archer (Transport & Environment), Richard Knubben (Leaseurope), Pieter Goosens (Athlon), Frank van Gool (Renta), Johan Meysen (CARA), Tristan Koch (Centric), Marco Van Dijke (Yor24/Fleet Support), Peter Mock (ICCT), Wolfgang Schade (M-FIVE), Phil Summerton (Cambridge Econometrics)

All costs presented are expressed in 2014€.

3 Cost and Performance Dataset

3.1 Segments and Powertrains Covered

The focus of this study is on the Total Cost of Ownership (TCO) for passenger cars between 2015 and 2030. Vehicle costs and fuel and electricity consumption figures are provided by Element Energy's Car Cost and Performance Model. To capture the differences between cars of different sizes, this model provides outputs for each of the nine vehicle segments of the UK Society of Motor Manufacturers & Traders (SMMT), which is very similar to the classification scheme used by the European Automobile Manufacturers Association (ACEA) in their annual Pocket Guide. The only difference between the two is that there is no Segment G: Specialist Sports in ACEA's scheme. Since specialist sports cars have very low market shares (<1%), this has a negligible effect on the model's applicability to a European study. The SMMT and ACEA classification both contain the same example models for each segment (see Figure 1) and so use of the SMMT classification in the Car Cost and Performance Model is directly transferable to the EU market.
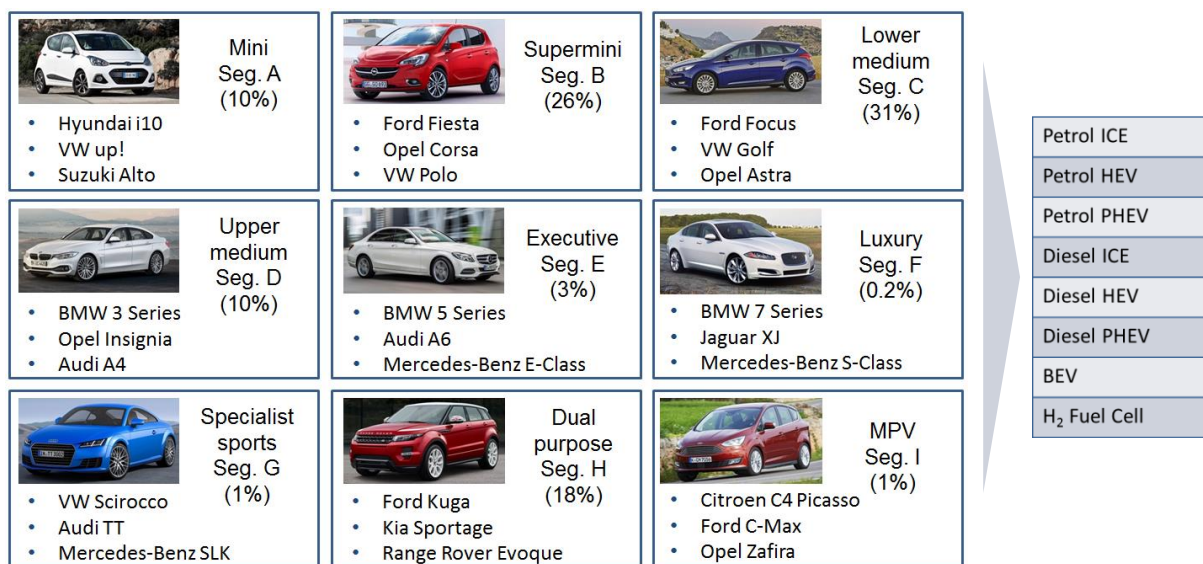

Figure 1: Segmentation of cars in EE's Cost and Performance Model and powertrains covered.[5] Approximate market shares shown in brackets[6]

Within each segment, the Cost and Performance Model was used to generate outputs for each of the powertrains presented in Figure 1. This allows Total Costs of Ownership to be assessed for the full range of likely powertrains on the market from 2015 to 2030, from conventional petrol and diesel models (ICEs) and pure hybrids (HEVs) through to ultra-low emission powertrains such as plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). This was considered representative of the powertrains available within Europe in the period 2015-30. Additional low-carbon options such as natural gas and biofuels were not considered within the scope of this study. However, the trends in petrol ICE efficiency are indicative of the improvements to energy consumption that may occur for these additional powertrains, since they would benefit from engine improvements as well as wider developments such as improved aerodynamics or rolling resistance.

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[5] ICE = internal combustion engine, HEV = full hybrid, PHEV = plug-in hybrid, BEV = battery electric vehicle, FCV = fuel cell vehicles
[6] ICCT Pocketbook 2014

3.2 Modelling Approach

To generate the total purchase price of vehicles, the Cost and Performance Model employs a bottom up approach, where the costs of individual powertrain specific components are added to an *original chassis cost* (see Figure 2). The *original chassis cost* encompasses all non-powertrain specific components, for example excluding the engine, motors, and efficiency technologies deployed on future vehicles. It is calculated for each segment by removing the sales margin, and costs of the engine, efficiency measures and additional transmission components from the average purchase price of 2015 petrol and diesel ICE vehicles (see Section 3.3.1).
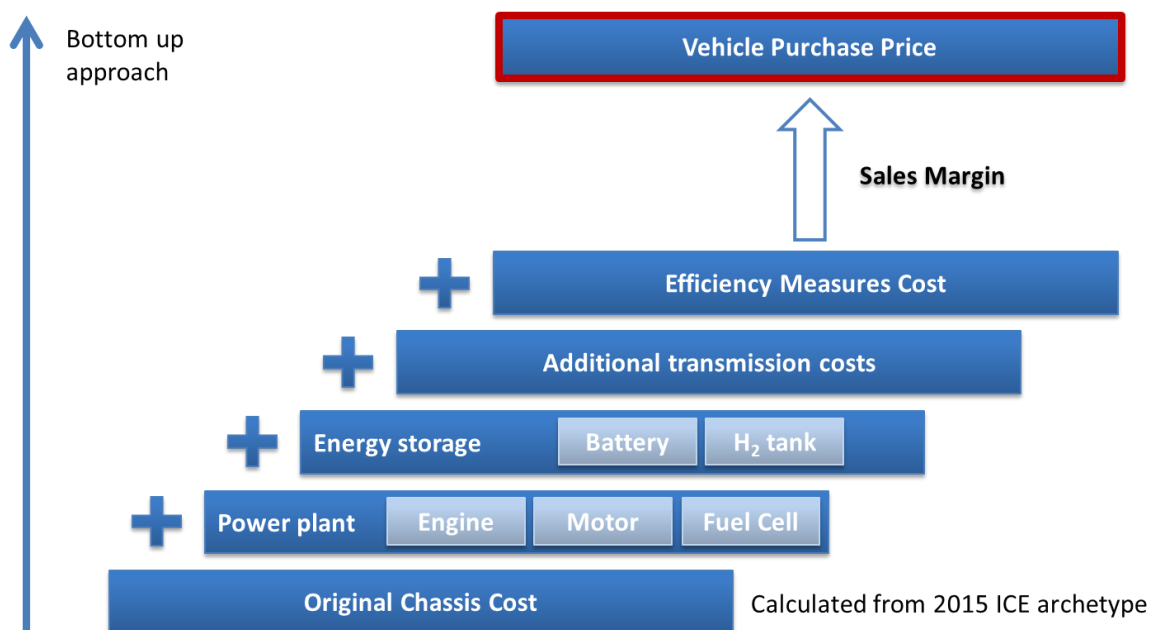
Figure 2: Representation of the bottom-up approach employed in the Cost and Performance Model

The inputs were drawn from a variety of sources, for example:

- Costs for incremental vehicle efficiency technologies were drawn from the Ricardo-AEA (2015) study on cost curves that was commissioned by the European Commission[7]
- Battery costs for PHEVs and BEVs were derived from Element Energy's component-based battery cost model originally developed for the UK Committee on Climate Change[8]
- Fuel cell system and hydrogen storage costs were drawn from a review of academic literature and discussion with leading fuel cell vehicle manufacturers
- Adjustment factors accounting for the gap between test cycle flexibilities and real-world emissions were taken from Element Energy and the ICCT's work for the UK Committee in Climate Change[9]

The technology costs from the 2015 Ricardo-AEA study for the European Commission were chosen as they represent the latest and most detailed dataset and have been extensively reviewed by automotive experts and industry stakeholders such as component suppliers and manufacturers. The costs in the 2015 study are lower than previous estimates by TNO (2011) and IKA (2012 and 2015), and higher

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[7] Ricardo-AEA (2015) Improving understanding of technology and costs for CO_2 reductions from cars and LCVs in the period to 2030 and development of cost curves
[8] Element Energy (2012) Costs and performance of EV batteries.
[9] Element Energy and ICCT (2015): Quantifying the impact of real-world driving on total CO2 emissions from UK cars and vans.

than the recent ICCT cost curves[10]. This provides a balanced central estimate of technology costs for use in the TCO analysis in this study. A further advantage of the use of the Commission cost curves for incremental technologies is alignment with the datasets that are likely to be used to inform post-2020 policymaking for light vehicles.

The assumptions surrounding each of the powertrain specific components are as follows:

3.2.1   Engine and Motor costs

The costs of internal combustion engines (denoted simply as "engines" in this report), expressed on a per kW of output basis, are used to calculate the cost impact of changes in engine power levels in future models, including power reductions in hybrid and plug-in hybrid vehicles. Costs are assumed to gradually decrease, on a per kW basis, as per the Ricardo-AEA's 2015 cost curves study. The cost per kW of ICE and HEV engines decreases by ~8% from 2015-30. Due to their smaller sizes, PHEV engines are slightly more expensive per kW, and decrease by only ~5% over the same period.

Due to the potential for increased volume manufacturing, the cost of electric motors (referred to as "motors") are projected to decrease from €24/kW in 2020 to €15/kW in 2030.[11]

3.2.2   Battery costs

Batteries for plug-in hybrid and battery electric vehicles have a strong influence on vehicle costs, with the cost of the battery increasing with capacity. Hence, the car manufacturers face a trade-off between maximising electric driving range and minimising vehicle costs. In this study, battery costs and energy densities are based on Element Energy's recent component cost modelling exercise for automotive batteries, which provides outputs for different battery sizes on a kWh basis. Cost on a per kWh basis decreases with battery size as the contribution of fixed costs (for example wiring, the battery management system) becomes smaller per kWh. Figure 3 shows the baseline cost scenario for a 35-60 kWh battery pack, with which most BEVs will be equipped 2015-30.

€2014/kWh pack
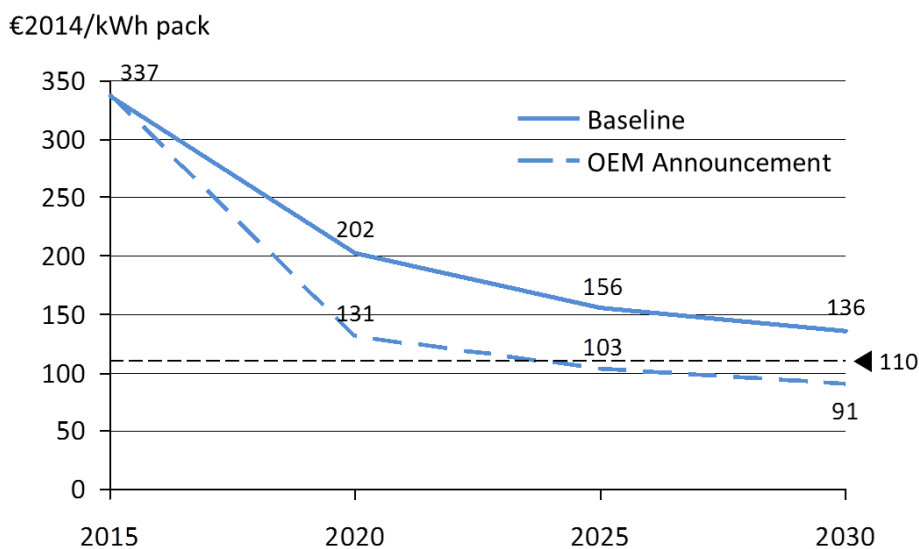
Figure 3: Battery cost scenarios for a 35-60 kWh battery from Element Energy's recent component cost modelling

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[10] ICCT (2016) CO_2 reduction technologies for the European car and van fleet, a 2025-2030 assessment. [A comparison with other cost curve studies is featured in: ICCT (2016) 2020–2030 CO_2 standards for new cars and light-commercial vehicles in the European Union]

[11] R-AEA for CCC (2012) A review of the efficiency and cost assumptions for road transport vehicles to 2050

Recent announcements from OEMs suggest that automotive battery costs may be even lower than the range presented here. Chevrolet reported that they have agreed a price of $145/kWh at the cell level with LG Chem for their upcoming 60 kWh Bolt BEV, expected in 2017. This equates to about €150/kWh at the pack level. In addition, Tesla is aiming for battery cell costs of $100/kWh, equivalent to €110/kWh packs, by 2020. There are reasons to believe that these very low targets underestimate near term costs, given potential delays in Tesla's production ramp-up for its Model 3 and the fact that GM's statement on LG Chem's cell costs reflect a particularly competitive price that depends on their collaboration in other areas of the car. Consequently, this study uses a central cost scenario drawn from our component-based battery model, but also tests a more aggressive cost reduction scenario (*OEM Announcement*) based on these manufacturer announcements.[12]

3.2.3   Fuel Cell and H_2 Tank

Fuel cell costs and hydrogen tank costs were based on a review of publicly available cost projections[13], as well as discussions held with participants in the Hydrogen Mobility coalitions present in countries such as Germany, France and the UK. The long term costs for fuel cells are broadly in-line with the US Department for Energy's long term target for light vehicle fuel cells. Hydrogen tank costs for 700 bar gaseous storage are expected to decrease strongly to 2020, though tank costs are more heavily linked to marked prices for carbon fibre than the volume of hydrogen tank production itself.

Table 1: Fuel cell and H_2 tank costs

	2015	2020	2025	2030
Fuel Cell (€/kW)	276	92	72	57
H_2 Tank (€/kg H_2)	1,428	694	599	541

3.2.4   Additional Transmission Components and Exhaust After-treatment

The additional transmission components are those that are powertrain-specific and so not contained within the *original chassis cost*. These include electric vehicle components such as heavy gauge wiring and battery charger and management system, and conventional vehicle components such as the introduction of advanced exhaust after-treatment systems in diesel powertrains from 2017 to comply with increasingly strict PM and NO_x air quality standards (including real world testing of NO_x emissions). Adoption of direct injection technology in petrol engines has been shown to increase particulate emissions, and so they will likely also require additional equipment to meet particulate limits after 2017[14]. However, since the cost of a particulate matter filter is only ~€50[15], it has not been included in the technology cost database. The other cost figures are sourced from Element Energy's previous TCO study for LowCVP in 2011.[16]

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[12] From forthcoming study from the European Climate Foundation into sustainable transport in Germany
[13] US Department of Energy (2015) DOE Hydrogen and Fuel Cells Program Record; Roland Berger for the FCH JU (2015) Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe
[14] Daimler announced the inclusion of particulate filters in new models in May 2016. https://www.daimler.com/innovation/specials/engineoffensive.html
[15] Transport & Environment (2015) Don't Breathe Here: beware the invisible killer. Tackling Air Pollution from vehicles
[16] Element Energy for LowCVP (2011) Influences on the Low Carbon Cars Market from 2020–2030

Table 2: Additional transmission components and associated costs

Component	Cost, €				Powertrains
	2015	2020	2025	2030	
Battery charger	409	373	339	303	HEVs, PHEVs, BEVs, FCEVs
Additional transmission	225	225	225	225	HEVs, PHEVs, BEVs, FCEVs
Heavy gauge wiring	178	178	178	178	PHEVs, BEVs, FCEVs
Battery systems hardware	884	884	884	884	HEVs, PHEVs, BEVs, FCEVs
Advanced exhaust	-	880	880	880	All diesel

3.2.5 Efficiency Measures

Ricardo-AEA's technology cost and performance dataset[17] features a wide range of technologies that can be applied to passenger cars to improve efficiency and reduce CO_2 emissions. These are categorised as:

- Improvements in the efficiency of the internal combustion engine e.g. from downsizing and combustion efficiency improvements
- Hybridization e.g. stop-start technology and regenerative braking
- Advanced transmissions and gearbox optimization
- Driving resistance reduction e.g. weight reduction and improved aerodynamics
- Improvements to auxiliary systems, such as fluid pump efficiencies and higher voltage electrical systems

For each technology, Ricardo-AEA's technology cost dataset defines at 5 year intervals from 2015-30:

- The specific percentage energy saving based on a specified test cycle. The savings tend to increase over time as the technology improves.
- The technology cost, which decreases over time as manufacturers take advantage of learning rates. This is a function of cumulative deployed volume of each technology.
- The level of deployment across new passenger cars, which define the overall technology packages installed in each vehicle.

This information is provided for 45 technologies (see Figure 4) for each powertrain (including electric powertrains) within small (A and B), medium (C, D and I) and large (E, F, G and H)[18] segments. These technologies cover only the measures that influence the energy consumption of a car during a laboratory test cycle (known as 'on-cycle measures'). Off-cycle measures, such as high efficiency LED headlamps that may provide a real-world fuel saving but do not change test cycle energy consumption, are not directly included as these are a much smaller contribution to overall vehicle efficiency than the measures captured here.

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[17] The source data for the 2015 Ricardo-AEA cost curve study are available at: http://ec.europa.eu/clima/policies/transport/vehicles/docs/technology_sources_web.xlsx

[18] Segment G is considered "large" as it shares many of the characteristics of the F (luxury) and E (executive) segments, such as high power and technologies deployed
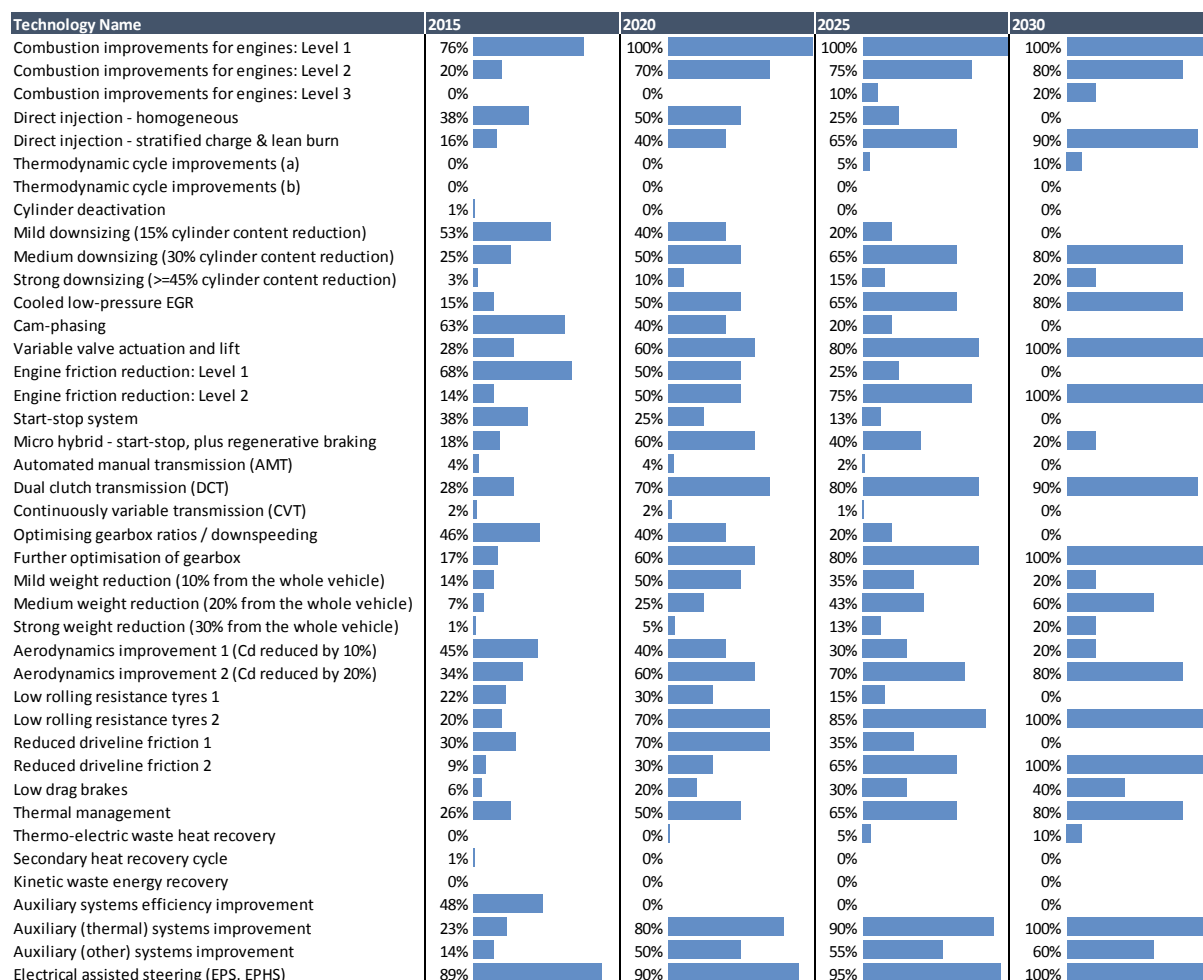
Technology Name	2015	2020	2025	2030
Combustion improvements for engines: Level 1	76%	100%	100%	100%
Combustion improvements for engines: Level 2	20%	70%	75%	80%
Combustion improvements for engines: Level 3	0%	0%	10%	20%
Direct injection - homogeneous	38%	50%	25%	0%
Direct injection - stratified charge & lean burn	16%	40%	65%	90%
Thermodynamic cycle improvements (a)	0%	0%	5%	10%
Thermodynamic cycle improvements (b)	0%	0%	0%	0%
Cylinder deactivation	1%	0%	0%	0%
Mild downsizing (15% cylinder content reduction)	53%	40%	20%	0%
Medium downsizing (30% cylinder content reduction)	25%	50%	65%	80%
Strong downsizing (>=45% cylinder content reduction)	3%	10%	15%	20%
Cooled low-pressure EGR	15%	50%	65%	80%
Cam-phasing	63%	40%	20%	0%
Variable valve actuation and lift	28%	60%	80%	100%
Engine friction reduction: Level 1	68%	50%	25%	0%
Engine friction reduction: Level 2	14%	50%	75%	100%
Start-stop system	38%	25%	13%	0%
Micro hybrid - start-stop, plus regenerative braking	18%	60%	40%	20%
Automated manual transmission (AMT)	4%	4%	2%	0%
Dual clutch transmission (DCT)	28%	70%	80%	90%
Continuously variable transmission (CVT)	2%	2%	1%	0%
Optimising gearbox ratios / downspeeding	46%	40%	20%	0%
Further optimisation of gearbox	17%	60%	80%	100%
Mild weight reduction (10% from the whole vehicle)	14%	50%	35%	20%
Medium weight reduction (20% from the whole vehicle)	7%	25%	43%	60%
Strong weight reduction (30% from the whole vehicle)	1%	5%	13%	20%
Aerodynamics improvement 1 (Cd reduced by 10%)	45%	40%	30%	20%
Aerodynamics improvement 2 (Cd reduced by 20%)	34%	60%	70%	80%
Low rolling resistance tyres 1	22%	30%	15%	0%
Low rolling resistance tyres 2	20%	70%	85%	100%
Reduced driveline friction 1	30%	70%	35%	0%
Reduced driveline friction 2	9%	30%	65%	100%
Low drag brakes	6%	20%	30%	40%
Thermal management	26%	50%	65%	80%
Thermo-electric waste heat recovery	0%	0%	5%	10%
Secondary heat recovery cycle	1%	0%	0%	0%
Kinetic waste energy recovery	0%	0%	0%	0%
Auxiliary systems efficiency improvement	48%	0%	0%	0%
Auxiliary (thermal) systems improvement	23%	80%	90%	100%
Auxiliary (other) systems improvement	14%	50%	55%	60%
Electrical assisted steering (EPS, EPHS)	89%	90%	95%	100%

Figure 4: Segment C&D Petrol ICE deployment schedule for the on-cycle efficiency technologies[19]

It is stated that the technology deployment schedule, and thus fuel efficiency improvement, is driven by the 95 gCO_2/km target in 2021, and beyond that the EU's long-term objective to cut greenhouse gas emissions in transport by 60% in 2050 compared with 1990 levels. It does is not driven by a specific medium term target, such as an extension to the fleet CO_2 target in 2025 or 2030. An example deployment schedule for medium sized petrol ICEs is shown in Figure 4. The Ricardo-AEA study included data validation from automotive industry stakeholders, and so the CO_2 abatement trajectory also incorporates current manufacturer expectations. The trajectory for a selection of ICEs is presented in Figure 5, Section 3.3.2, and its implications with regards to future targets and ULEV market share is discussed in Section 7.4.

3.2.6   Sales Margins

The Cost and Performance Model outputs the total vehicle production costs for the manufacturer (the factory gate cost). However, a sales margin must be added to estimate the purchase price to be used in the TCO calculation. In this study, the sales margin is defined as the percentage decrease between the vehicle purchase price (excluding sales taxes, such as VAT, and incentives, such as grants) and the vehicle factory gate cost (i.e. the sum of the component costs from the bottom up model). It therefore includes both the OEM margin and the dealer, logistics and marketing margins.

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[19] Ricardo-AEA (2015) Light duty vehicle cost and efficiency scenarios

Quantifying margins is challenging due to their commercially sensitive nature, and the fact that margins vary across segment, country and manufacturer. However, a review of available literature[20] suggests indicative margins for conventional ICE vehicles, with lower margins observed for smaller segments (19% for A and B segments), while premium segments command a higher margin (29% for segment E, F and G). Segments C, D, H and I were found to have an average sales margin of 24%.

For all other powertrains, the margin is set at the same absolute value of the equivalent petrol or diesel ICE powertrain (BEVs and H_2 FCs take the average of this value). This reflects the fact that several components of the margin e.g. dealer costs and marketing are likely to be the same for a car of a given size whether it has a petrol/diesel engine or a more expensive powertrain. Current market data suggests that margins are lower than this for some ultra-low emission models, reflecting the need to meet lower price points to stimulate the early market. For example, the Cost and Performance Model calculates the factory gate cost of a 2015 Segment C BEV to be €28,833, which is only €1,400 less than the average purchase price (excl. VAT and grants) of a Nissan Leaf 24kWh. This compares with an average sales margin of €5,100 for a Segment C ICE. The margin is calibrated to reflect this so called "OEM discounting" and increased over time to the ICE value, at the maximum rate that does not result in the vehicle price increasing. Under this methodology, no discounted pricing strategies are predicted to be in place by 2020.

3.3 Conventional Petrol and Diesel ICEs

3.3.1 2015 ICE vehicle baselines

The Cost and Performance Model is baselined against 'average' or 'archetypal' petrol and diesel ICEs from 2015. These were developed from a comprehensive market review of the UK's top five selling petrol and diesel models within each segment in 2015. Sales weighted average values were calculated for a range of attributes such as: price, engine power, kerb weight, type approval (NEDC) fuel consumption and CO_2 rating (gCO_2/km), and insurance and maintenance costs.

Fuel consumption for each archetype is calibrated against average petrol and diesel CO_2 emissions for new cars in each segment in the UK, provided by SMMT. Despite the model being originally developed for the UK, the average CO_2 figure in 2015 when EU-28 segment market shares are applied is 121.4 gCO_2/km. This lies very close to the 123.4 gCO_2/km published in the latest European Environment Agency CO_2 report,[21] and helps validate this model for application in a Europe-wide TCO study. Indeed, a discrepancy of this magnitude is very small on the scale of a TCO calculation given that a single gCO_2/km difference is of the order of only €10 per year in fuel costs.

3.3.2 Forecasting future attributes

Future engine costs are based on forecasted changes in the engine power. Up to 2020, it is assumed that power-to-weight ratios (calculated by dividing the peak engine power by the mass of the vehicle) continue on the trends observed 2010-15, although for some segments it is held constant to avoid excessively high engine powers. This is summarised in Table 3.

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[20] Roland Berger (2014) Global Automotive Supplier Study; KPMG (2013) Automotive Now, Trade in crisis; Holweg M & Pil F K (2004) The second century: reconnecting customer and value chain through build-to-order: moving beyond mass and lean production in the auto industry; Argonne (1999) Evaluation of Electric Vehicle Production and Operating Costs

[21] European Environment Agency (2015) Monitoring CO2 emissions from new passenger cars and vans in 2014

Table 3: Assumed annual % increase in power-to-weight ratio 2015-2020

Fuel	Segment	Annual power to weight ratio Change
Diesel	All	+1.3%
Petrol	A	+3.0%
Petrol	B	+3.5%
Petrol	C	+3.5%
Petrol	D	-
Petrol	E, F, G	-
Petrol	H	+1.5%
Petrol	I	-

The change in vehicle kerb weight is calculated from the additional deployment of vehicle weight reduction technology packages. Beyond 2020, engine power is held constant, yet power-to-weight continues to rise as vehicles become lighter.

Improvements to ICE fuel consumption for each archetype are calculated from the change in overall vehicle efficiency due to changes in deployed efficiency technologies. As with cost, the percentage decrease in fuel consumption resulting from each technology is provided by the Ricardo-AEA's 2015 cost curve study.[17] The efficiency gains tend to increase over time as the technology improves. To calculate the net reduction in fuel consumption due to the technologies deployed, the same multiplicative approach is used as to calculate the Ricardo-AEA cost curves.

$$\% \ reduction \ in \ fuel \ consumption = 1 - \prod_{i}^{n}(1 - e_i d_i)$$

n = 45 efficiency technologies, i = technology index, e_i = percentage efficiency gain of technology i, d_i = percentage deployment of technology i across new cars. In addition, correction factors are applied to take into account the impact of overlapping technologies, where one technology may reduce the effectiveness of another. The efficiency gains of petrol and diesel engine technologies are reduced by 15% and 5% respectively, as suggested in the European Commission's previous cost curve study.[22] The overall percentage reduction in fuel consumption is relative to the Ricardo-AEA cost curve's baseline vehicle, and so in the Cost and Performance Model these values are re-baselined against the 2015 petrol and diesel ICE archetypes. The overall combined impact of the efficiency technologies relative to the relevant ICE archetype is termed the *efficiency factor*.

$$efficiency \ factor = \frac{total \ efficiency \ saving \ for \ vehicle \ j}{total \ efficiency \ saving \ for \ 2015 \ ICE \ car}$$

Fuel consumption of vehicle *j* is calculated by multiplying the fuel consumption of the relevant 2015 ICE archetype by the *efficiency factor*. Figure 5 shows the impact of this approach on the expected CO_2 emissions, and thus fuel consumption, used in this study for ICEs of various segments. This incorporates the technology deployment schedule and estimated efficiency gains from the Ricardo-AEA 2015 Cost Curve study, as discussed in Section 3.2.5. The general trend is for ICE CO_2 emissions to

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[22] TNO (2011) Support for the revision of Regulation (EC) No 443/2009 on CO2 emissions from cars

continue to fall quickly to 2020 in order meet the 95 gCO_2/km target. This is followed by a more gradual decrease post-2020 as the industry looks towards the EU's long term emissions targets, and OEMs increasingly rely on ULEVs to lower emissions. Note that this trajectory is based on continued improvements in vehicle technology consistent with tightening of future CO_2 standards, but the Ricardo-AEA study does not appear to make an explicit assumption on what future CO_2 targets could be for light
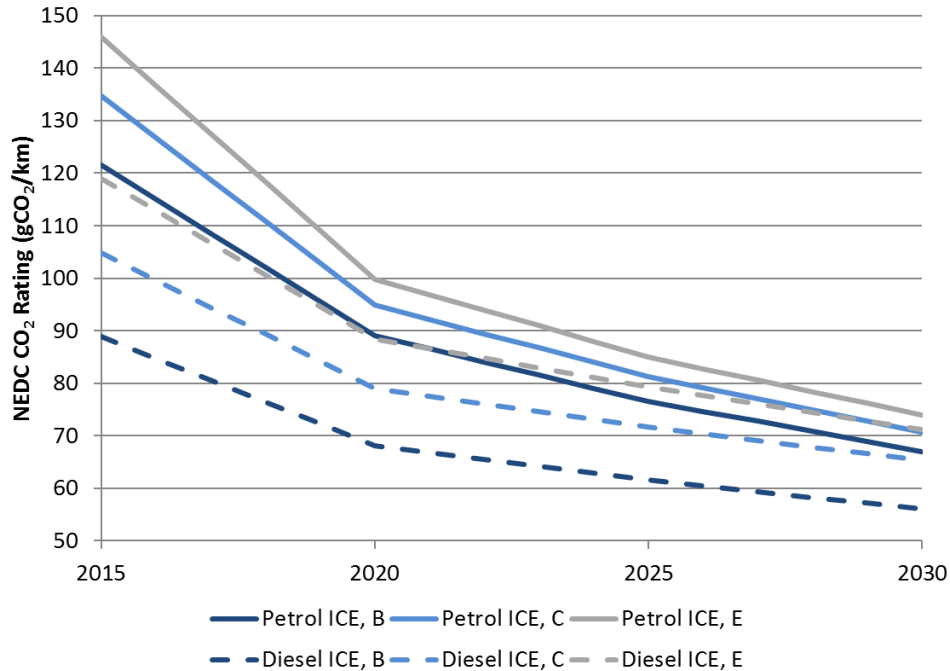
vehicles.

Figure 5: NEDC CO_2 emissions for petrol and diesel ICEs in segments B, C and E. Note that this does not include the impact of further exploitation of test cycle flexibilities

Technology deployed across ICEs includes stop-start, regenerative braking and micro or mild-hybridisation which provides similar functionality to HEVs. However, in this study ICEs and HEVs remain distinct powertrains, differentiated by the capability of HEVs to drive under electric power only for a limited distance. This is in contrast with the Ricardo-AEA 2015 cost curve study which treats ICEs and HEVs as a single powertrain category, and assumes full hybridisation is deployed across all new conventionally fuelled vehicle in the 2030s. However, future consumer appetite for HEVs is uncertain and for the purposes of this study forecasting growth in the HEV market share is unnecessary. Thus, treating ICEs and HEV separately allows for continued comparison between the cost competitiveness of both powertrains, although it should be remembered the distinction between ICEs and HEVs becomes increasingly blurred over time.

The impact of deploying efficiency technologies on the cost of ICE vehicles is shown in Figure 6:
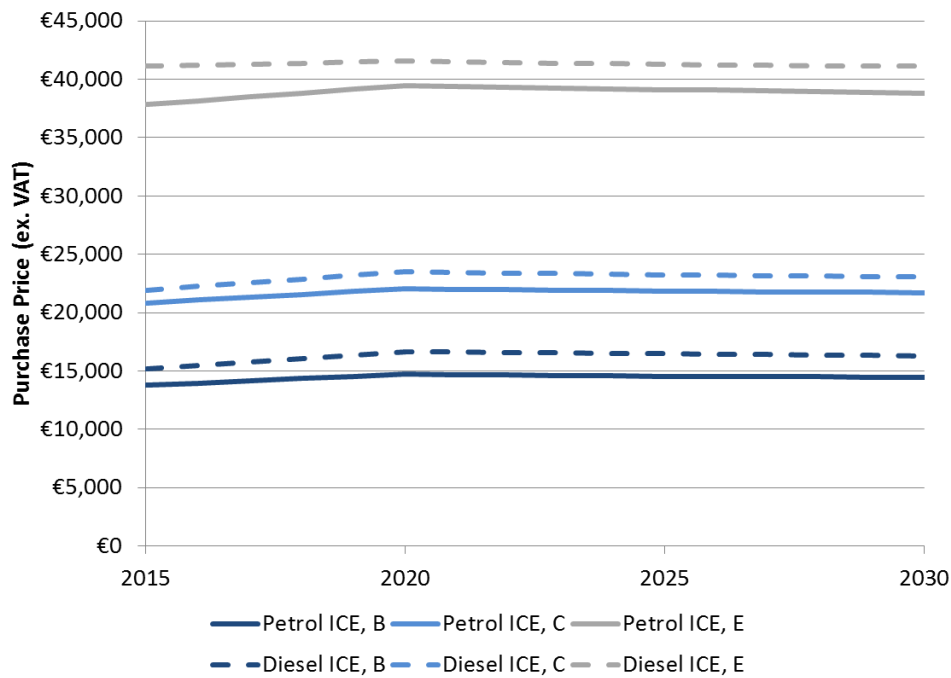
Figure 6: Purchase price, excluding VAT and purchases taxes, for Segment B, C and E petrol and diesel ICEs

3.4 Electric Vehicles

A review of all currently available full hybrid and plug-in electric vehicles was carried out to collect information on electricity consumption, range, battery capacity, as well as all the attributes considered in the development of the 2015 ICE archetypes. The relatively low number of electric vehicles available means that it is not possible in many cases to derive segment average values for each powertrain. However, this exercise provides valuable data points to inform model inputs and calibrate outputs.

3.4.1 Electric Range

The NEDC type-approval electric range of PHEVs for all segments is set at 50 km, which reflects the observed value for recently introduced PHEVs, such as the Audi A3 and Q7 e-tron, Volvo V60, Golf GTE and the Mitsubishi Outlander. In general, PHEVs drive under electric power only, with the engine sometimes providing additional power during periods of high acceleration or uphill driving, until the battery is fully depleted. The longer the electric range, therefore, the greater the proportion of driving that can be done under electric power before the battery is empty. However, additional electric range comes with the expense of requiring higher battery capacity.

European trip statistics suggest that the majority of trips are short, and so a relatively low range is sufficient to cover a proportion of driving. For example, analysis of data from the UK National Travel Survey shows how the majority of car trips are less than 10 km, and a study of German trip patterns found that the optimum real world driving range of PHEVs for CO_2 abatement costs is 16-23 km,[23] The current trend of 50 km range, expressed in terms of NEDC testing, is viewed as striking a good balance between vehicle cost and electric kilometres driven. As the frequency of longer trips decreases with trip length, so too does the marginal gain of increasing the electric range with regards to proportion of electric kilometres. Since PHEVs are currently more costly than conventional petrol or diesel cars, it is

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[23] Ozdemir (2014) Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types

expected that car manufacturers will focus using future battery cost improvements to reduce vehicle costs rather than increasing electric range further.

For BEVs, electric range (NEDC) is based on currently available vehicles and OEM announcements for future vehicle releases. The impact of higher vehicle ranges is explored as a sensitivity in the results section. The baseline future range assumptions are shown in Figure 7.
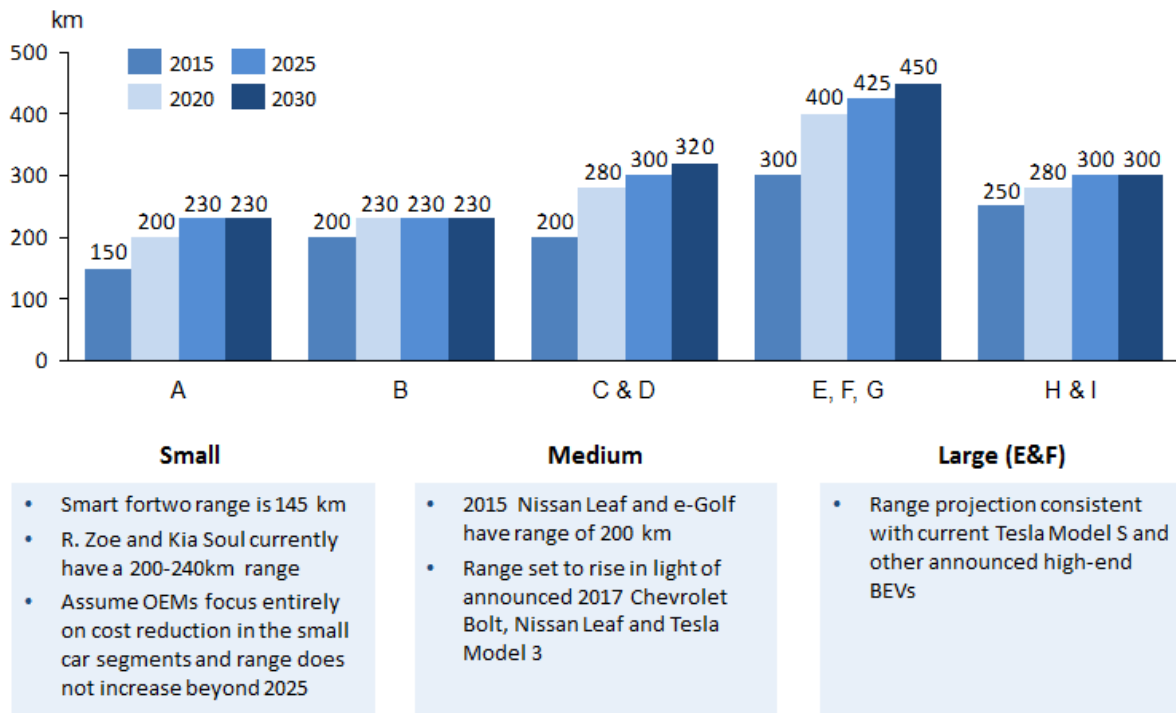

Small
- Smart fortwo range is 145 km
- R. Zoe and Kia Soul currently have a 200-240km range
- Assume OEMs focus entirely on cost reduction in the small car segments and range does not increase beyond 2025

Medium
- 2015 Nissan Leaf and e-Golf have range of 200 km
- Range set to rise in light of announced 2017 Chevrolet Bolt, Nissan Leaf and Tesla Model 3

Large (E&F)
- Range projection consistent with current Tesla Model S and other announced high-end BEVs

Figure 7: Electric range (NEDC) projections used in the Cost and Performance Model

In combination with the modelled electricity consumption, the electric ranges are used to calculate the required size of the battery pack (both attributes are considered in terms of NEDC type-approval energy consumption). For this purpose, HEVs and fuel cell vehicles are assumed to have a small electric range of 2 km as per the Toyota Prius.[24] The depth of discharge defines the portion of useable battery capacity and for each powertrain technology was taken from Element Energy's recent work into automotive batteries.

Table 4: Battery depth of discharge assumed for all years

Full Hybrid	PHEV	BEV	Fuel Cell
20%	70%	85%	20%

During the market review of available vehicles, it was noted that there was significant difference between the published useable battery capacity and that predicted by multiplying the type-approval electricity consumption and range. For example, the 2015 Nissan Leaf has an NEDC type-approval range of 200 km and electricity consumption of 0.15 kWh/km. NEDC-rated electricity consumption is measured against electricity delivered during charging, but only ~90% (at 20°C) [25] of this electricity is stored in the battery due to charging inefficiencies. Therefore, NEDC electricity consumption when

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[24] Toyota: The Prius Story, https://www.toyota.co.uk/world-of-toyota/stories-news-events/the-prius-story.json [accessed 19/07/2016]

[25] Green Emotion (2014) Deliverable 6.2: Performance validation – Results from EV measurements

driving on battery power is 0.135 kWh/km (i.e. 0.15 kWh/km × 90%). To achieve the range of 200 km the useable battery capacity should therefore be 27 kWh (i.e. 200 km × 0.135 kWh/km) which is significantly more than the reported useable battery capacity of 21.3 kWh, and in fact even more than the total battery capacity of 24 kWh. It is believed that this is the result of electricity consumption and range being measured under different NEDC test procedures. Consumption is measured from a fully charged battery over a number of test cycles equating to only 11 km, whereas range is measured by continuously driving on the same set of test cycles until the battery is depleted. It appears, therefore, that for BEVs the average electricity consumption over the course of complete battery depletion is less than at near full state of charge. To account for this and to avoid over-predicting battery sizes (and hence costs) for battery electric vehicles, correction factors were applied to the projected NEDC ranges, which are calibrated against what is observed in the market.

3.4.2 Relative Engine/Motor Size

The market review also provides data points for the relative engine and motor powers of electrified powertrains. These are compared to the engine powers of the ICE counterparts, and expressed as a percentage of this value. Relative engine sizes are of the order of 70% for full hybrids and 75% for plug-in hybrids. Similarly, relative motor sizes are of the order of 40% for hybrids, 70% for plug-in hybrids and 100% for BEVs by definition (since there is no internal combustion engine).

3.4.3 Modelling energy consumption

Fuel consumption of HEVs and PHEVs when running on the internal combustion engine is less than that of an equivalent ICE due to the presence of hybridization technology. In the Cost and Performance Model, fuel consumption for hybrid powertrains is calculated relative to the 2015 ICE Archetype, similarly to the calculation of future year ICEs (see Section 3.3.2). However, the impact of hybridization technology is also included in the *efficiency factor*, which results in lower fuel consumption. Once again, the deployment schedule and efficiency gains for technology installed in the advanced powertrains are provided by the Ricardo-AEA 2015 Cost Curve study (see Section 3.2.5).
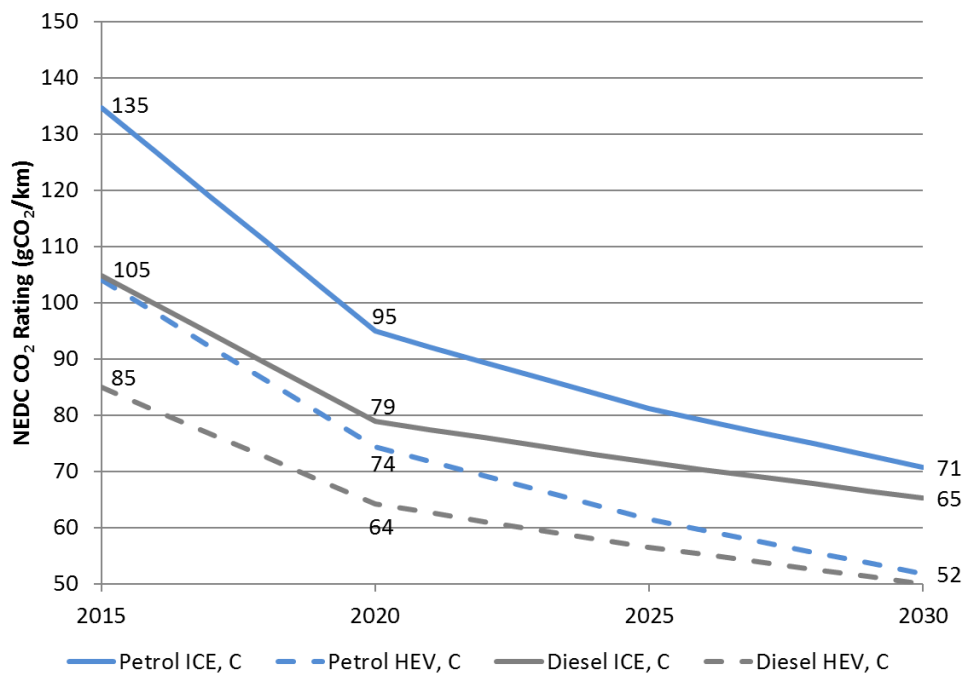

Figure 8: NEDC CO$_2$ emissions for Segment C petrol/diesel HEVs vs ICEs

Electricity consumption is also calculated relative to the 2015 ICE Archetype, but the *efficiency factor* in this case also takes into account the difference in efficiency between a motor (~22%) and an internal

combustion engine (~90%). In this case, only those technologies that contribute to reducing energy consumption in the vehicle's electric powertrain are included in the *efficiency factor*. For PHEVs, for example, technology that improves the internal combustion engine efficiency will have no impact on the vehicle's electricity consumption when driving on electric power.

The calculated electricity consumption is used to size the battery, and an efficiency penalty is applied to take into account the battery's weight. The charging efficiency (90%[25]) must also be incorporated to give the actual NEDC-rated electricity consumption.

3.4.4 Fuel Cell Vehicles

H_2 fuel cell vehicles are assumed to have the same specification as BEVs i.e. the same efficiency technology and maximum power. The fuel cell is sized according to this power requirement, and the battery is sized according to the BEV's electricity consumption (before charging efficiency is included), and the same range and depth of discharge characteristics as an HEV. This results in a small battery of ~1 kWh, similar to what is employed by full hybrids, as well as in the Toyota Mirai (1.6 kWh) and Hyundai Tucson Fuel Cell (0.95 kWh).

The final hydrogen energy consumption figure is calculated assuming a fuel cell efficiency of 55% in 2015 and 60% from 2020 onwards.[16] This is combined with an assumed range of 500 km, as per the Toyota Mirai, to size the required hydrogen tank. As with other electric powertrains, a weight penalty is applied to take into account the additional weight of the whole H_2 fuel cell/battery system.

3.5 Real World Driving Correction

It is widely observed that a significant gap exists between energy consumption and CO_2 emissions recorded on the NEDC test cycle and under real world driving conditions. The TCOs calculated in this study are based on real world consumption figures, as this reflects what drivers would actually pay while operating their car. As well as the impact on the NEDC-rated fuel and electricity consumption, Ricardo-AEA's 2015 Cost Curve dataset provides the efficiency improvement with each technology for a real world driving cycle. This allows future real world fuel consumption to be calculated from a 2015 baseline vehicle expressed in terms of real world driving.

In 2015, Element Energy and the ICCT carried out a study on behalf of the UK Committee on Climate Change in order to quantify the size of the *real world emissions gap*: the difference between NEDC type-approval and real world CO_2 emissions.[26] This identified on average a 35% increase in real world emissions over the current NEDC-rated values, from a top down analysis of real world driving data. The fuel consumption values of the 2015 ICE Archetypes can be corrected for real world driving through factoring in the size of the emissions gap for small, medium and large petrol and diesel cars, as presented in Figure 9.

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[26] Element Energy and ICCT (2015) Quantifying the impact of real-world driving on total CO2 emissions from UK cars and vans
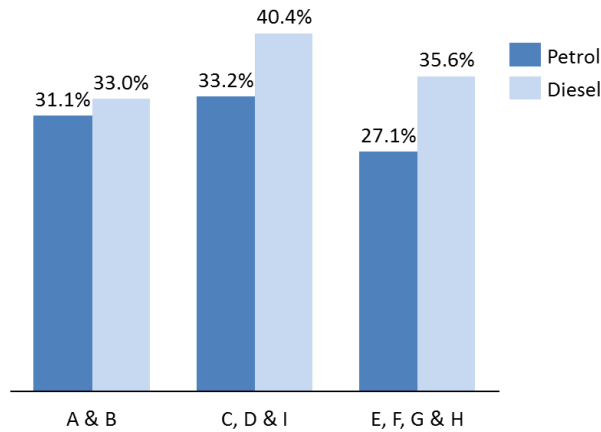
Figure 9: Increase in emissions from type-approval to real world driving[26]

As per calculating the NEDC fuel consumption, real world figures for future ICEs and advanced powertrains can be calculated by applying the relative impact of the technology packages deployed, but now expressed in terms of the real world driving cycle.
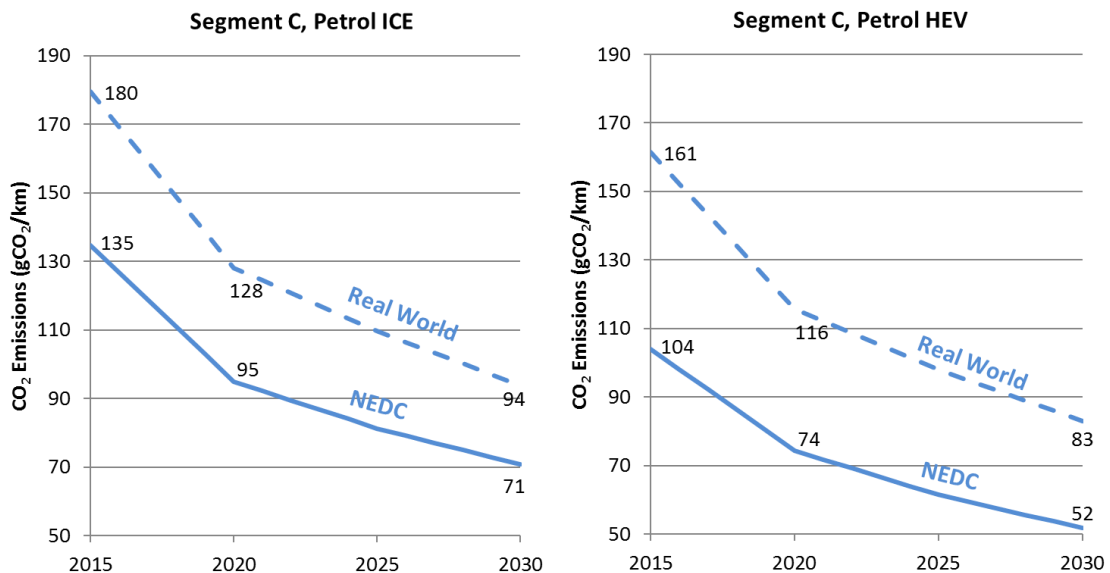

Figure 10: NEDC and real world CO$_2$ emissions for Segment C petrol ICE and HEV

Similarly, for electric vehicles, analysis of data from Spritmonitor.de revealed that real world electricity consumption is currently on average 25% higher than the NEDC-rated value. This is applied to the 2015 real world outputs in the Cost and Performance Model, with future values incorporating the changes to the electric powertrain efficiency technologies.

The existence of the emissions gap owes itself to two factors: the fact that the NEDC is not representative of real-world driving and overestimates the benefits of technologies like stop-start systems; and the increased use of flexibilities in the test procedure (such as test temperatures) to maximise performance in the laboratory test. The Element Energy/ICCT study revealed that the exploitation of flexibilities has grown in recent years, having been responsible for a 4% increase in real world emissions over NEDC in 2002, and 25% in 2014. With the replacement of the NEDC with the Worldwide harmonized Light vehicles Test Procedure (WLTP) in 2017, it is unclear to what extent this will continue to grow. All NEDC results presented in this study do not include any additional increase in test cycle optimization as, for the purposes of the TCO, only real world figures are of interest. All changes to real world energy consumption are factored into the changing technology packages.

4 Ongoing Ownership Assumptions

4.1 Fuel and Electricity Prices

In the baseline, forward projections in fuel prices are estimated from the IEA World Energy Outlook 2015 central case. This predicts the current low oil price rebounds to $80/bbl in 2020, rising to $113/bbl in 2030 and $128/bbl in 2040[27]. The Cambridge Econometrics *Technology Potential* oil price scenario[28] is used as an alternative forecast to model the impact of lower oil demand, driven by the expected improvements in fuel efficiency and growth in the ULEV market share in the 2020s, Here, the price of oil is forecast to settle between $80-90 from 2025. This is presented as a sensitivity in Section 7.3.2.

The wholesale petrol and diesel costs are calculated using the historic relationship between oil price and pre-tax fuel prices over the last 10 years across all EU member states. An average EU-28 fuel duty (€0.55 per litre) and VAT rate (21%), both assumed constant over time, are applied to give the petrol and diesel retail price. With a static fuel duty rate, lower carbon new vehicles will inherently result in lower fuel duty revenue. Although some of this revenue loss will be due to the uptake of electric vehicles, the major contributor will be improved fuel efficiency of petrol and diesel vehicles. While fuel duty can be increased, raising tax revenue from EV electricity usage is practically challenging. Instead, the gap in fuel tax revenue may need to be closed by other means, such as taxation on a per vehicle or per kilometre basis and differentiated by CO_2 emissions. Large scale changes in vehicle and fuel taxation were not explicitly assessed in this study.
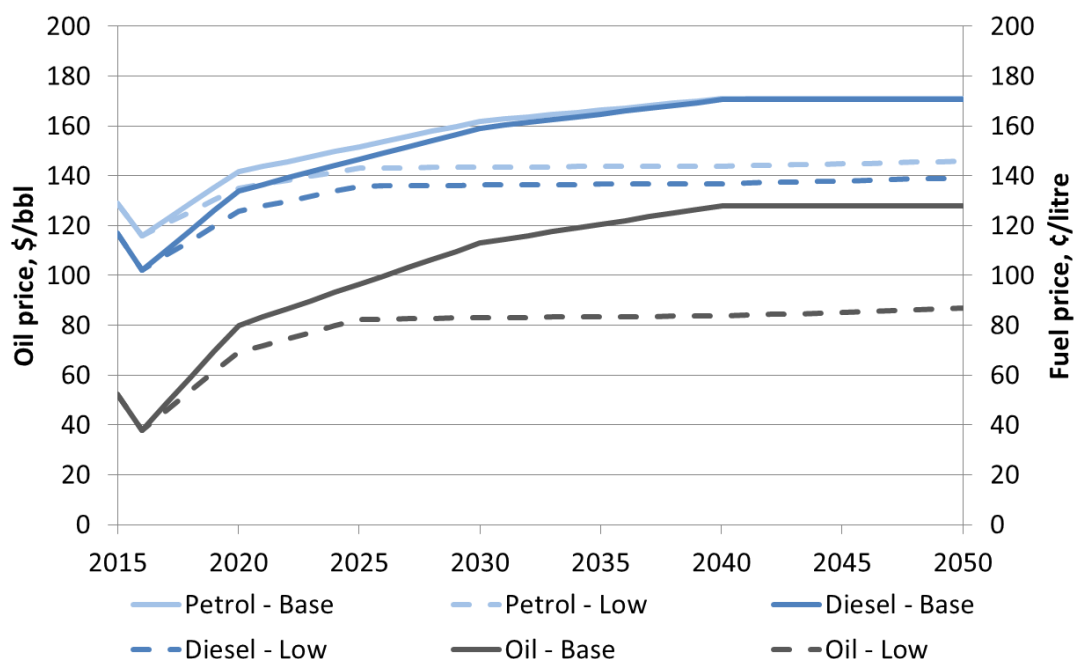
Figure 11: Petrol and diesel prices under baseline (IEA World Energy Outlook 2015 Central) and low (Cambridge Econometrics Technology Potential) oil price scenarios

Projections from 2015-2045 for the average domestic price of electricity for each member state were sourced from Eurostat. A simple average was taken to derive an EU-28 value. The cost of electricity is forecast to rise into the future due to additional infrastructure investment and increased decarbonisation. However, the tendency to charge vehicles overnight, where electricity demand is reduced, means that

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[27] IEA World Energy Outlook 2016 was published after the analysis in this study was finalised, but their central oil price forecast ($79/bbl in 2020, $111/bbl in 2030, $123/bbl in 2040) did not significantly differ from their 2015 edition

[28] Cambridge Econometrics (2016) Oil Market Futures

these prices will likely overstate the overall cost of charging. The exact cost of vehicle charging is hard to quantify, as it is dependent on when an owner chooses to charge, whether they use public and rapid charge points, and the value of grid balancing services offered. In this study, we have assumed a fixed 30% discount for EV electricity relative to the average electricity price, reflecting current off-peak tariffs observed in Europe. For example, Ecotricity in the UK offers a tariff with an overnight electricity price of 9.7 cents/kWh, versus a 20.3 cents/kWh flat rate tariff (including the daily Standing Charge). In France, EDF offers an off-peak charge of 11.5 cents/kWh, against a fixed rate of 15.0 cents/kWh. With continued decarbonisation necessary within the electricity grid, supply volatility is expected to increase with greater penetration of renewables. Even today, some member states, such as Germany and Austria, experience negative wholesale electricity prices during times of high solar generation. EV's will play an important role in balancing the grid and so suppliers will be incentivised to make provision for their uptake with cheap off-peak tariffs or managed charging schemes designed specifically for EV owners. 30% is seen as a relatively conservative estimate given its availability today, but under this assumption, the electricity costs are approximately 20-30% the cost of petrol and diesel on a per kilometre basis. Changes in this discount have a relatively small influence on the difference in TCO between electric and conventional ICE cars. This is investigated in a sensitivity analysis in Section 7.3.3.
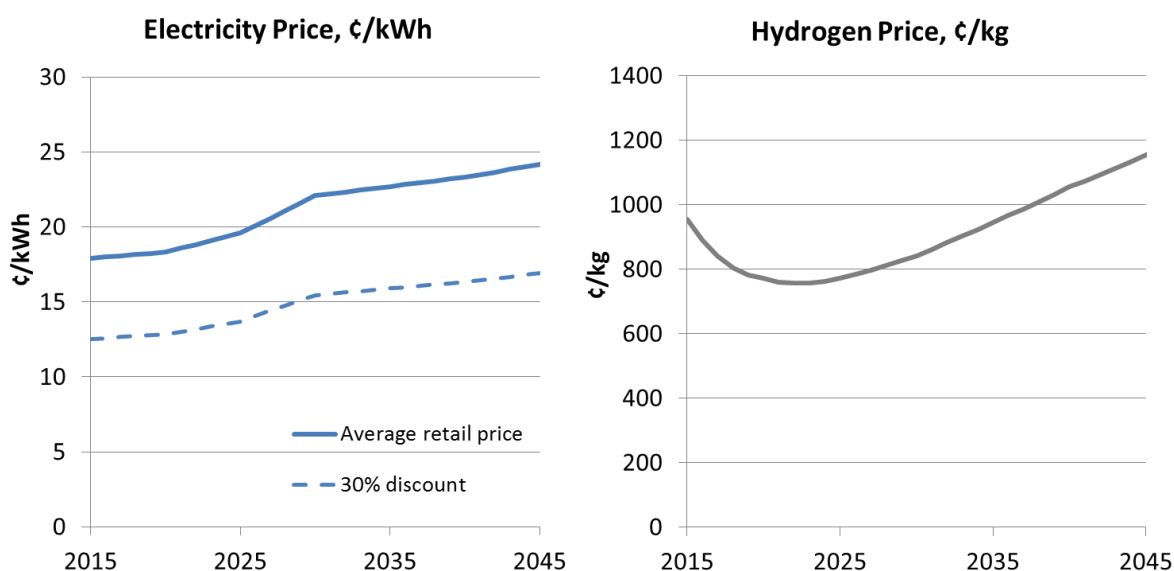
Figure 12: Domestic electricity and hydrogen price scenarios used.[29] 30% discount applied to the electricity price from Eurostat to reflect use of off-peak electricity overnight

The wholesale price of hydrogen is taken from Element Energy's internal modelling, and incorporates future natural gas, coal and electricity prices. This gives final hydrogen prices of €7.72/kg in 2020 and €8.41/kg in 2030, which is consistent with assumptions used by the various 'Hydrogen Mobility' initiatives in France, the UK and Germany. Gas and coal prices from the DECC Updated Energy & Emissions Projections[30] have been used.

4.2 Depreciation and residual values

Depreciation, defined as the difference between the purchase price of a vehicle and its residual or resale value at the end of the ownership period, is the largest component of total costs of ownership for the first owner. While projecting residual values for vehicles in the 2020-2030 is inherently uncertain, there is particular uncertainty in the residual values of plug-in vehicles, whose second hand market is not yet established in large volumes. Discussions with members of the Roundtable and bilateral

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[29] Average domestic electricity price projections from Eurostat
[30] DECC Updated Energy & Emissions Projections – September 2014 (Annex M)

interviews with lease companies and residual specialists highlighted the following factors that are likely to influence resale values of ultra-low emission vehicles:

- **The presence of upfront or ongoing incentives applied to ULEVs** – High upfront incentives such as purchase grants, can have the effect of lowering both new vehicle prices and the residual value for the first owner. Conversely, strong ongoing incentives such as reduced circulation taxes or permission to use bus lanes can increase residual values for ULEVs by increasing demand among second hand buyers. This phenomenon is observed by lease companies, who often export used EVs to Norway, where generous ongoing incentives create a strong second hand market for these vehicles

- **Fuel costs and electricity prices** – for second and third owners, fuel costs become a more significant component of their ownership costs as the first owner has already absorbed the steep initial depreciation of a new car. Since ULEVs have the potential to offer significant fuel cost savings, they may also support a higher residual value than an equivalent petrol or diesel car, all other things being equal. In other words, second hand buyers may be willing to pay more. This is consistent with recent findings that suggest that fuel economy is valued more highly by second hand car buyers compared with new car buyers.[31]

- **Maintenance costs –** evidence from lease companies to date is that maintenance costs are lower for ULEVs (particularly battery electric vehicles) relative to conventional cars, since they have fewer wearing parts, do not require regular oil/fluid changes and have reduced brake wear due to regenerative braking. This lower maintenance cost advantage is likely to be greater for older vehicles, where comparable petrol or diesel cars begin to experience higher costs for component failures such as fuel injectors, turbochargers. These lower maintenance costs (and risk of high repair bills for older petrol/diesel cars) should in theory be reflected in the residual values for ULEVs, assuming this is recognised by second and third hand owners.

- **Battery longevity –** The real or perceived risk of having to replace a battery during the life of a plug-in hybrid or BEV is likely to affect residual values of older vehicles. Many car manufacturers offer 8 year warranties for vehicle batteries, replacing packs which suffer excessive capacity reduction before that age. However, it is not yet clear whether current or future EVs will require replacements of their battery packs during the life of the vehicle, which is on average 16 years according to analysis of European vehicle stock data.[32] The impact of battery replacements, if needed, will depend on whether individual modules rather than the whole pack can be replaced, whether owners benefit from increased capacities and lower costs of future batteries, and the value for 'second life' batteries that can be used for stationary power storage even when their capacity has dropped below levels acceptable for use in vehicles.

- **Charging infrastructure availability –** the presence of widespread charging infrastructure maximises the number of potential buyers for ULEVs and increases their residual value relative to a case where only car buyers living in the largest cities can feasibly operate such vehicles

- **Improvements in battery technology** – the rate of improvement in plug-in vehicle batteries may also influence the residual values of ULEVs by suppressing resale values of previous generation vehicles. The rapid fall in purchase prices and performance improvements of new EVs during the period 2010-15 made them an attractive proposition compared to used EVs, and this subsequently lowered the value of the latter. Evidence of this effect continuing is likely to emerge in the next year when the next generation of BEVs and PHEVs with longer electric ranges are released to the market, however, continued improvements beyond this point are likely to be less drastic.

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[31] TM Leuven (2016) Data gathering and analysis to improve the understanding of 2nd hand car and LDV markets and implications for the cost effectiveness and social equity of LDV CO2 regulations. Available at http://ec.europa.eu/clima/policies/transport/vehicles/docs/2nd_hand_cars_en.pdf

[32] Median technical life of 17 years estimated from Element Energy analysis of historic scrappage rates in the European car stock

The factors above make it difficult to predict whether residual values for ULEVs will be systematically higher or lower than for petrol or diesel cars of a given age. Data for current vehicles suggest similar residual values for ULEVs and petrol/diesel cars, once purchase grants are taken into account and VAT is excluded. This can be seen in Figure 13 and Figure 14 for UK data for Nissan and Mitsubishi vehicles, where the annual depreciation in percent is very similar to comparable vehicles, but only if the 'net' price after the deduction of the £5,000 purchase grant is considered. This is consistent with recent evidence that the presence of upfront incentives depresses residual values as consumers base their second hand price expectations on the 'on the road' price of the new model[33], and hence if upfront grants are removed the depreciation is likely to match that of a conventional car on a 'no incentive' basis, as long as the current low prices of second hand EVs in subsidised markets have not set a price expectation among used car buyers that cannot evolve with market conditions.
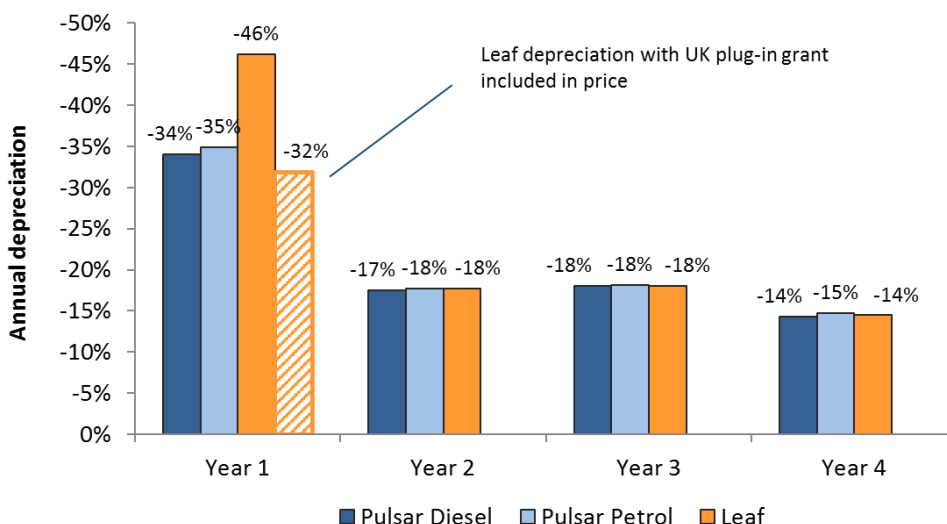
Figure 13: Annual depreciation of UK Nissan Leaf and Pulsar cars. VAT excluded from initial purchase price. Source: WhatCar
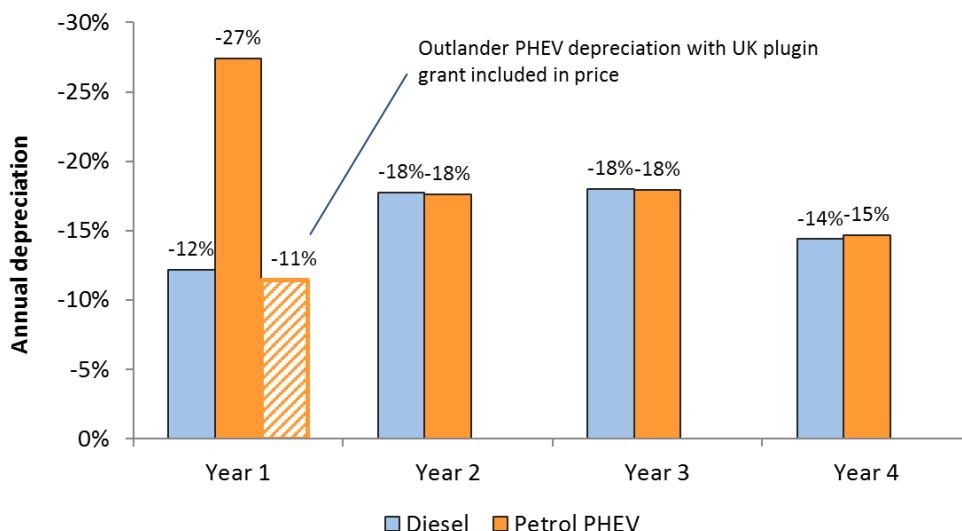
Figure 14: Annual depreciation of Mitsubishi Outlander diesel and petrol PHEV cars. VAT excluded from initial purchase price. Source: WhatCar

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[33] CAP Consulting - Impact of government subsidies for electric vehicles on used market values. Available at: http://www.groen7.nl/images/wp2013/divers/CAP-tweedehands-EV-prijzen.pdf

For this study, a central assumption of equal percentage annual depreciation is used for all powertrains. The residual value for a new vehicle over its lifetime is set out in Figure 15.
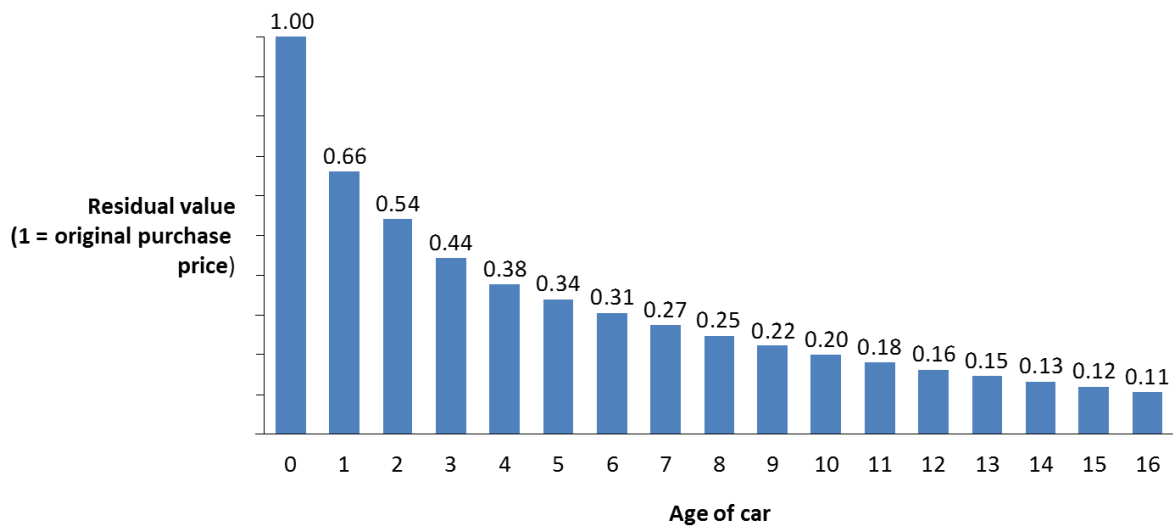

Figure 15: Residual values assumed for all powertrains in the TCO analysis

4.3 Insurance and Maintenance

As part of the market reviews to develop 2015 ICE Archetypes and gather PHEV and BEV data points, typical insurance and maintenance costs for each vehicle model were collected. Insurance costs for BEVs and PHEVs compared with conventional vehicles were found to be comparable within each segment. Insurance costs are therefore assumed the same across all powertrains in the TCO calculation, and to increase at the historic rate of 0.2% per annum.
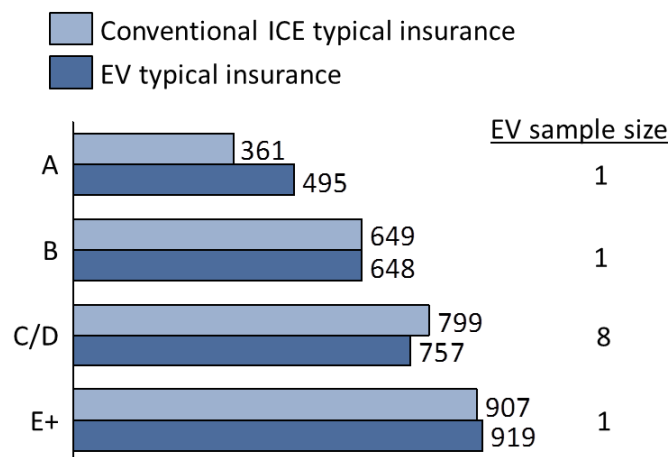
Figure 16: Typical annual insurance premiums (€), from Element Energy's EV market review

Servicing costs for BEVs are not generally reported, however, as stated in Section 4.2, it is believed that they are lower than for their ICE counterparts. For example, a recent survey of drivers by Go Ultra Low campaign, a joint initiative between the UK Society of Motor Manufacturers and Office for Low Emission Vehicles, found servicing and maintenance costs of electric vehicles were a quarter of those

of petrol and diesel cars.[34] However, Element Energy's own consultation with fleet managers provided evidence that costs were generally half what would be expected for an equivalent ICE car. This is despite reports that the heavier kerb weight of current ULEVs leads to faster tyre degradation compared with ICEs. Servicing costs for the Mitsubishi Outlander PHEV were found to be of the order of €500 less than the diesel ICE model over 3 years.[35] Consequently, a 30% and 50% reduction has been applied to the cost of PHEV and BEV maintenance respectively (reflecting the avoided costs of all engine maintenance for the latter), relative to a petrol or diesel model in the same segment. No reduction is assumed for HEVs, and FCVs are assigned to the same values as BEVs due to the similarity in powertrain components.

The maintenance cost does not include the potential cost of battery replacement during the lifetime of the vehicle. The impact of battery replacements is discussed in the results section, though it should be noted that replacement of individual modules or an established market for second life batteries in the stationary power sector could lower the costs to a second or third owner relative to making a like for like replacement of a complete battery pack. Potential battery replacement costs are somewhat counteracted by the fact that maintenance and repair costs increase over time for petrol and diesel cars due to the higher probability of component failures such as injectors or turbochargers. These repair costs are not explicitly included in the TCO modelling as they do not occur to all users (unlike regular maintenance costs).

4.4 Ownership periods

The TCO results in this study are given for first, second and third owners of passenger cars, with ownership periods of 4, 5 and 7 years in length respectively. This reflects the tendency for ownership periods to increase with vehicle age. Correspondingly, annual vehicle driving distance is also known to decrease with vehicle age,[36] and as such annual mileages of 15,000 km, 12,000 km and 10,000 km are applied to the TCO calculation of average EU-28 first, second and third hand owners respectively.

4.5 Proportion of Driving in Electric Mode

The cost differential between electricity and liquid fuels, and efficiency of an electric powertrain, makes the TCO of a PHEV largely dependent on the proportion of driving carried out under electric power, denoted the *utility factor* in the WLTP.[37] This is a function of driving patterns, recharging behaviour and electric range. The NEDC test procedure takes a simple approach to calculating the *utility factor*, assuming on average 25 km is driven between battery depletion and recharging:[38]

$$Utility\ Factor = \frac{D_e}{D_e + D_{av}}$$

D_e = vehicle's electric range (NEDC)

D_{av} = 25 km (assumed average distance between two battery recharges)

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[34] Go Ultra Low Press Release: *Motorists could save £304 a year on car maintenance by going electric*, February 24th 2016 [https://www.goultralow.com/press-centre/releases/2243-2/]

[35] Whatcar: 3-year service cost of ca. £1,900 and ca. £1,400 for the Outlander ICE and PHEV models

[36] Ricardo-AEA (2015) Improvements to the definition of lifetime mileage of light duty vehicles

[37] European Commission, Riemersma I (2015) Technical Report on the development of a World-wide Worldwide harmonised Light duty driving Test Procedure (WLTP), doc no. GRPE-72-02

[38] E/ECE/324/Rev.2/Add.100/Rev.3−E/ECE/TRANS/505/Rev.2/Add.100/Rev.3

The WLTP uses a more sophisticated methodology, and employs a relationship with vehicle range, based on real world trip statistics. The *utility factor* is calculated using a function derived from real world trip statistics, which relates electric range to the proportion of driving in electric mode:[39]

WLTP Utility Factor Equation
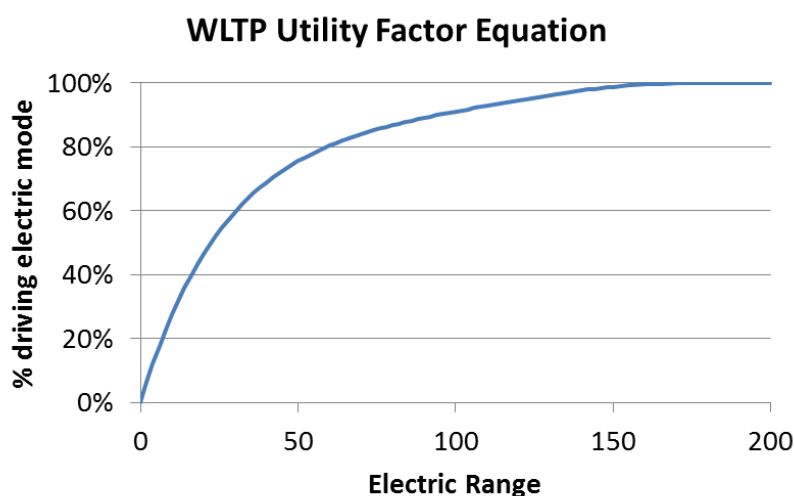
Figure 17: Relationship between plug-in hybrid electric range and proportion of driving in electric mode, as used in the WLTP

As this is based on real world statistics, the same relationship can be used to estimate the proportion of driving carried out in electric mode under real world driving conditions, based on real world electric range. For example, in 2015 the real world electric range of a Segment C petrol PHEV is estimated to be 40 km, which corresponds to 69% of driving on electric power.

If it is assumed that no fuel is used when driving in electric mode, an overall fuel consumption value is calculated by multiplying the fuel consumption in non-electric mode (i.e. when using the combustion engine) by the *utility factor*. In the case of a Segment C petrol PHEV, the real world CO_2 emissions are predicted to be 40% higher than the NEDC-rated value in 2015. Analysis of current real world data from Spritmonitor.de reveals that real world fuel consumption of PHEVs is currently more than twice the type approval value. For example, the Mitsubishi Outlander PHEV shows an average real world consumption of 4.17 L/100km, which is 2.3 times that NEDC figure of 1.80 L/100km. This is consistent with anecdotal evidence from fleet managers which suggests that many company car drivers are purchasing PHEVs to take advantage of favourable tax breaks, but then rarely charge them as it is much easier to expense the fuel cost compared with electricity. It is likely therefore that currently the proportion of driving in electric mode is considerably lower than it should be for PHEVs. It is expected though that as charging infrastructure becomes more widely available, drivers are educated on the financial benefits of maximising 'electric kilometres' and other barriers such as billing for electricity used in company cars are resolved, the proportion of driving in electric mode will increase to that predicted by trip statistics.

To show the impact of charging frequency, a *Limited Charging* scenario is proposed whereby the proportion of driving in electric mode is half that predicted by the WLTP *utility factor* relationship. For a 40 km real world range this equates to real world fuel consumption being 3 times larger than NEDC type-approval, slightly higher than the current ratio from Spritmonitor.

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[39] ECE/TRANS/WP.29/GRPE/2016/3, Annex 8, Appendix 5

5 Additional TCO Components

5.1 Financing Cost

A financing rate of 5% is applied to all purchases to reflect current vehicle leasing contracts. The cost of financing is calculated as per the industry standard approximation[40]:

$$financing\ cost = mean(purchase\ price, residual\ value) \times financing\ rate \times contract\ length$$

It should be noted that financing costs can be significantly lower than this (for example 2-3%) given the historically low interest rates in Europe in 2016. The use of a higher 5% value reflects a return to higher economy-wide interest rates in the 2020s, and avoids underestimating the impact of higher purchase prices of ultra-low emission vehicles (even though these costs are recouped through lower fuel costs). It should also be noted that since the purchase prices of all powertrains are expected to converge in the 2020s, the impact of financing costs on different vehicles is minimal compared with the total cost of ownership.

5.2 Charge Point Costs

It is expected that the majority of EV charging will take place at owners' homes and so most buyers will require a residential charge point to be installed. Home charging provides a low cost source of electricity and guaranteed access to a charge point. However, the purchase of an EV does not necessitate the installation of a residential charge point, particularly in the case of drivers that have previously owned an EV, moved into a property with a charge point already installed, or lack off-street parking and rely on public charge points. There are also low cost options such as reinforced 13 amp or 16 amp domestic sockets that allow charging at up to 3.7kW which may be sufficient for some customers[41]. The cost of buying and installing a residential has therefore been excluded from the TCO calculation since it doesn't apply to all users. However, it remains important to consider this potential additional cost when comparing the ownership costs of plug-in and conventional powertrains.

Dedicated domestic charging points (wallboxes) currently cost approximately €1,000 before incentives[42], of which €700 is for the hardware and the remainder for installation. However, the cost of materials is low and indicates that hardware costs could fall as incentive programmes end and as production volumes increase. The Fuelling Europe's Future decarbonisation cost study suggested a 10% reduction in hardware cost for every doubling in the number of points installed[43]. Installation costs are less affected by economies of scale and so no change is assumed.
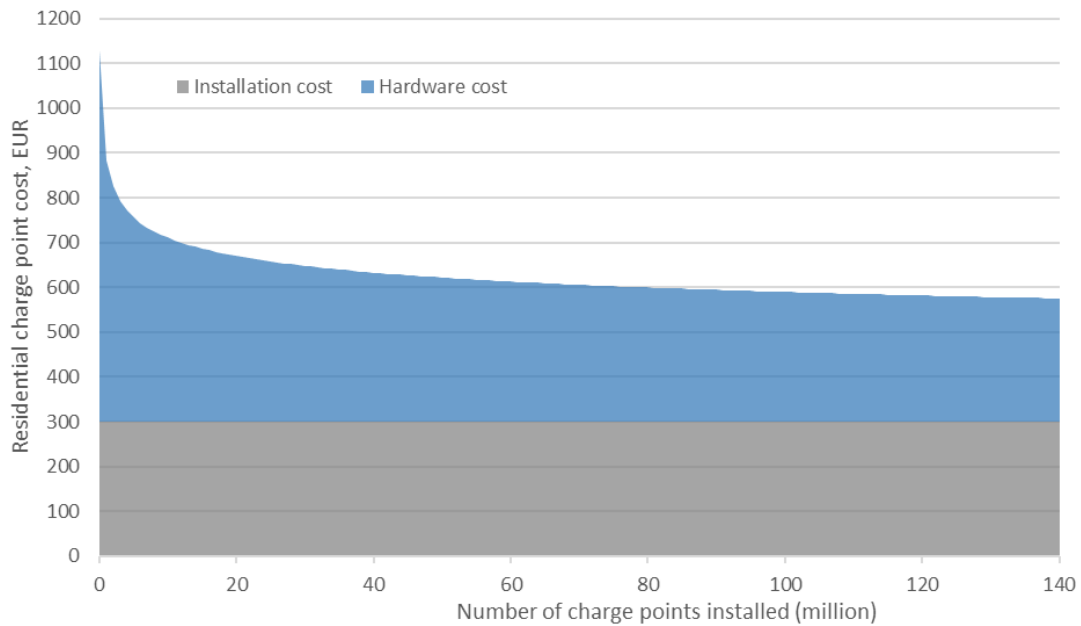
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[40] http://www.leaseguide.com/lease08/ [accessed: 23/04/2016]
[41] For example, Renault France offers a reinforced domestic socket in France at no extra cost with the purchase of a Zoe EV, and gives a standard price of c. €600 including installation.
[42] Cambridge Econometrics (2015) En route pour un transport durable
[43] Cambridge Econometrics (2013) Fuelling Europe's Future

Figure 18: Forecasted reduction in residential charge point cost, against cumulative number of points installed

Figure 18 illustrates how total cost of installing a residential charge point would change as the number of installations grows. The change in charge point cost over time is highly dependent on the rate of EV uptake up to 2030. The total number of light duty vehicles in the EU is 291m[44] (2014), thus if EVs make up 10% of the stock this represents approximately 30m vehicles. Although not all of these will require a residential charge point installation, the cost trend in Figure 18 reveals that beyond ~20m units the price of a charge point settles at €600-€650. However, the need for higher charge rates, as battery capacities increase, and smart charging systems will provide upward cost pressure that could partially offset these cost decreases.

6 Summary of TCO Composition
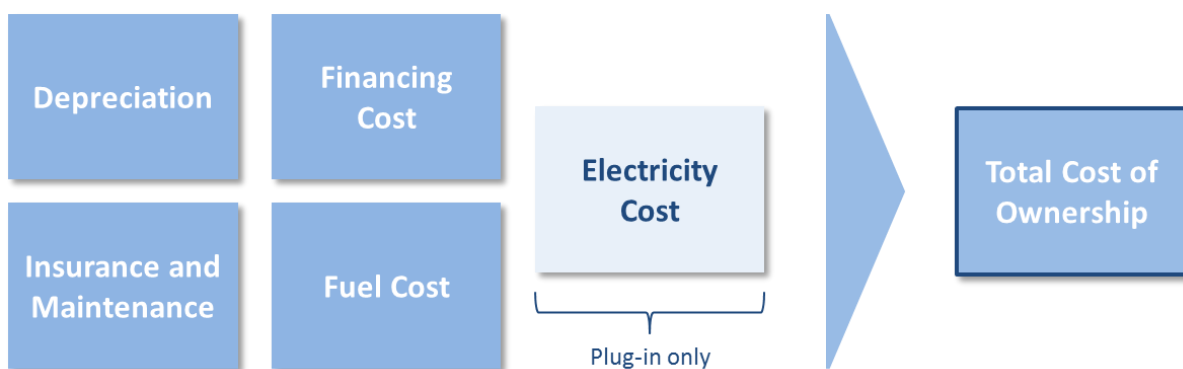
Figure 19: Components used in total cost of ownership calculation

Figure 19 summarises the components considered in the TCO calculation. Depreciation in this case is the purchase price, excluding purchase taxes and incentives, minus the residual value at the end of the ownership period considered. The TCO calculation does not consider vehicle VAT, purchase taxes or

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[44] ACEA Pocket Guide 2015/16

other incentives, which vary by Member State. As such they show the trends in the underlying vehicle costs and performance rather than policy choices which may favour some powertrains over others.

Table 5: Summary of TCO component assumptions and relevant sources

Component	Assumption	Source
Engine costs	Gradually decrease over time on a per kW basis, by 5-10% 2015-30	Ricardo (2015) Cost Curves [7]
Motor costs	Decreases from €24/kW in 2020 to €15/kW in 2030 Relative engine/motor size from Element Energy review of current EVs	Ricardo vehicle cost study for CCC (2012) [11]; EE EV market review
Battery costs and specifications	Baseline case from Element Energy's automotive battery modelling. Lower cost scenario based on announced OEM targets	EE analysis for ECF Germany economic study (to be published Autumn 2016)
Fuel cell and H_2 tank costs	Strong downward cost trend 2015-20, as volumes increase to serve mass market. Less aggressive cost decrease post 2020	EE analysis for ECF Germany economic study (to be published Autumn 2016)
Additional transmission components	Includes additional electrification components, and advanced diesel exhaust introduced 2020. Battery charger cost decreases, whereas other component costs assumed constant.	EE for Low CVP (2011) [16]
Efficiency technologies	45 efficiency technologies, defined in 5 year intervals for cost, efficiency gain and deployment level. 15% and 5% technology overlap factors applied to engine efficiency	Ricardo (2015) Cost Curves [7,17]; TNO (2011) [22]
Sales margins	Conventional ICEs: 19% for small cars (A&B), 24% for medium (C,D,H&I), 29% for large (E,F&G). Absolute value of equivalent ICE margin assumed for all other powertrains	Roland Berger (2014); KPMG (2013); Holweg & Pil (2004); Argonne (1999) [20]
Power-to-weight ratio	Follows historic trend 2010-15 for all diesel ICE and petrol ICE segments A, B, C and H to 2020. Power capped for all others to avoid excessive levels being reached	EE ICE market review
Electric range	PHEVs: 50 km assumed for all years BEVs: based on currently available vehicles and range growth from OEM announcements	Ozdemir (2014) [23]; EE EV market review

Real world driving	2015 fuel consumption from current real world emissions gap identified by EE/ICCT. 2015 electricity consumption from Spritmonitor data. Future consumption estimated from impact of efficiency technology on real world cycle	EE and ICCT (2015) [26]; Ricardo (2015) Cost Curves [7]
Liquid fuel prices	Liquid fuel prices calculated from oil price projections. Baseline oil price scenario reaches $113/bbl in 2030 and $128/bbl in 2040. Low oil price scenario settles at $80-90/bbl post 2025. Uses current fuel duty for both petrol and diesel and VAT, averaged across all EU member states	Baseline oil price: IEA World Energy Outlook (2015) Central Case Low oil price scenario: Cambridge Econometrics Oil Market Futures (2015) Technology Potential scenario [28]
Electricity prices	Domestic electricity price rises from 16 ¢/kWh to 23 ¢/kWh in 2040. Additional 30% discount applied to EV charging	Eurostat
Hydrogen prices	Calculated from coal, oil and electricity prices. 770-1050 ¢/kg 2020-40	Coal and gas price from DECC Updated Energy and Emissions Projection's [30]
Depreciation	The same annual % reduction in residual value for all powertrains	EE ICE market review
Maintenance	Same for petrol and diesel ICE and HEVs. 50% and 30% discounts for BEVs/FCVs and PHEVs respectively	EE ICE and EV market reviews; WhatCar
Insurance	Same across all powertrains, increasing with vehicle size	EE ICE and EV market reviews; WhatCar
Ownership periods	4 years for 1st hand, 5 years for 2nd hand, 7 years for 3rd hand.	European Commission study results presented to Roundtable
Mileage	Annual mileage decreases with age: 15,000 km for 1st hand, 12,000 km for 2nd hand, 10,000 km for 3rd hand	Ricardo-AEA (2015) [36]
Proportions of driving in electric mode	NEDC assumes average 25 km between battery depletion and charging. WLTP and real world use relationship presented in WLTP Technical Report based on real world trip statistics	E/ECE/324/Rev.2/Add.100/ Rev.3 [38]; ECE/TRANS/WP.29/GRPE/ 2016/3 [39]
Financing rate	5% and constant over time	

7 TCO Results

7.1 Baseline Results

The results shown in this section bring together the various upfront and ongoing cost inputs described in the previous chapters. Baseline results are shown with all inputs set to their 'central' values in the model; sensitivities showing the impact of changing these assumptions are then explored in Section 7.3.

7.1.1 Segment C, 4 year TCO new car, 2015

Input conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Battery cost: Baseline
- Driving distance: 15,000 km per year for all powertrains
- Country: Average EU-28
- PHEV range: Default (~69% of driving distance in electric mode)
- Oil price: IEA WEO 2015 central case
- Fuel price[45]: 116-129 c/l petrol; 102-118 c/l diesel; 954-805 c/kg H_2; 12.5-12.7 c/kWh electricity

	Petrol ICE	Petrol Full Hybrid	Petrol PHEV	Diesel ICE	Diesel Full Hybrid	Diesel PHEV	Electric	Fuel Cell
	25,607	27,524	30,179	24,192	25,948	29,881	27,565	49,926
% dif. to Petrol ICE		**7.5%**	**17.9%**	**-5.5%**	**1.3%**	**16.7%**	**7.6%**	**95.0%**
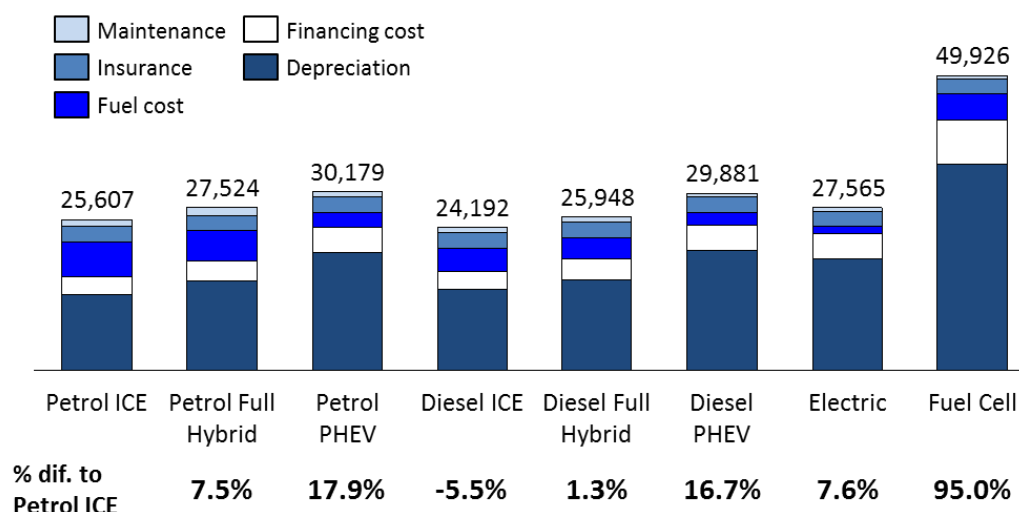
Figure 20: 4 year TCO (EUR) for a new Segment C car, purchased in 2015

In 2015, conventional petrol and diesel powertrains have the lowest 4 year TCO before incentives are considered, with PHEVs and BEVs showing a €3,000-€6,000 premium. This is of the order of current incentives in some EU markets. In France, for example, cars emitting less than 20 gCO_2/km (NEDC) receive a €6,300 'bonus', and in 2015 plug-in cars in the UK received a £5,000 grant (€6,200 in 2014€) subject to range and emission requirements. Although BEVs have a lower TCO than PHEVs, this is in part due to lower assumed margins of 5% for BEVs, versus 16% for PHEVs, reflecting values implied by market data. For example, the price in France (excluding VAT and grant) of an e-Golf (BEV) is

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[45] The price ranges shown are for the first and last years of the TCO period. The TCO is calculated using the specific costs from the period considered.

€31,825[46], ~4% cheaper than a Golf GTE (PHEV) at €33,000[47]. However, the current factory gate cost of a Segment C BEV is estimated to in fact be ~8% more than the Petrol PHEV.

The most significant contribution to the 4 year TCO is depreciation, which is disadvantageous for the more expensive electric powertrains when the depreciation rate is assumed the same for all powertrains. Based on current technology costs, this additional vehicle cost (and hence depreciation) is not fully offset by the cheaper running costs of plug-in cars over conventional ICEs and full hybrids. This justifies the current use of financial incentives employed in a number of Member States to reduce this TCO gap to petrol and diesel cars in this early part of ULEV deployment.

7.1.2 Segment C, 4 year TCO new car, 2020

Input conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Battery cost: Baseline
- Driving distance: 15,000 km per year for all powertrains
- Country: Average EU-28
- PHEV range: Default (~69% of driving distance in electric mode)
- Oil price: IEA WEO 2015 central case
- Fuel price: 142-148 c/l petrol; 134-142 c/l diesel; 772-758 c/kg H_2; 12.8-13.4 c/kWh electricity
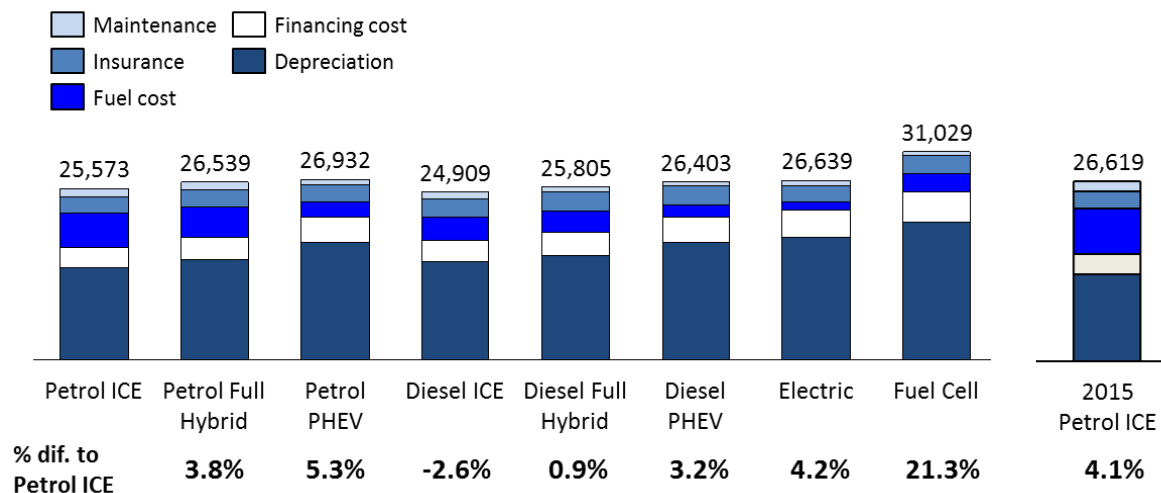
Figure 21: 4 year TCO (EUR) for a new Segment C car, purchased in 2020

The expected fall in EV technology costs between 2015 and 2020 significantly narrows the TCO premium over ICEs to ~€1,500. For example, the battery pack cost of a Segment C BEV has fallen from €11,100 to €7,100, despite the fact that the pack capacity has increased from 24.9 kWh to 31.6 kWh. The TCOs of PHEVs and BEVs are now near identical, with the greater TCO reduction of PHEVs relative to BEVs largely due to the use of standard margins for all vehicles beyond 2020.

The TCO of fuel cell vehicles has also fallen by almost 40% in five years, reflecting an anticipated step change in costs with second generation vehicles introduced around 2020, but fuel cell vehicles remain 21.3% more costly on a 4 year TCO basis than a petrol ICE, compared with 7-10% for plug-in powertrains.

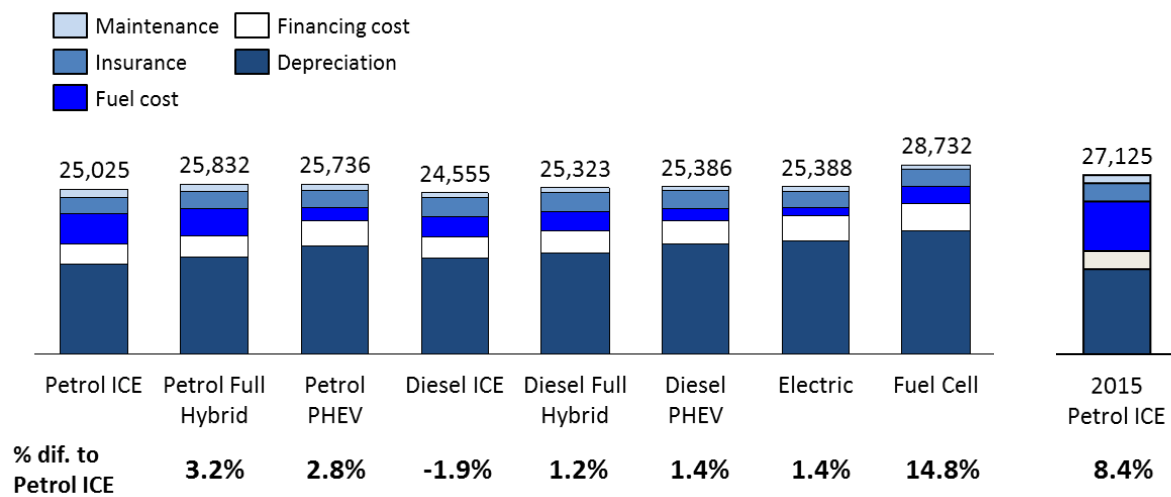[46] http://vw.sh05.net/_documentations/_tarifs/golf_7/tarifs_egolf.pdf
[47] http://vw.sh05.net/_documentations/modeles/golf/files/golf_tarifs.pdf

Also presented here is the TCO for a 2015 petrol ICE with 2020 fuel costs. The TCO is ~€1,000 more than for the equivalent 2020 petrol ICE (with fuel consumption consistent with the 95g/km fleet average target in 2021), demonstrating the overall cost savings that increased efficiency bring.

7.1.3 Segment C, 4 year TCO new car, 2025

Input conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Battery cost: Baseline
- Driving distance: 15,000 km per year for all powertrains
- Country: Average EU-28
- PHEV range: Default (~69% of driving distance in electric mode)
- Oil price: IEA WEO 2015 central case
- Fuel price: 152-158 c/l petrol; 147-154 c/l diesel; 772-810 c/kg H_2; 13.7-14.8 c/kWh electricity

	25,025	25,832	25,736	24,555	25,323	25,386	25,388	28,732	27,125

Legend: Maintenance, Financing cost, Insurance, Depreciation, Fuel cost

	Petrol ICE	Petrol Full Hybrid	Petrol PHEV	Diesel ICE	Diesel Full Hybrid	Diesel PHEV	Electric	Fuel Cell	2015 Petrol ICE
% dif. to Petrol ICE		3.2%	2.8%	-1.9%	1.2%	1.4%	1.4%	14.8%	8.4%

Figure 22: 4 year TCO (EUR) for a new Segment C car, purchased in 2025

Further convergence between the TCOs of all powertrains continues to 2025. ICEs remain the lowest cost option before any incentives are considered. This is primarily due to relatively low costs of efficiency improvements in the Ricardo-AEA 2015 cost data. This has the effect of lowering the TCO for petrol and diesel cars as the incremental purchase cost is outweighed by reductions in fuel use. In fact, the cost data suggest that even the purchase price of petrol and diesel cars will remain about constant or decrease slightly in the 2020s (see Figure 6), since the cost reductions from high volume deployment of efficiency measures outweighs the cost of additional technologies required in each year.

It should be noted that all powertrains (except fuel cell vehicles) have lower 4 year TCOs than a 2015 petrol vehicle (adjusted for fuel prices in 2025), again highlighting the consumer benefits of buying more efficient vehicles.
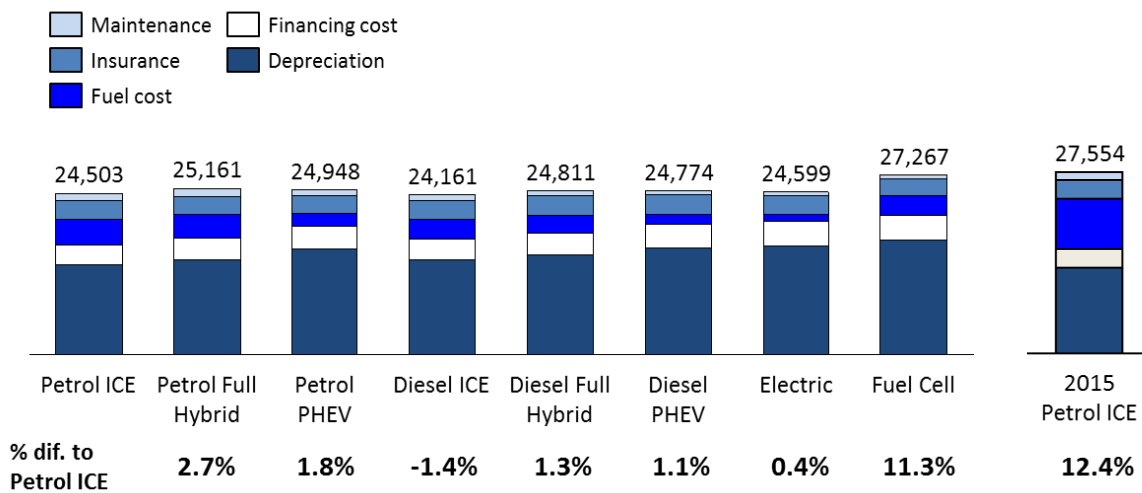
The TCOs of full hybrids remain between the ICE and PHEV, as the efficiency gain of full hybridisation relative to highly efficient petrol/diesel cars is not enough to fully offset the increased capital cost. However, by this stage the deployment of stop-start, regenerative braking and micro-hybridisation technology across ICEs is widespread and the divide between ICEs and HEVs is less distinct. Although the TCO premium of 'full' HEVs over ICEs persists, this is a result of some hybridisation being introduced to ICEs rather than a failure of full hybridisation technology to become cost competitive. The gap between the 4-year TCO of Segment C petrol HEVs to ICEs has reduced from 7.5% (€1,900) in 2015 to 3.2% (€800) in 2025. Although it appears that full hybridisation remains more expensive for the

first owner than the partial hybridisation found in future ICEs, some buyers may show a willingness to pay for the benefits of a small all-electric range, for example, those with high urban mileage without access to a charging infrastructure.

7.1.4   Segment C, 4 year TCO new car, 2030

Input Conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Battery cost: Baseline
- Driving distance: 15,000 km per year for all powertrains
- Country: Average EU-28
- PHEV range: Default (~69% of driving distance in electric mode)
- Oil price: IEA WEO 2015 central case
- Fuel price: 162-165 c/l petrol; 159-163 c/l diesel; 841-902 c/kg H_2; 15.5-15.7 c/kWh electricity

	Petrol Full Hybrid	Petrol PHEV	Diesel ICE	Diesel Full Hybrid	Diesel PHEV	Electric	Fuel Cell	2015 Petrol ICE
% dif. to Petrol ICE	2.7%	1.8%	-1.4%	1.3%	1.1%	0.4%	11.3%	12.4%

Figure 23: 4 year TCO (EUR) for a new Segment C car, purchased in 2030

In 2030, the TCO premium of plug-in EVs over ICEs is predicted to fall to ~€500, with Segment C BEVs costing almost the same on as Petrol ICEs over 4 years. This shows that relatively only modest financial incentives, such as discounted circulation taxes (which are worth approximately €500 over 4 years in the UK for example), are needed to reach parity in total costs of ownership across nearly all powertrains. Again, the TCO reduction for PHEVs and BEVs has been slightly offset by a further reduction in the TCOs of conventional vehicles. ICE costs have continued to fall despite efficiency improving, as efficiency measures become both cheaper and more effective. The continued rise in oil prices is not fully realised in the petrol and diesel retail price, for which the wholesale fuel price only contributes about half along with fuel duty and VAT.

To put the remaining EV cost premium into context, it is worth noting that many of the most popular optional extras cost of the of the order of €500 - €1000, with the 4-year depreciation cost of these extras each adding about €500 to the first owner TCO (see Table 6). Car buyers can therefore spend €100s to several €1000s on extras, making the TCO premium of EVs comparatively small. Some features of electrified vehicles, such as the low noise or the ability to pre-cool or pre-heat the car before a journey, may make some prospective buyers willing to pay a premium for these vehicles in a similar manner to purchasing other optional features. For other buyers, modest but continued financial incentives, or non-financial 'perks' such as priority parking in cities may be needed to encourage sales across the widest range of customer types.

Table 6: Purchase price and 4-year depreciation cost of popular Segment C optional extras[48]

Optional Extra	Purchase price (ex. VAT)	Depreciation cost over 4 years
Leather seats	€1,263	€891
Integrated satellite navigation	€750	€552
Alloy wheels	€709	€594
Front parking sensor	€601	€518
Rear parking sensor	€522	€443
USB interface	€492	€437
Bluetooth connection	€465	€405
Air conditioning	€391	€250
Park assist camera	€323	€269

Figure 24 summarises the trends in baseline TCO over time, which is of a convergence between all powertrains between 2015 and 2030, primarily driven by decreases in the costs of advanced powertrains and to a lesser extent an increase in petrol and diesel prices from currently low levels.
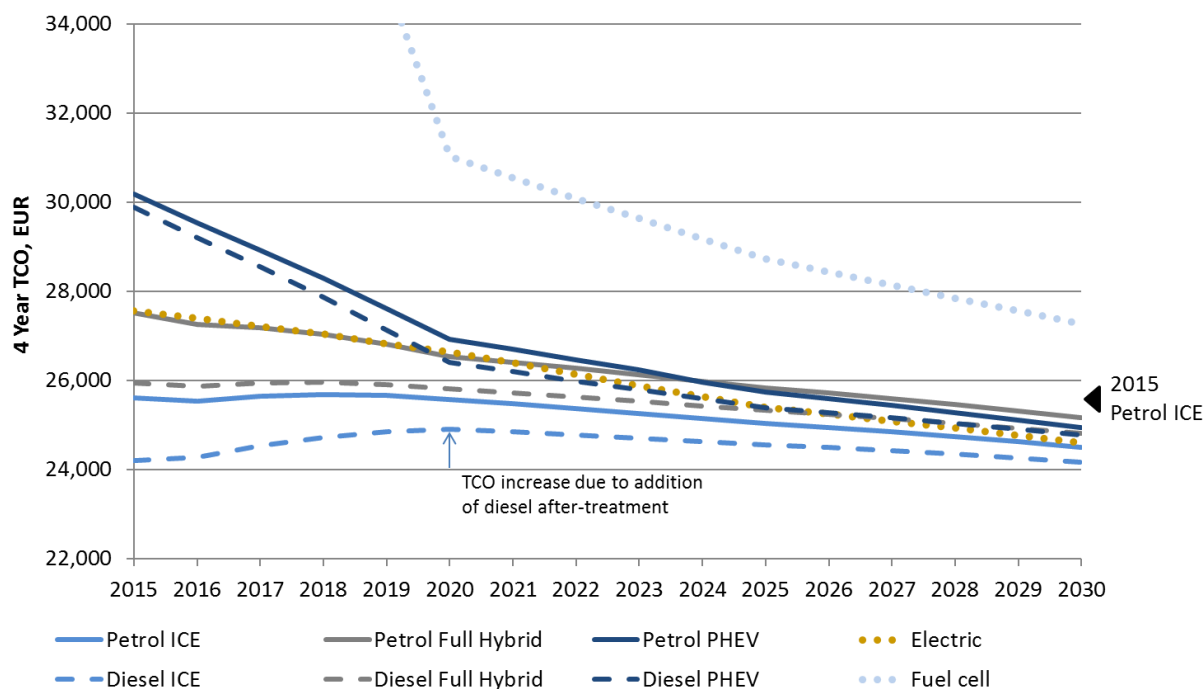
Figure 24: Change in 4 year TCO (EUR) over time, for all Segment C powertrains, baseline

The increase in the TCO of the diesel ICE between 2015 and 2020 is largely due to the addition of a €700 exhaust after-treatment necessary to meet future air quality standards. However, the efficiency improvements to 2030 provide enough fuel savings to more than offset not only the cost of after-treatment but also the efficiency measures themselves.

In 2030, all powertrains except fuel cells have similar or lower 4 year costs compared with a petrol ICE car in 2015. In other words, buyers of a new car in 2030 will pay the same or less than they do today over 4 years no matter which powertrain they choose. This is despite the fact that both fuel and electricity costs are projected to rise throughout this period. This highlights the benefits of policies to

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[48] Prices and residual values of optional extras from: European Commission (2016) UK Automotive Study on the Pricing and Fitment of Optional Extras to Passenger Cars and Light Commercials

drive further efficiency improvements in new cars beyond 2020, since any additional vehicle cost is offset by the fuel savings.

It is important to note that the TCOs presented in Figure 20-Figure 24 do not include the cost of a charge point. As discussed in Section 5.2, installing a charge point with every EV purchase will not always be necessary, but by 2030 this will likely cost approximately €600 to purchase and install. This would make the TCO premium of electric vehicles for the first owner approximately €1,000 in 2025-2030. However, this is still well within the average value of optional equipment purchased on conventional cars.

7.2 Additional Results

The results above show the TCO for a medium (C segment) car over the first four years of ownership. Additional results are set out below for small (B segment) and large (E segment) cars, as well as results for second and third owners.

7.2.1 Segment B 4 year TCO new car, 2015-30

Input Conditions:

- Baseline
- Fuel price: 116-165 c/l petrol; 102-163 c/l diesel; 954-902 c/kg H_2; 12.5-15.7 c/kWh electricity
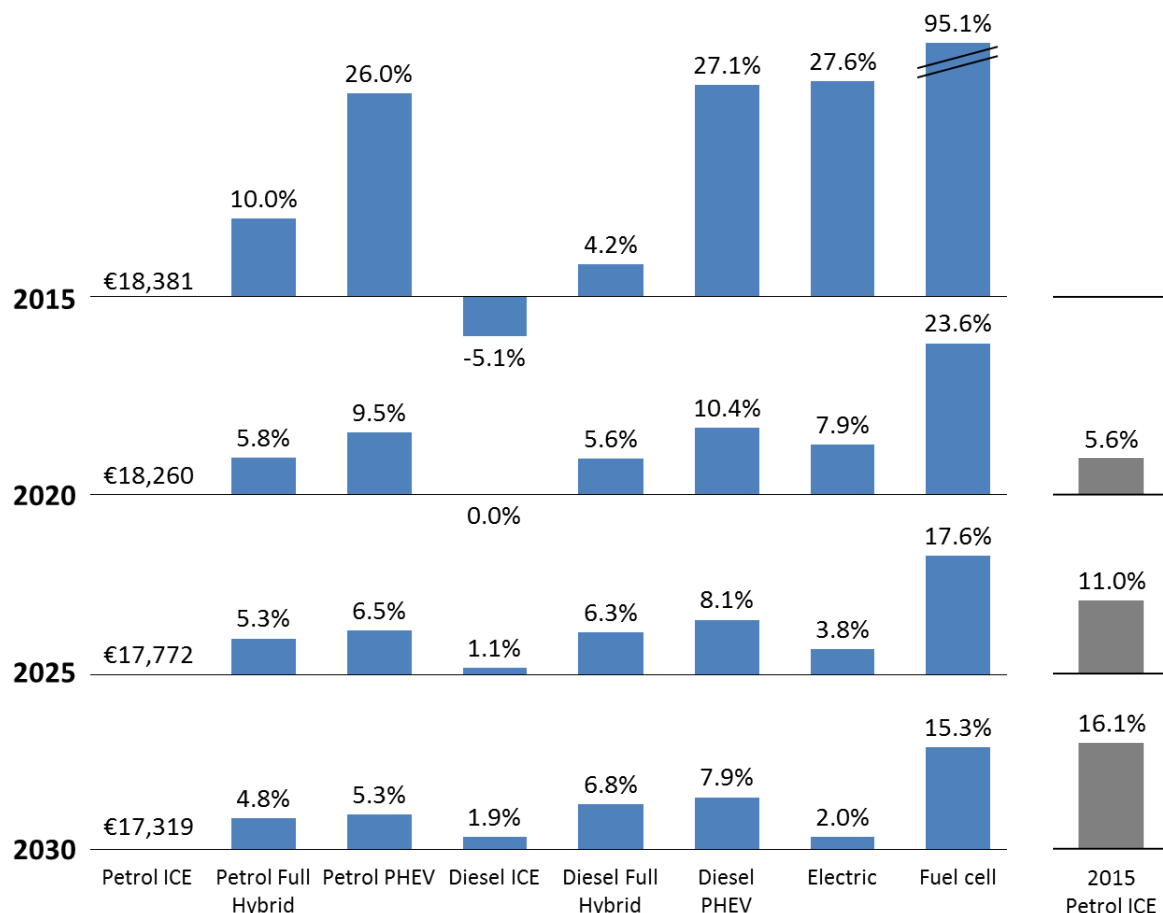
Figure 25: 4 year TCO for new Segment B car, relative to Petrol ICE

For small cars, PHEVs and BEVs appear less competitive with ICEs compared with Segment C. However, this is primarily because the TCO premium over ICEs starts from a considerably higher point in 2015. The BEV TCO is 27.6% greater than the Petrol ICE TCO for Segment B, compared with 7.6%

for Segment C. Much of the difference in 2015 is due to no OEM discounting assumed for Segment B plug-in cars, as the margins in this segment are already very low. In reality, lower than normal margins are implied by the current Renault Zoe price, but not for the pricier but similarly specified Kia Soul EV.

Despite this, the premium over ICEs is still larger in 2020 for Segment B compared with Segment C, even though all discounting has been removed by this point, and this remains the case throughout the 2020s. There are two complementary factors responsible for this:

- Small BEVs have higher component costs as a proportion of the base vehicle price compared with medium or large cars: The electric powertrain components of a small plug-in car make up a larger proportion of the total factory gate cost, cersus a medium sized car. For example, in 2020, this is 51% for a Segment B BEV and 48% for a Segment C BEV, the difference being worth ~€700. It is therefore relatively more expensive to create a Segment B BEV versus a Segment C, due in part to the smaller battery being more expensive on a per kWh basis.
- The TCO of small petrol cars is already low in the 2020s: this is due to the low fuel consumption of small cars, which reduces the running cost savings of a comparable EV, and also due to decreases in the cost of efficiency measures for new cars, which make up a higher proportion of the factory gate cost for small cars than for medium cars and hence have a stronger impact on the purchase price.

7.2.2 Segment E 4 year TCO new car, 2015-30

Input Conditions:

- Baseline
- Fuel price: 116-165 c/l petrol; 102-163 c/l diesel; 954-902 c/kg H_2; 12.5-15.7 c/kWh electricity
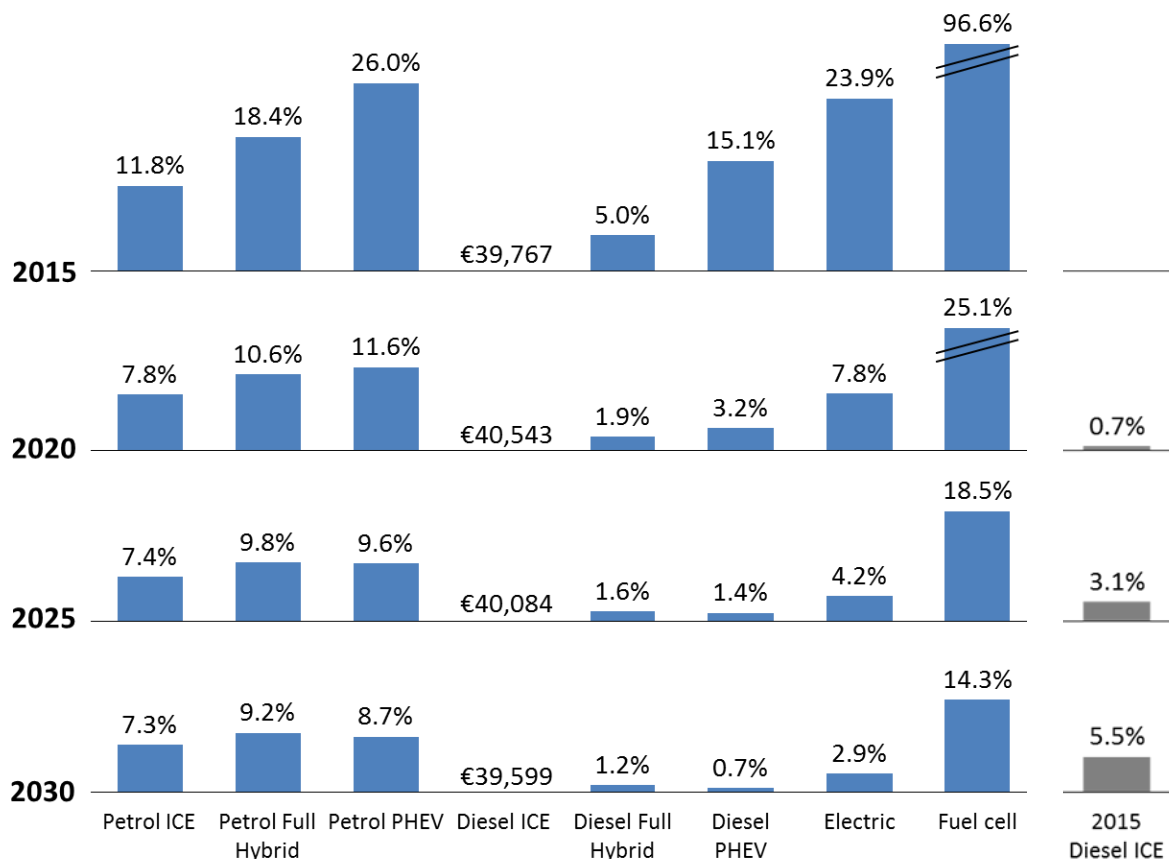

Figure 26: 4 year TCO for new Segment E car, relative to Diesel ICE

Sales of Segment E cars are strongly weighted towards diesel (88% in 2014[49]), with the available petrol cars often limited to powerful and inefficient model variants, which are consequently expensive. The Segment E petrol ICE does not provide a good baseline to compare TCOs against, and so Figure 26 shows all TCOs relative to the cheaper diesel ICE. The TCO relative to the 2015 diesel ICE is not shown because the addition of exhaust after-treatment between 2015 and 2020 would make this a misleading comparison, since the 2015 model would not be legal in the 2020s.

Although relative to the cheaper diesel, the 4 year TCO for a Segment E BEV still appears appealing, getting to within 2.9% of the diesel ICE in 2030 (€1,100 in absolute terms). PHEVs get even closer to the TCOs of their ICE counterparts, with an average TCO premium of €400 in 2030.

The reasons for this favourable outlook for large EVs are the opposite to that of small EVs. The cost of the electric powertrain in a Segment E BEV contributes only 39% to the total factory gate cost in 2020, compared with 48% for Segment C and 51% for Segment B. Fixed costs, such as in battery packaging, make up a smaller proportion of the total cost. It is therefore relatively cheaper to electrify a large car.

Likewise, efficiency measures make up a smaller proportion of overall selling price of petrol and diesel models, and so the impact of efficiency technology becoming cheaper over time is lower as a proportion of total costs. Therefore, the rate of cost reduction for conventional Segment E cars is slower.

Whilst the TCOs of EVs look more favourable for larger cars, it should be noted that buyers of premium Segment E cars are less cost constrained and so more willing to consider non-financial attributes as well. Assuming that the electric range and availability of infrastructure is sufficient, premium BEVs have a range of other selling points such as superior acceleration and refinement, potential to improve vehicle handling using electronic differentials and torque vectoring etc.

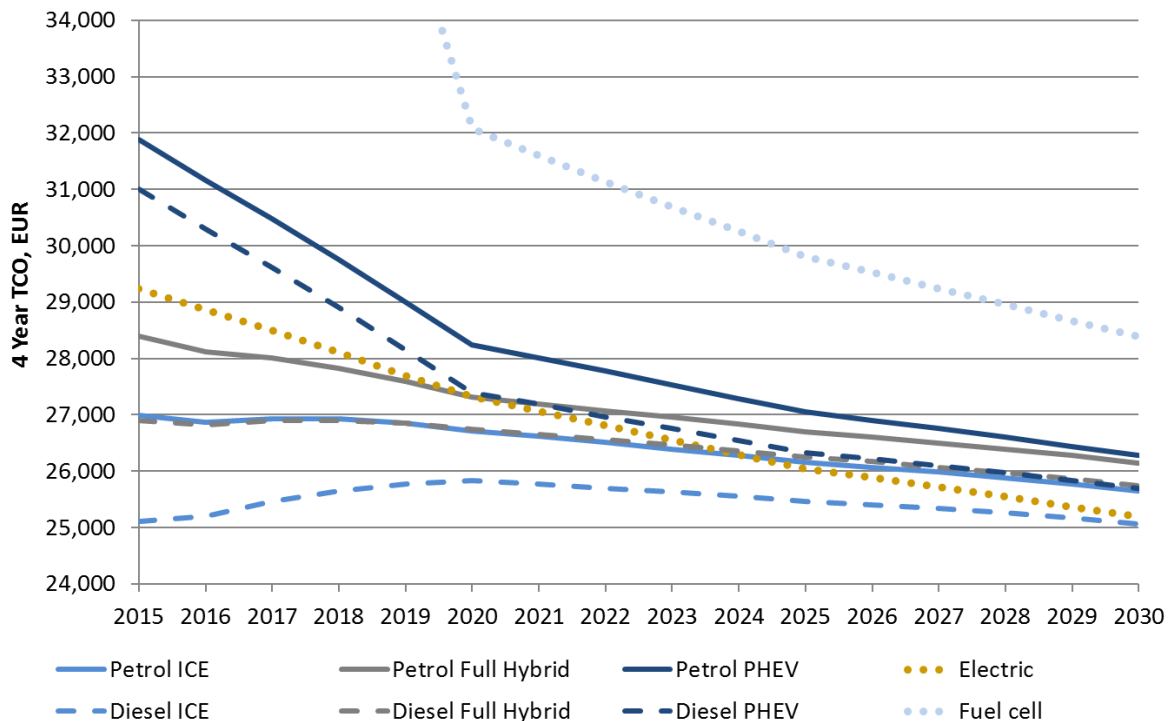### 7.2.3 Change in 4-year TCO over time, averaged over all segments

Figure 27: Average 4-year TCO of each powertrain, weighted by 2015 segment shares

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[49] Data provided by ICCT

A segment-weighted average of the 4-year TCO for each powertrain, shown in Figure 27, reveals a similar convergence over time as was observed for Segment C. Without including the cost of a charge point, PHEVs are on average €600 more expensive to own over 4 years than the equivalent ICEs in 2030, and very similar to the equivalent HEVs. BEVs become the second cheapest powertrain and are on average €100 more than diesel ICEs and €500 cheaper than Petrol ICEs in 2030.

Average 4-year TCOs for small, medium and large cars are presented in Appendix 9.2.

7.2.4 Segment C, TCO over whole vehicle life, 2020

The results so far have been intentionally focused on the first owner, as they are the actors who make the decision on which powertrain to purchase or lease. However, it is equally important to consider ownership costs for second and third owners, partly because the secondary market influences the depreciation experienced by the first owner but also to confirm whether advanced powertrains offer TCO savings over their full design lifetimes.

Input Conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Ownership: 1st hand owner keeps vehicle for 4 years, 2nd hand for 5 years, 3rd hand for 7 years
- Driving distance: 15,000 km for 1st hand owner, 12,000km for 2nd hand owner, 10,000 for 3rd hand
- Country: Average EU-28
- PHEV range: Default (~69% of driving distance in electric mode)
- Oil price: IEA WEO 2015 central scenario
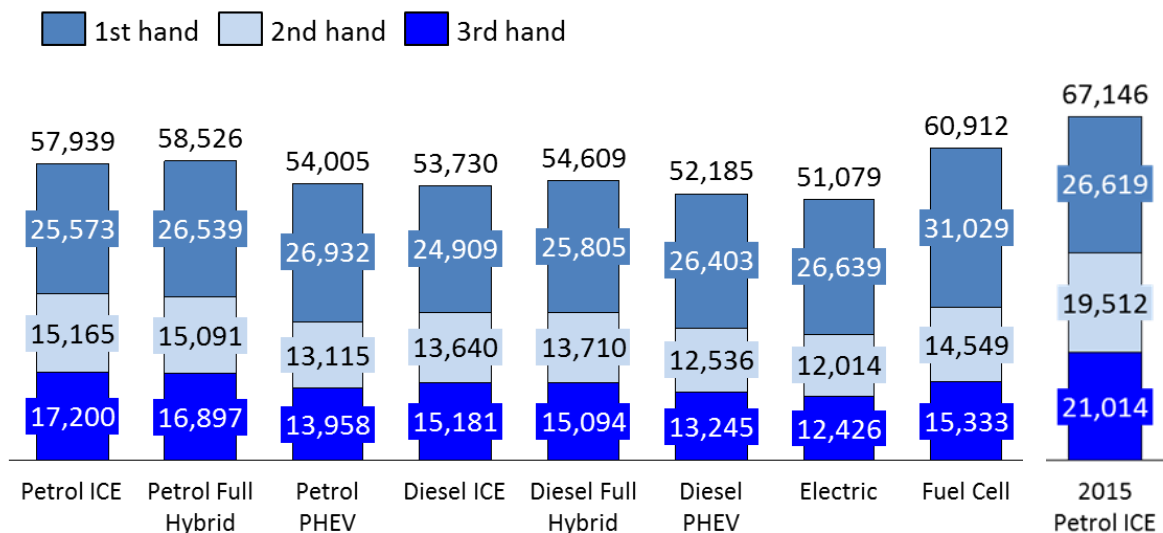- Fuel price: 142-167 c/l petrol; 134-166 c/l diesel; 772-966 c/kg H_2; 12.8-16.0 c/kWh electricity

Figure 28: 16 year TCO (EUR), spread between 1st, 2nd and 3rd hand owners, initially purchased in 2020

When second and third hand owners are included in the TCO, capturing the whole lifetime of the vehicle, BEVs become considerably cheaper than both petrol and diesel ICEs as early as 2020. However, this does not account for fact that all three owners may need to purchase a charge point at a cost of €600-€1000 each, which would bring BEVs and diesel ICEs to near cost parity.

Even with the cost of a charge point, the TCO for second and third hand PHEV owners is lower than their ICE counterparts. Since it has been assumed that all powertrains depreciate at the same rate, the

first owner bears most of this cost. At the point of resale, the absolute difference between the residual values of each powertrain is relatively small. Under this scenario, second and third hand owners can enjoy the benefits of cheaper running costs without paying substantially more in capital costs. This advantage is of particular relevance to many of the newer EU-13 Member States, where a high proportion of vehicles are over 10 years old and there is a large market for imported used cars.
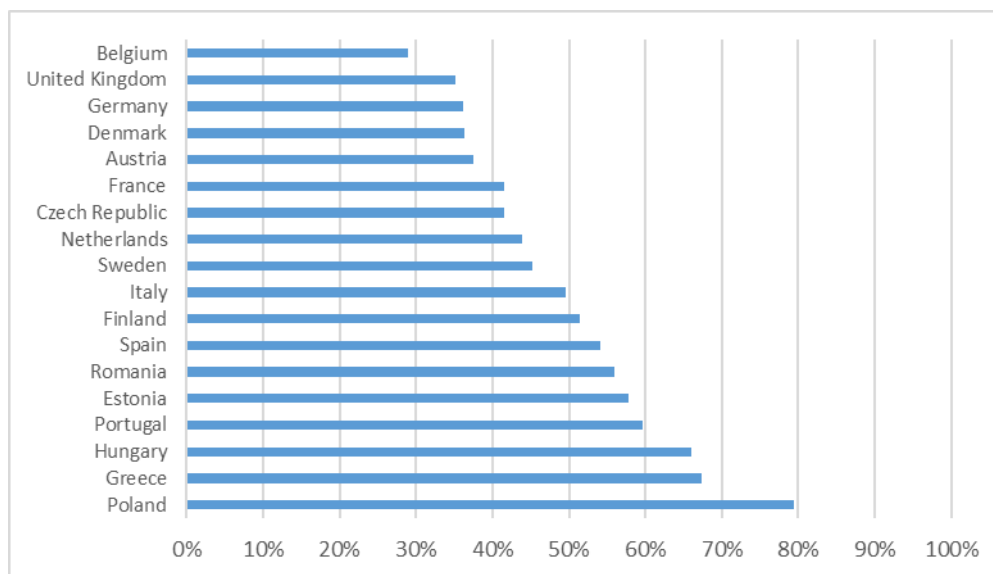
Figure 29: Share of vehicles over 10 years old in EU Member States, 2014, from ACEA Pocket Guide 2016/17. Sourced data unavailable for some Members.

However, these significantly lower costs for second and third owners also imply that residual values for 4-year-old plug-in vehicles will strengthen in the future, as the market 'prices in' the future running cost savings. This would reduce the depreciation experienced by the first owners, and given the small TCO premium shown for the first 4 years of ownership in Section 7.1, this could lead to TCO parity for advanced powertrains for the first owner.

The results presented in Figure 28 do not include the cost of battery replacement during the vehicle lifetime. A replacement battery for a 2020 Segment C BEV is predicted to cost €5,100 (plus a margin) in 2030 which would significantly alter the lifetime TCO and eliminate the lifetime advantage relative to both a diesel ICE car and a petrol ICE. However, simply including this cost in the TCO is likely to overstate the impact on ULEV operating costs for the following reason

- This replacement cost does not take into account the potential resale cost of the used battery for use in a function with lower cycling demand, such as stationary storage. Nissan currently offers ~€750 for a used 24 kWh Leaf battery, and has released its xStorage device, designed for residential electricity storage, which used recycled Leaf batteries.
- The timing of the battery replacement, and whether it is necessary at all, is highly uncertain. The oldest current generation EVs are only 5-6 years old, and so battery lifetimes under real world driving conditions are not yet fully known. Tesla have stated that they expect a minimum lifetime 10-15 years from their batteries, while the Nissan Leaf 30 kWh, BMW i3 and VW eGolf are all issued with an 8 year/160,000km warranty against the battery losing more than 25% of its capacity. For reference, the current average lifetime mileage of diesel ICEs is 208,000 km and for petrol ICEs is 160,000 km,[36] and so the Nissan/BMW/VW battery warranty already covers the average whole life mileage of a Petrol ICE (although not its technical lifetime). As battery costs are projected to continue falling in the 2020s and 2030s, the later the replacement takes place the cheaper it will be.

- Replacing the battery after 10 years would likely extend the technical life of the vehicle well beyond the current 16-year technical life of an ICE, due to the lower number of moving parts in the rest of the powertrain. Tesla, for example, recently announced a goal of producing powertrains that last 1 million miles,[50] which would be particularly beneficial in high distance duty cycles like taxis or future autonomous or shared cars. This would have to be factored into a considerably higher residual value for BEVs at 16 years.
- Annual mileage tends to decrease with age, for example, driving during the first 8 years accounts for ~60% of the lifetime mileage.[36] A like-for-like battery replacement therefore may not be necessary and a cheaper, lower capacity battery could suffice.
- ICEs will also bear the cost of unscheduled component replacement in the latter stages of their lifetime. For example, injectors and turbochargers often require replacement during the vehicle lifetime which would offset the costs of a battery replacement in an ULEV.

Battery lifetime is a key uncertainty that warrants further study as current EVs on the road continue to age. It also suggests car manufacturers should continue to work to reduce the likelihood of batteries needing to be replaced and to minimise that cost, for example by ensuring that individual modules can be replaced instead of whole packs, or next generation batteries can be retrofitted to older EVs.

7.2.5 Segment C, TCO over whole vehicle life, 2025 and 2030

Input Conditions, 2025

- Same as in Section 7.2.4, other than fuel price
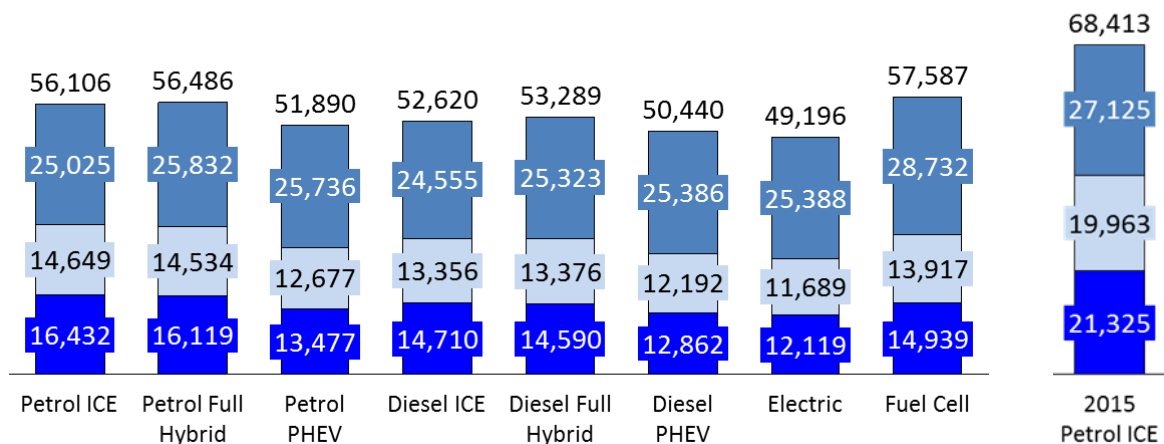- Fuel price: 152-171 c/l petrol; 147-171 c/l diesel; 772-1,073 c/kg H_2; 13.7-16.4 c/kWh electricity

Figure 30: 16 year TCO (EUR), spread between 1st, 2nd and 3rd hand owners, initially purchased in 2025

Input Conditions, 2030

- Same as in Section 7.2.4, other than fuel price
- Fuel price: 162-171 c/l petrol; 159-171 c/l diesel; 841-1179 c/kg H_2; 15.5-17.0 c/kWh electricity

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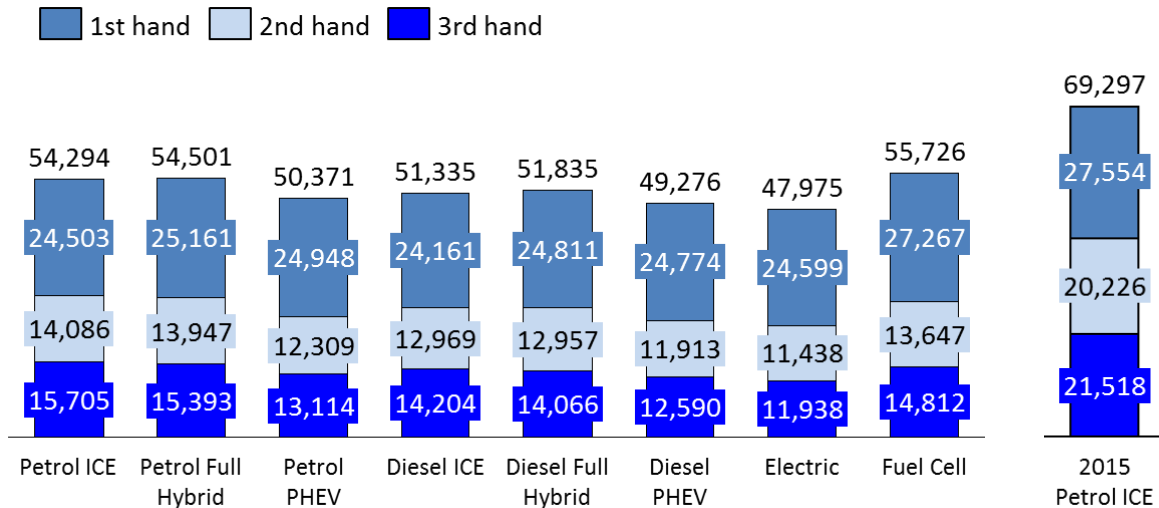[50] Tesla (2015) – available at https://www.tesla.com/blog/three-dog-day [accessed: 19/07/2016]

Figure 31: 16 year TCO (EUR), spread between 1st, 2nd and 3rd hand owners, initially purchased in 2030

Repeating the same 16 year TCO for Segment C vehicles purchased in 2025 and 2030 reveals BEVs have open up the lifetime cost gap to diesel ICEs. The cost of batteries is projected to fall 32% (per kWh) between 2020 and 2030, resulting in a decrease in BEV purchase price; however, some of the savings in battery cost are offset by an increased range (280 km to 320 km, NEDC). In addition, the cost of ICE ownership is also reduced by continued improvements in fuel efficiency and a fall in the cost of deployed efficiency technology. This is made clear when comparing to the lifetime cost of a 2015 petrol ICE if it were purchased in 2030, which is €15,000 more expensive over its lifetime than the more efficient 2030 model.
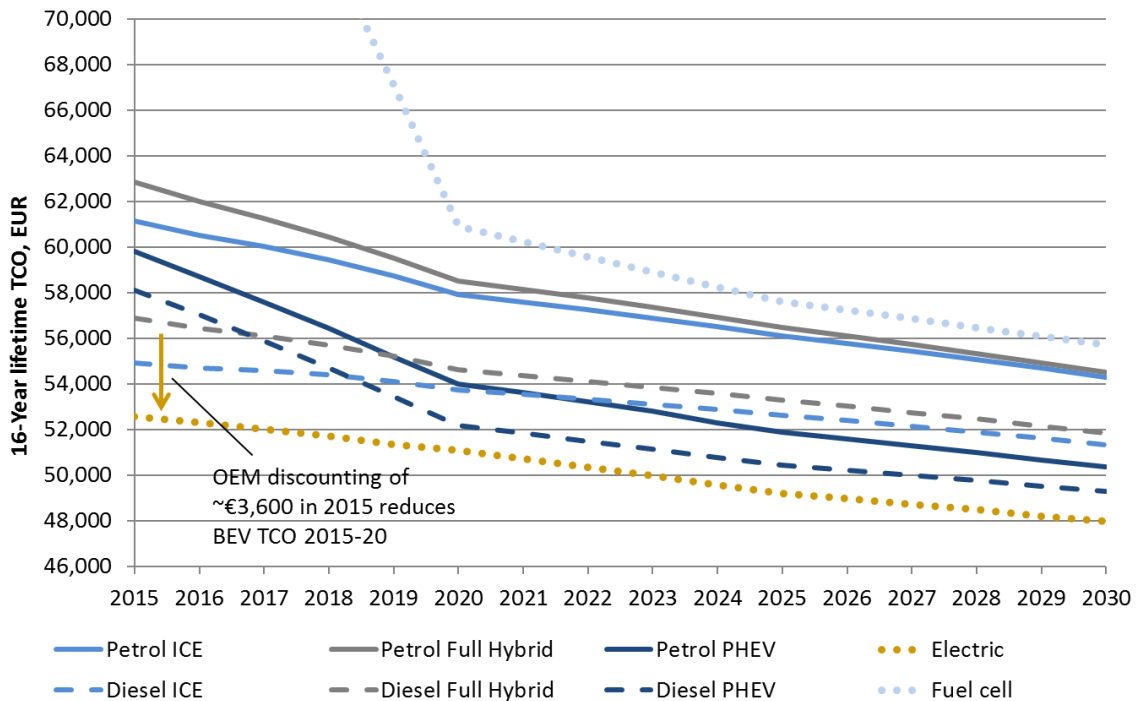

Figure 32: Change in lifetime (16 year) TCO (EUR) over time, for all Segment C powertrains, baseline

Figure 32 summarises the evolution of the technical lifetime TCO for all Segment C powertrains. Although BEVs appears to have low costs in 2015 (on a lifetime basis), these current vehicles are likely

to have smaller margins than conventional vehicles. If the full margin is applied in 2015, then the lifetime TCO of a Segment C BEV would be €56,200, placing it closer to the other plug-in powertrains. However, if BEVs are assumed to be old with standard industry margins beyond 2020, BEVs continue to offer a cost advantage over their lifetimes compared with all other powertrains. If the cost of three charge points is included, BEVs remain the lowest cost option, while PHEVs would remain highly competitive with ICEs.

7.2.6 Change in whole life TCO over time, averaged over all segments

As per the 4-year TCO, the 16-year lifetime TCO can be weighted by 2015 segment shares to provide a representative average TCO for each powertrain (Figure 33). The trend is similar to that for Segment C (Figure 32), with lifetime costs an average of €4,400 (-8.2%) cheaper than diesel ICEs in 2030 (compared with €3,400 or -6.5% for Segment C). The change in lifetime TCO's for small, medium, and large vehicles are shown in Appendix 9.3.
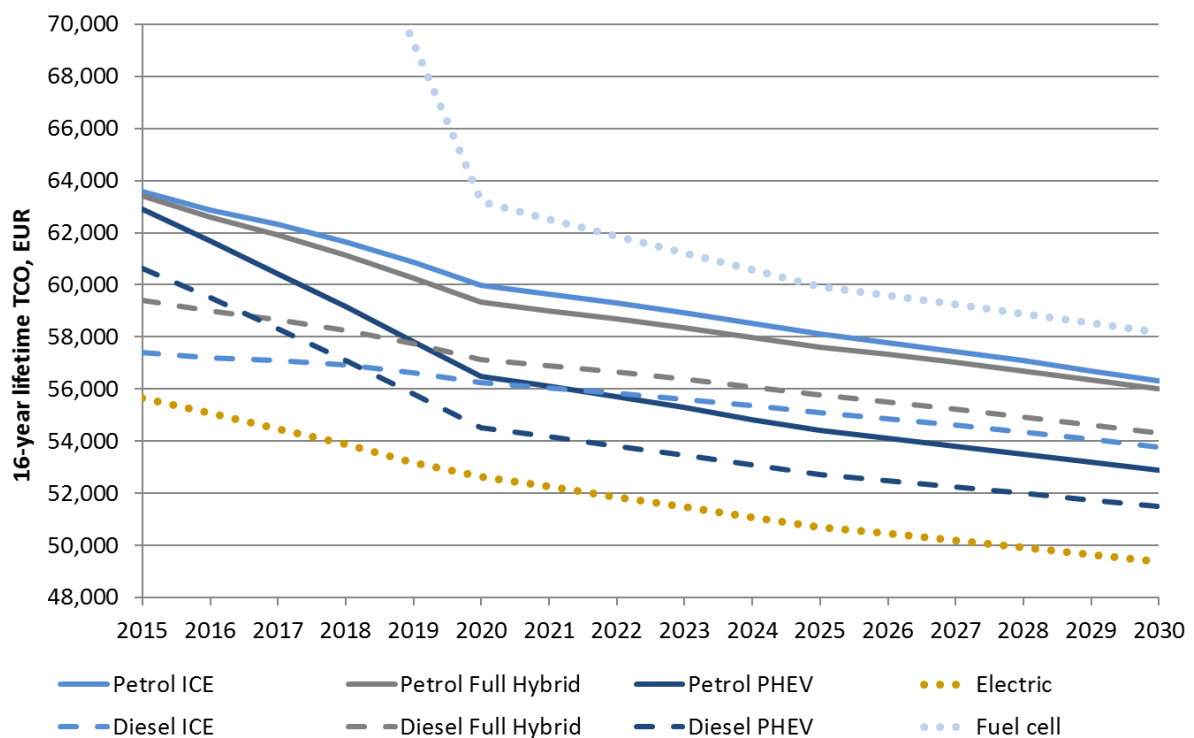

Figure 33: Change in average lifetime (16 year) TCO (EUR) over time, weighted by 2015 segment shares

7.3 Sensitivities

The results below explore the impact of changing some of the key modelling assumptions on the TCO results. Sensitivities were generated for:

- The proportion of PHEV driving distances covered in electric mode
- A low oil price scenario
- Undiscounted retail electricity prices
- High and low annual driving distance compared with the base case

7.3.1 Percentage driving in electric mode with PHEVs

Input Conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Battery cost: Baseline
- Driving distance: 15,000 km per year for all powertrains
- Country: Average EU-28
- Oil price: IEA WEO 2015 central scenario
- Fuel price: 116-165 c/l petrol; 102-163 c/l diesel; 954-902 c/kg H2; 12.5-15.7 c/kWh electricity
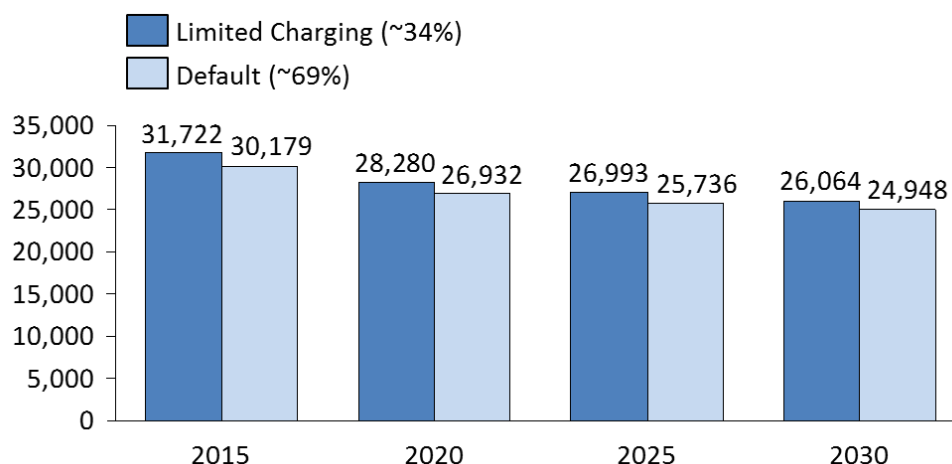
Figure 34: 4 year TCO (EUR), Segment C Petrol PHEV, different % driving in electric mode scenarios

Doubling the percentage of driving in electric mode is worth €1,000-1,500 over a 4 year TCO for Segment C Petrol PHEVs. Its value becomes smaller over time as the efficiency of the ICE improves quicker than the electric powertrain, and electricity costs continue to rise post-2025 while fuel cost remains nearly constant. Regardless, the level of these potential savings should be sufficient to encourage petrol PHEV drivers to maximize the proportion of electric kilometres they drive.

For Segment C Diesel PHEVs, the impact of doubling the percentage driving in electric mode is worth only €600-900. The efficiency of diesel powertrains, and lower diesel price, result in considerably cheaper overall fuel costs. Hence the value of fuel saved is smaller.

7.3.2 Low oil price

Input Conditions:

- Residual value scenario: Medium (Same relative depreciation)
- Driving distance: 15,000 km per year for all powertrains
- Country: Average EU-28
- PHEV range: Default (~69% of driving distance in electric mode)
- Baseline Oil Price: IEA World Energy Outlook 2015 Central; 142-165 c/l petrol; 134-163 c/l diesel
- Low Oil Price: Cambridge Econometrics Technology Potential; 135-144 c/l petrol; 126-136 c/l diesel
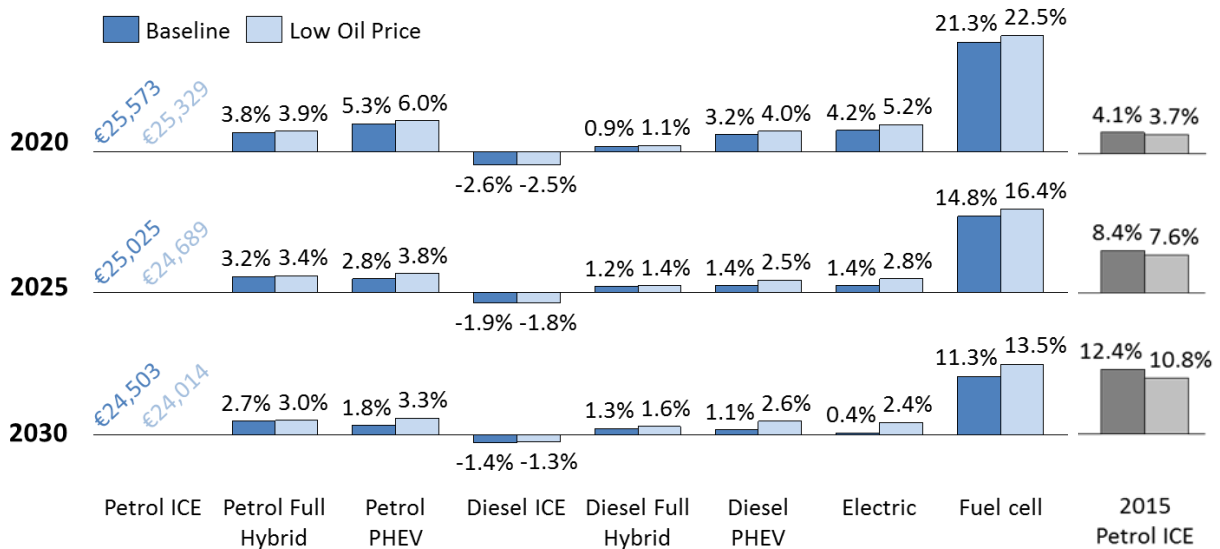- 772-902 c/kg H2; 12.8-15.7 c/kWh electricity;

Figure 35: 4 year TCO (EUR), Segment C, under base and low oil price scenarios

The effect of a low oil price scenario on the TCO results is relatively small. Although the EV premium over ICEs increases, the order of cheapest powertrain to most expensive stays largely the same. This is in part because the relatively high fuel taxes in Europe (compared with the US for example) dampen the impact on petrol and diesel prices for a given reduction in the crude oil price. For example, in the low oil price scenario, crude oil is 27% lower in price in 2030 than in the base case, but petrol and diesel prices are only 11% and 14% lower, respectively. The lack of sensitivity to oil prices underlines the benefit of future efficiency improvements in petrol and diesel vehicles. For example, increasing the 2025 oil price from a baseline of $97/bbl to its record historical monthly peak of $133 (July 2008) would only imply an additional ~€130 per year for a new petrol or diesel car purchased in 2025, given its very low fuel consumption. However, the side effect of this is that future changes in oil price are unlikely to substantially change the relative TCO of petrol/diesel versus electric cars.

7.3.3 Undiscounted retail electricity price

Input Conditions:

- Baseline, other than electricity price
- Electricity prices: 12.8-15.7 c/kWh with 30% discount (baseline), 18.3-22.5 c/kWh undiscounted
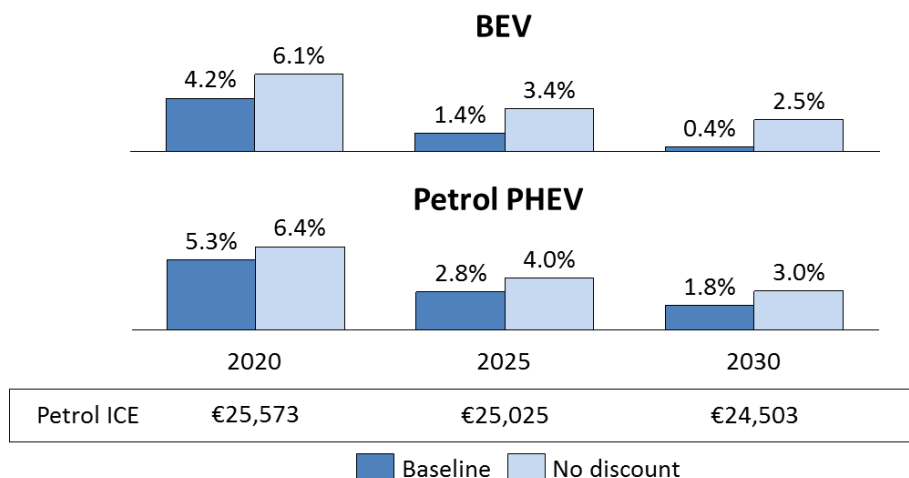

Figure 36: 4 year TCO relative to Petrol ICE for Segment C BEV and Petrol PHEV, with a 30% discount applied the price of electricity (baseline) and undiscounted electricity

In Section 4.1 it is described how an assumed 30% discount is applied to the retail price of electricity to take into account the likelihood that charging will take place during off-peak electricity demand periods, and the provision of grid services by EVs. Removing this discount adds ~€500 to the 4 year TCO of Segment C BEVs, and ~€300 for Segment C petrol and diesel PHEVs throughout the 2020s. This opens up the premium to petrol ICEs by ~2% points for BEVs and ~1% point for PHEVs.

Over the 16-year technical lifetime of the vehicle, the difference in electricity spend for a Segment C BEV with undiscounted electricity is estimated to be ~€1,700 throughout the 2020s, which is not enough to push it above the cost of a diesel ICE. Correspondingly, Segment C PHEVs would become €900-€1,000 more expensive over their lifetime, but again the petrol PHEV remains cheaper than the petrol ICE.

Undiscounted domestic electricity is an unlikely scenario in the 2020s for the reasons presented in Section 4.1. However, this sensitivity can be used to illustrate the case for owners that may not have access to overnight charging at home and are forced to rely on a more expensive public charging infrastructure. Despite making EVs more expensive, it is important to recognise that EVs do not become uneconomical under this higher electricity price scenario, and in fact remain cheaper than conventional petrol cars over their lifetime.

7.3.4 High and Low Mileage

Input Conditions:

- Baseline, other than mileage
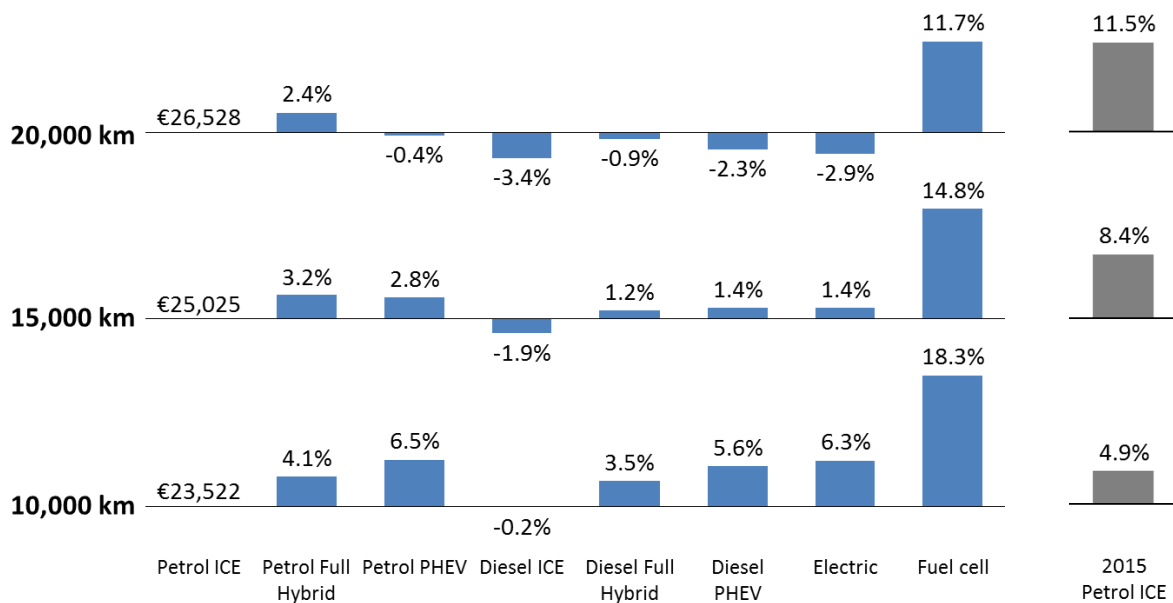
Figure 37: 4 year TCO relative to Petrol ICE for Segment C cars in 2025 under different annual mileage scenarios

Unlike oil prices, the annual mileage has a directly proportional impact on annual fuel and electricity costs. Figure 37 shows how a 33% increase in annual mileage to 20,000km results in Segment C BEVs becoming cheaper than petrol ICEs on a 4 year TCO basis in 2025. The 2025 TCO of Segment C BEVs relative to diesel ICEs also decreases from 3.4% to 0.6% (€800 vs €100; not shown in Figure 37). This scenario does not include any change in vehicle depreciation with increased mileage.

This result shows the potential for BEVs on a cost basis amongst high mileage users. However, it is likely that the trips driven by such users will on average be longer and hence the range limitation of
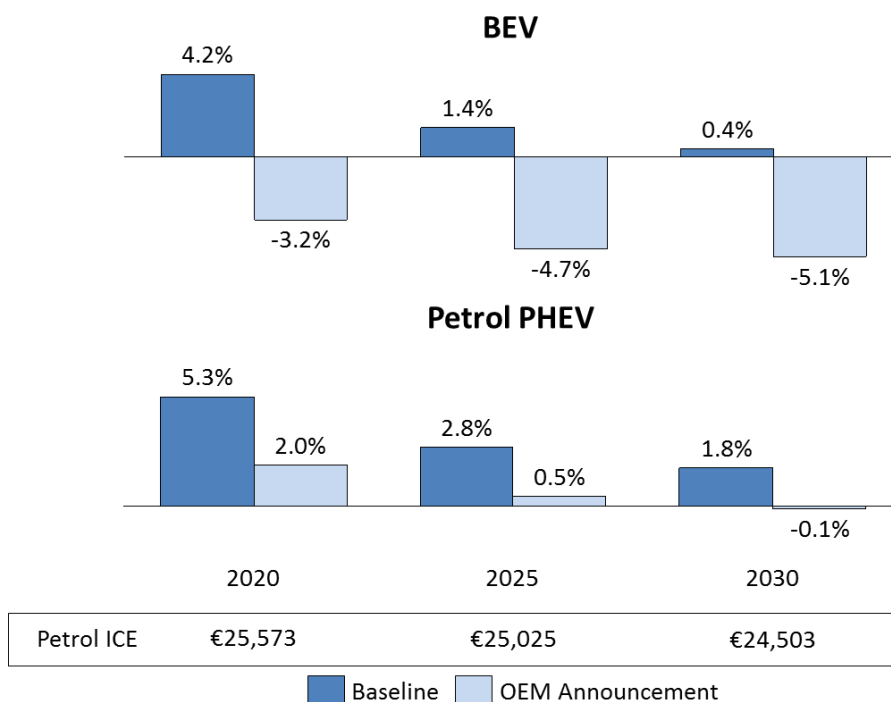
BEVs may become an issue for very high annual distances (e.g. over 50,000km per year, equivalent to 200km per day for 250 working days per year) unless charging infrastructure with acceptable charging times is widely available. In addition, the costs shown in Figure 37 do not assume any changes to the percentage of driving in electric mode for PHEVs, which will occur with longer average trips lengths. However, for high mileage drivers there is still considerable benefit to maximising the electric kilometres driven. For example, the difference in fuel/electricity costs between the baseline (~69% electric kilometres) and *Limited Charging* (~34% electric kilometres) scenario for a Segment C petrol PHEV with an annual mileage of 50,000 km is worth more than €1,000 per year in 2025.

7.3.5 Low battery cost

As mentioned, in Section 3.2.2, the baseline battery scenario is likely a conservative estimate of future costs. OEMs have announced considerably faster cost reduction estimates, though it is not yet clear that these will be achieved on the expected timescales. To test the impact of meeting these targets, the 4 year TCO for Segment C BEVs and petrol PHEVs was calculated with the low cost *OEM Announcement* scenario presented in Section 3.2.2.

Input Conditions:

- Baseline, other than battery costs

BEV

4.2%   1.4%   0.4%
-3.2%   -4.7%   -5.1%

Petrol PHEV

5.3%   2.8%   1.8%
2.0%   0.5%   -0.1%

	2020	2025	2030
Petrol ICE	€25,573	€25,025	€24,503

■ Baseline □ OEM Announcement

Figure 38: 4 year TCO relative to petrol ICE for Segment C BEV and Petrol PHEV, under base and low cost battery scenarios (OEM Announcement)

Under the *OEM Announcement* scenario, Segment C BEVs achieves cost parity with petrol ICEs by 2020, on a 4 year TCO (and diesel ICEs, although not shown in Figure 38). The impact on PHEVs is much smaller, due to their battery capacities being <10 kWh, while the Segment C BEV has >30 kWh. Lower than expected battery costs will provide car manufacturers with a choice of whether to minimise vehicle purchase costs for price-sensitive customers, or to increase vehicle ranges for the same cost to maximise the proportion of customers for whom EVs are a viable solution for their travel needs. In reality, manufacturers may offer models with several battery sizes (e.g. the current Nissan Leaf with 24kWh and 30kWh pack sizes, or the Tesla Model S offering 60-90 kWh) to maximise customer choice.
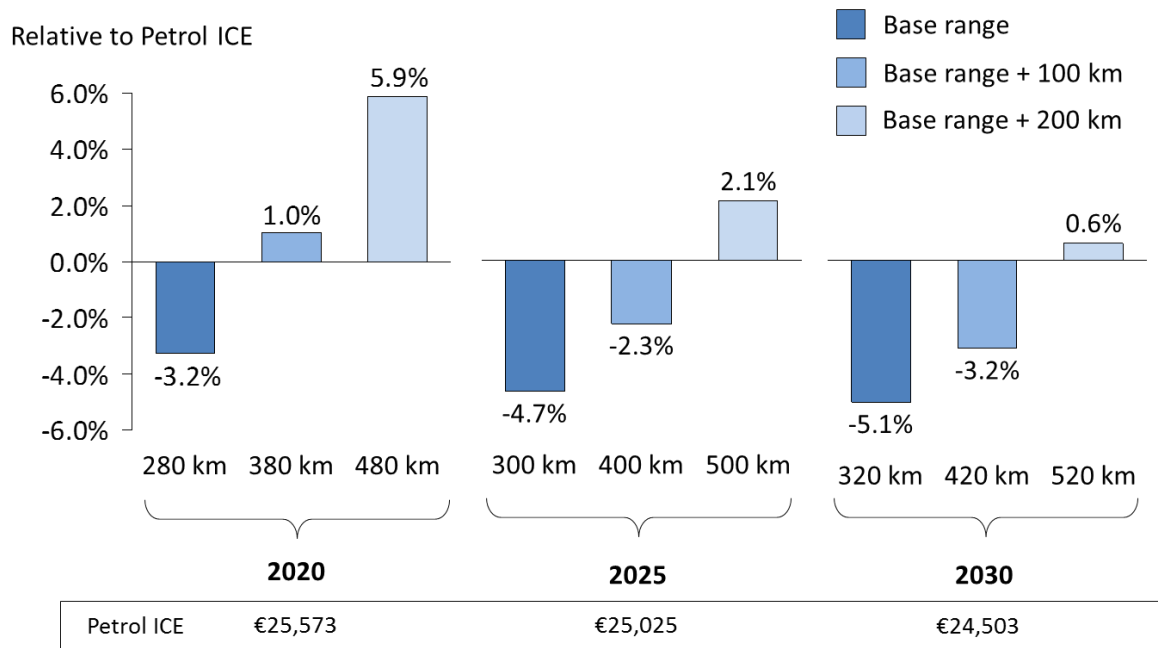
elementenergy

Relative to Petrol ICE

	Base range
	Base range + 100 km
	Base range + 200 km

| Petrol ICE | €25,573 | €25,025 | €24,503 |

Figure 39: 4 year TCO relative to Petrol ICE for Segment C BEVs with OEM Announcement battery cost scenario, for different ranges (NEDC)

Figure 39 shows the impact on the 4 year TCO relative to petrol ICE of increasing the range by both 100 km and 200 km under the *OEM Announcement* battery cost scenario. In 2025, increasing the range by 100 km would increase the battery capacity from 32 kWh to 45 kWh and the TCO by €600. Increasing further by 200 km increases the battery capacity to 59 kWh and the TCO by €1,700. The increase in both battery capacity and TCO is not linear because the larger battery imposes a weight penalty, thus increasing electricity consumption and reducing range. An additional 200 km of range in 2030 gives a 4 year TCO comparable with the battery costs from the baseline battery cost scenario (0.6% relative to petrol ICE).

7.3.6 No additional deployment of efficiency technology for ICEs

In this sensitivity the value of continued efficiency improvements to vehicles is shown by comparing the baseline TCO results of Segment C petrol and diesel ICEs, against scenarios which further deployment of efficiency technology is completely halted from either 2015 or 2020 i.e. after the 95 gCO$_2$/km target has been met. This differs from the representative TCO of the 2015 petrol ICE in most of the results presented in Section 7 as it accounts for the likely cost decrease for already deployed technologies over time. In this sensitivity it is assumed that the cost of efficiency technology continues to fall at same rate as in the baseline scenario. As a consequence, the vehicle purchase prices still fall in the 2020s, as shown in Figure 40, despite the deployed technology packages remaining the same. Note much of the price increase from 2015-20 is due to the increase in engine power and diesel exhaust after-treatment, as well as additional efficiency technology. Fuel consumption is assumed to remain constant

from the point where further deployment is stopped, to represent a case with no further improvements in vehicle efficiency.
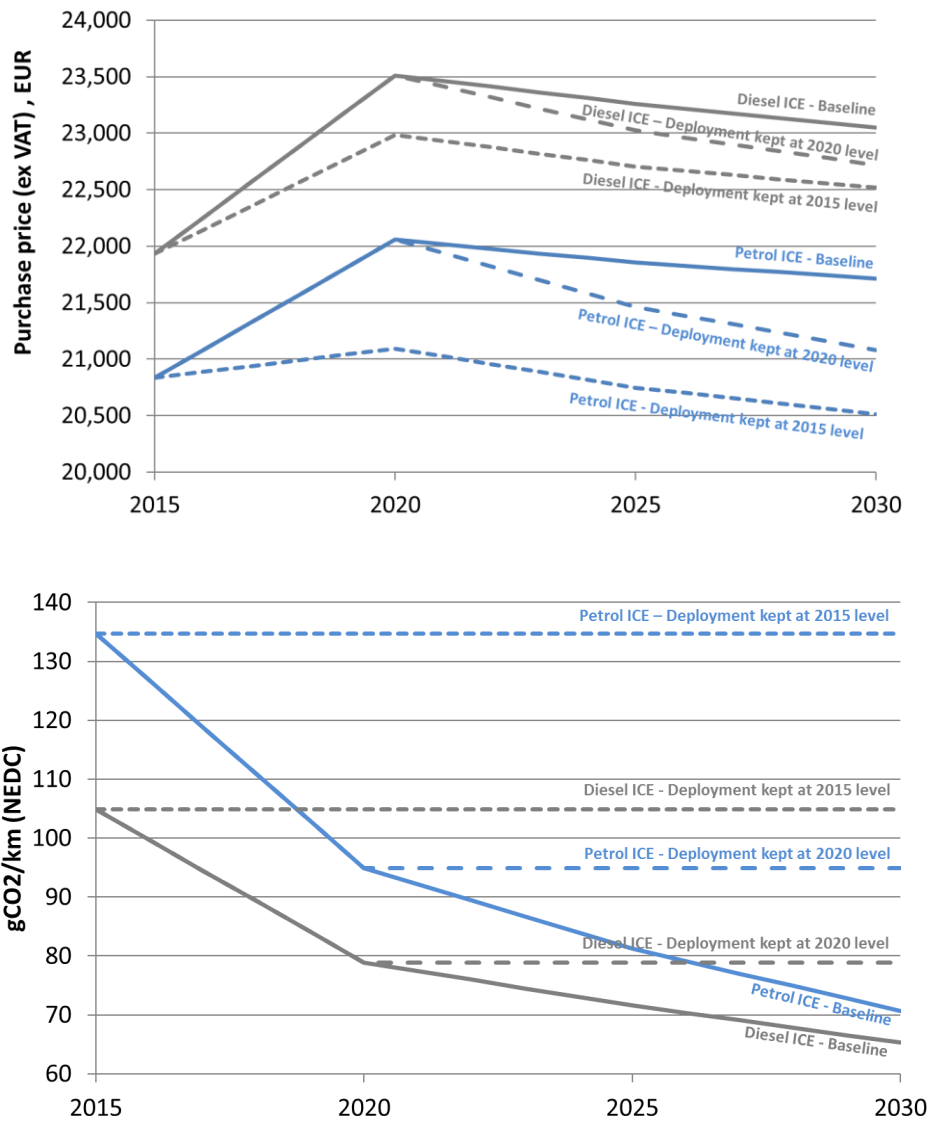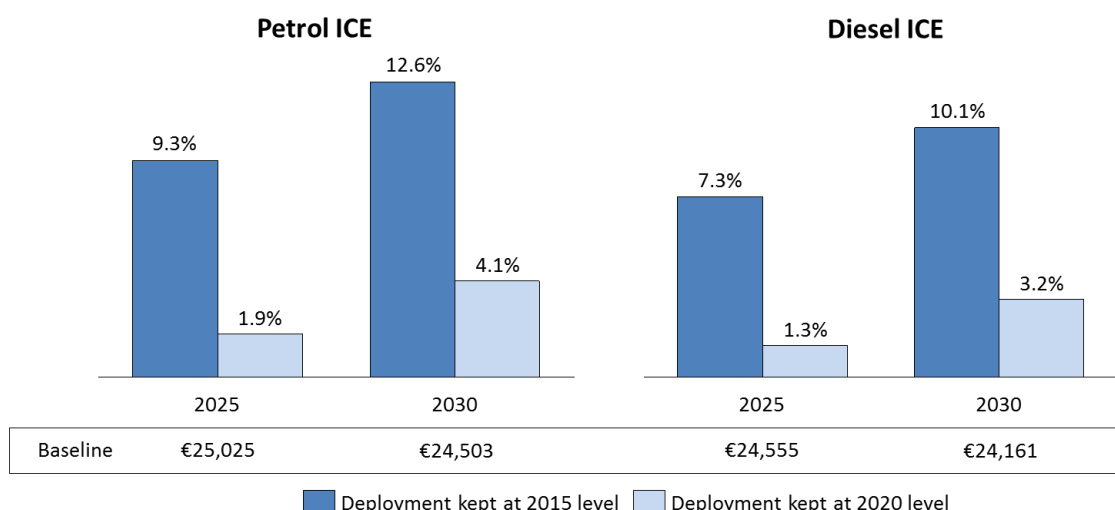

Figure 40: Trend in purchase price (ex VAT) and NEDC CO$_2$ rating for the baseline Segment C ICEs, and alternative scenarios where additional technology deployment is stopped in 2015 and 2020

Input Conditions:

- Baseline
- Fuel price: 152-165 c/l petrol; 147-163 c/l diesel; 772-902 c/kg H2; 13.7-15.7 c/kWh electricity

Petrol ICE

Diesel ICE

| Baseline | €25,025 | €24,503 | €24,555 | €24,161 |

Deployment kept at 2015 level ▮   Deployment kept at 2020 level ▯

Figure 41: Percentage increase in 4 year TCO for Segment C ICEs without further deployment of efficiency technology from 2015 and 2020, versus the baseline ICEs

Figure 41 shows that despite having lower purchase prices, Segment C petrol and diesel ICEs with 2015 and 2020 technology packages cost more on a 4 year TCO basis, as the fuel savings of the more efficient baseline vehicle offset its higher price. This is most evident for the case where deployment is stopped in 2015, as there is significant potential for fuel savings with this vehicle. Here, the petrol ICE would cost an additional €3,100 over 4 years in 2030, and the diesel ICE an extra €2,400 compared with the baseline scenario.

Table 7: Payback periods for additional efficiency technology in 2025 baseline vehicle relative to 2015 and 2020 level deployment, without any improvement to deployed technology[51]

Baseline 2025 vehicle relative to:	Powertrain	Segment Group	Additional Purchase Price	Fuel Saving, l/100km	First Year Fuel Cost Saving	Payback Period, years
Deployment kept at 2015 level	Petrol ICE	Small (A&B)	€618	2.62	€595	1.1
		Medium (C,D,I)	€733	3.10	€705	1.1
		Large (E,F,G,H)	€814	3.99	€907	0.9
		Average	**€710**	**3.13**	**€712**	**1.1**
	Diesel ICE	Small (A&B)	€306	1.72	€379	0.8
		Medium (C,D,I)	€304	2.32	€511	0.6
		Large (E,F,G,H)	€326	3.12	€687	0.5
		Average	**€310**	**2.29**	**€504**	**0.7**
Deployment kept at 2020 level	Petrol ICE	Small (A&B)	€307	0.72	€164	2.0
		Medium (C,D,I)	€391	0.82	€187	2.2
		Large (E,F,G,H)	€473	1.05	€238	2.1
		Average	**€380**	**0.84**	**€191**	**2.1**
	Diesel ICE	Small (A&B)	€191	0.44	€98	2.1
		Medium (C,D,I)	€236	0.57	€124	2.0
		Large (E,F,G,H)	€291	0.79	€174	1.8
		Average	**€232**	**0.57**	**€126**	**2.0**

[51] The payback period is calculated assuming annual mileage of 15,000 km for the first 4 years, and 12,000 km for years 5-10. The 5% financing rate is applied annually to the outstanding balance in each year. This is analogous to applying a 5% discount rate to future cash flows. Segments averaged by 2014 market shares.

Table 7 shows the payback period for the additional efficiency technology deployed in the 2025 baseline ICE vehicles compared with these alternative static deployment scenarios. The trends are broadly similar across all segments. Under both scenarios, the additional technology is easily paid back during the first ownership period (4 years). Diesel ICE technology pays back marginally quicker than petrol ICE, however, as observed in Figure 41, overall savings from petrol ICE technology is greater once the additional system costs have been recouped. Although the cost of the efficiency technology deployed in the baseline petrol ICE is more than for the diesel ICE, this results in a higher percentage reduction in fuel consumption relative to the 2015/20 baseline car, and therefore greater cost savings. Over the vehicle lifetime, the impact of these saving will grow as further benefit from lower running costs is realised.
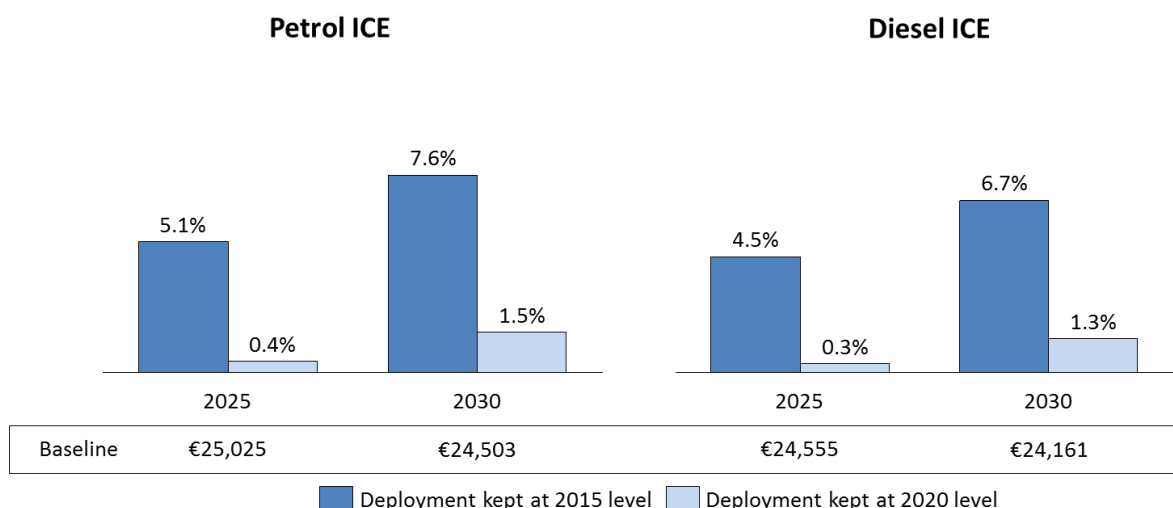
An additional scenario can be devised in which further technology deployment is halted, and each technology receives not only the same cost reduction but also the same incremental improvement in the efficiency gain. This represents a "best case" scenario since the assumed cost reduction is calculated against the higher cumulative deployment of each technology in the baseline, while the efficiency gains are unlikely to improve at the same rate if the driving force of a CO_2 target is removed.
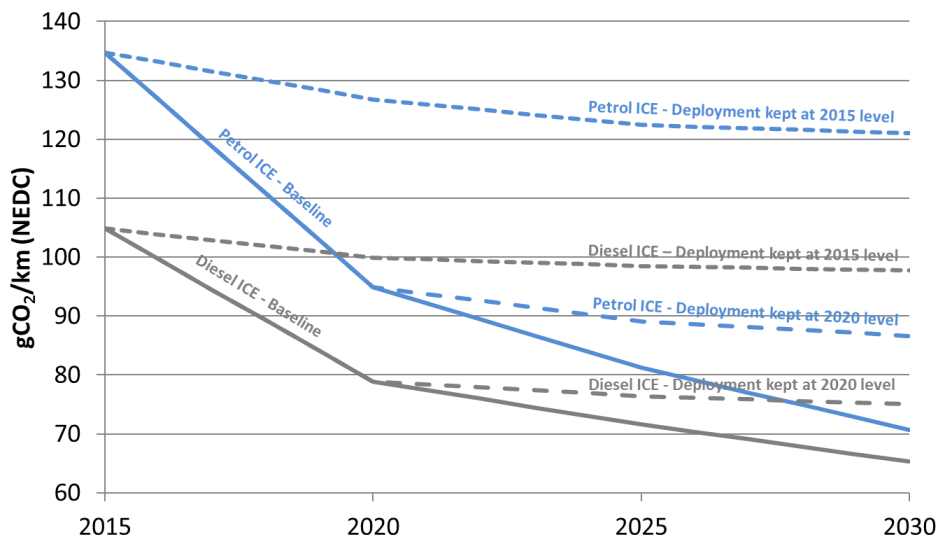
Figure 42: Trend in NEDC CO_2 rating for the alternative scenarios where additional technology deployment is stopped in 2015 and 2020, but improvements to efficiency gain of each technology continued

Figure 42 shows the impact on CO_2 emissions if the efficiency of each technology is allowed to continue to improve at the same rate as in the baseline, without additional deployment from both 2015 and 2020.

Petrol ICE   **Diesel ICE**

| Baseline | €25,025 | €24,503 | €24,555 | €24,161 |

■ Deployment kept at 2015 level   □ Deployment kept at 2020 level

Figure 43: Percentage increase in 4 year TCO for Segment C ICEs without further deployment of efficiency technology from 2015 and 2020, but with continued technology cost and efficiency improvements, versus the baseline ICEs

Even under this "best case" scenario, Segment C petrol and diesel ICE vehicles still fail to become cheaper on a 4 year TCO basis in 2025 and 2030 (Figure 43). Payback periods for the additional technology deployed (Table 8) under both scenarios are within 5 years for all segments. Where deployment is halted from 2015, the payback periods are similar to the scenario where no improvement in technology is forecast. This illustrates the benefit of the technology that is expected to be deployed 2016-2020 in order to meet the 95 gCO$_2$/km target.

Table 8: Payback periods for additional efficiency technology in 2025 baseline vehicle relative to 2015 and 2020 level deployment, efficiency gain of each technology improves at baseline rate

| Baseline 2025 vehicle relative to:	Powertrain	Segment Group	Additional Purchase Price	Fuel Saving, l/100km	First Year Fuel Cost Saving	Payback Period, years
Deployment kept at 2015 level	Petrol ICE	Small (A&B)	€618	1.66	€378	1.8
		Medium (C,D,I)	€733	1.96	€445	1.7
		Large (E,F,G,H)	€814	2.51	€571	1.5
		Average	**€710**	**1.98**	**€450**	**1.7**
	Diesel ICE	Small (A&B)	€306	1.13	€249	1.3
		Medium (C,D,I)	€304	1.52	€335	1.0
		Large (E,F,G,H)	€326	2.07	€456	0.7
		Average	**€310**	**1.51**	**€332**	**1.0**
Deployment kept at 2020 level	Petrol ICE	Small (A&B)	€307	0.39	€89	3.8
		Medium (C,D,I)	€391	0.43	€99	4.5
		Large (E,F,G,H)	€473	0.54	€122	4.4
		Average	**€380**	**0.44**	**€101**	**4.3**
	Diesel ICE	Small (A&B)	€191	0.24	€53	4.0
		Medium (C,D,I)	€236	0.30	€66	3.9
		Large (E,F,G,H)	€291	0.44	€96	3.3
		Average	**€232**	**0.31**	**€68**	**3.8**

elementenergy

If further technology deployment is halted in 2020, but installed technology improves over time at the baseline rate, then payback of the baseline ICEs is noticeably slower and similar to the expected first ownership period of 4 years. Under this methodology, the financial benefit of the baseline ICEs appears to be observed by subsequent owners only. However, in reality a first owner will recoup a large portion of the additional purchase price in the residual value of the car, yet gain all the benefit of the fuel savings. As a consequence, the first owner in all cases will still observe a net financial benefit as shown for Segment C ICEs in Figure 43.

Both sets of alternative deployment scenarios demonstrate the value to the consumer of regulating further efficiency requirements. It should also be recognised that continued deployment of efficiency technology, as in the baseline, has not been assumed to come at the expense of OEM profit margins here. Under the scenarios presented in Figure 41 and Figure 43, the fixed percentage sales margin has been maintained in all cases, and so the more expensive baseline vehicle in fact commands a higher absolute margin. Were this additional margin to be removed then the case for more efficient vehicles would appear even stronger.

7.4 Implications for CO_2 emissions of new cars

The TCO results in this study have implications for efforts to drive further decarbonisation of light vehicles in the 2020s, and in particular to create a growing market for cost-effective, ultra-low emission cars that will be needed to meet long term climate goals. For example, if the cost trends on ultra-low emission vehicles showed very high future costs compared to petrol/diesel cars or hybrid electric vehicles, this sets a lower bound on the emissions from future new cars because very few ULEVs can be deployed without costly incentives or imposing high costs on vehicle buyers. However, the results of our TCO analysis suggests convergence of ownership costs between different powertrains, and this suggests very low average emissions for new cars in the 2020s can be achieved without a high societal cost (and in fact with a net benefit when considered over the full vehicle lifetime).

Figure 44 shows the expected average emissions of ICEs, HEVs and PHEVs assuming no change in segment shares and the petrol/diesel ratios in each segment. The ratio of petrol and diesel shares may change in future due to costs required to meet more stringent limits for NO_x and particulate matter. However, as shown in Figure 5, the efficiency of petrol engines is expected to improve faster than diesel and so the difference in CO_2 emissions eventually becomes relatively small. This makes average emissions fairly insensitive to the future petrol/diesel ratio.

Average ICE Emissions

Average HEV Emissions

Average PHEV Emissions
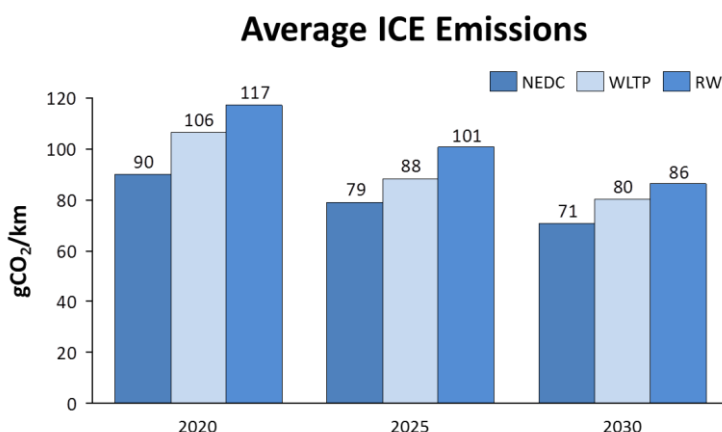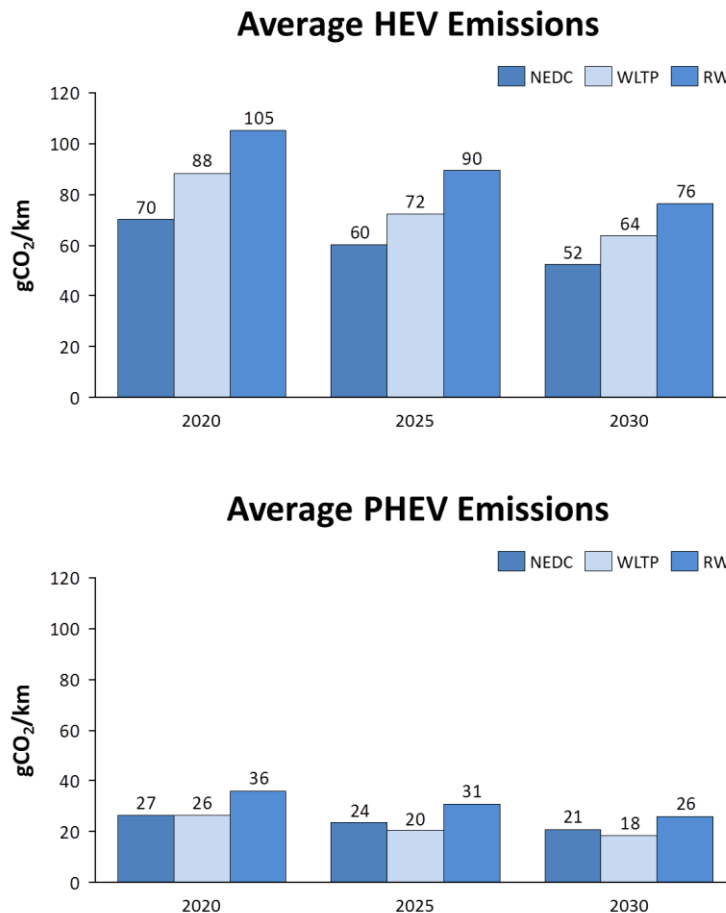
Figure 44: Average emissions (gCO₂/km) of ICEs, HEVs, and PHEVs with 2015 segment shares and petrol/diesel ratio within each segment

Beyond 2020, all cars will be tested solely on the WLTP and compliance with any future emissions target will be based on WLTP CO_2 emissions. The targets discussed here are therefore defined in terms of WLTP. The Ricardo-AEA 2015 Cost Curves dataset provides the efficiency improvements of each technology expressed in WLTP, as well as NEDC and real world, and so the Cost and Performance Model can also be used to output estimated WLTP emissions. Using a similar method as to calculate real world values, the 2015 ICE archetypes are converted to WLTP using conversion factors from ADAC EcoTest laboratory tests[52]. Future values are projected from changes in the WLTP *efficiency factors* (see Section 3.3.2). A further correction must be made to account for the removal of test cycle flexibilities expected to be enforced in the WLTP. These are calculated from a bottom-up analysis of all the factors that influence the real world emissions gap, which identifies those that are unlikely to be passed through to the WLTP.[26] For example, test cycle flexibilities are estimated to account for a 25% decrease in real world to NEDC type-approval emissions in 2014. This is estimated to fall to 11% in the switch to WLTP. Further test cycle optimization is expected between 2020 and 2025, when this grows back to 19%, with no additional change assumed post-2025.

Figure 45 shows average new car emissions in 2025 and 2030, on a WLTP basis, for different levels of uptake of HEVs, PHEVs and BEVs. Average emissions of each powertrain are assumed to be those in the baseline presented in Figure 44. Our analysis suggests that average WLTP emissions of petrol and diesel ICE cars alone will be c.88g/km in 2025 and 80g/km in 2030 (see Figure 44), even with zero deployment of hybrids, PHEVs or BEVs/FCEVs. Deployment of large numbers of pure hybrids (without

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[52] ICCT (2014) The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU

a plug-in capability) would reduce fleet emissions by a further 10g/km, reflecting the relatively low CO_2 savings relative to an increasingly efficient petrol/diesel ICE which includes an increasing degree of micro/mild hybridisation.

Figure 45 shows the market shares of different ratios of HEVs, PHEVs and BEVs required to meet a given new car fleet average emissions level in 2025 and 2030. As an example, the shares required to meet illustrative levels of 75 gCO_2/km in 2025 and 50 gCO_2/km in 2030 (WLTP[53]) are highlighted. These are the estimated levels required to reduce car emissions by 30% between 2005-30, in line with the EU's 2030 Climate and Energy Package which aims to reduce emissions in the non-Emissions Trading Scheme (ETS) sectors by 30% from 2005 levels.
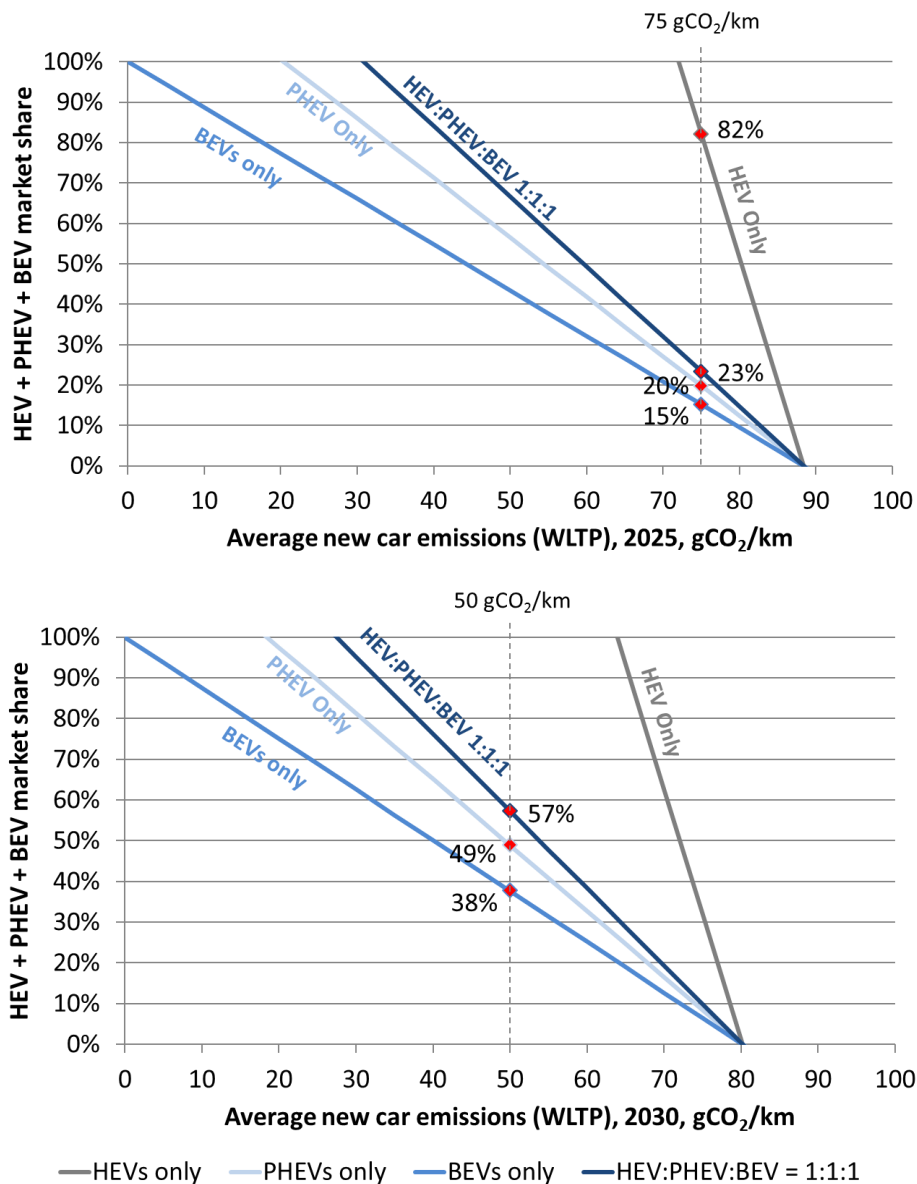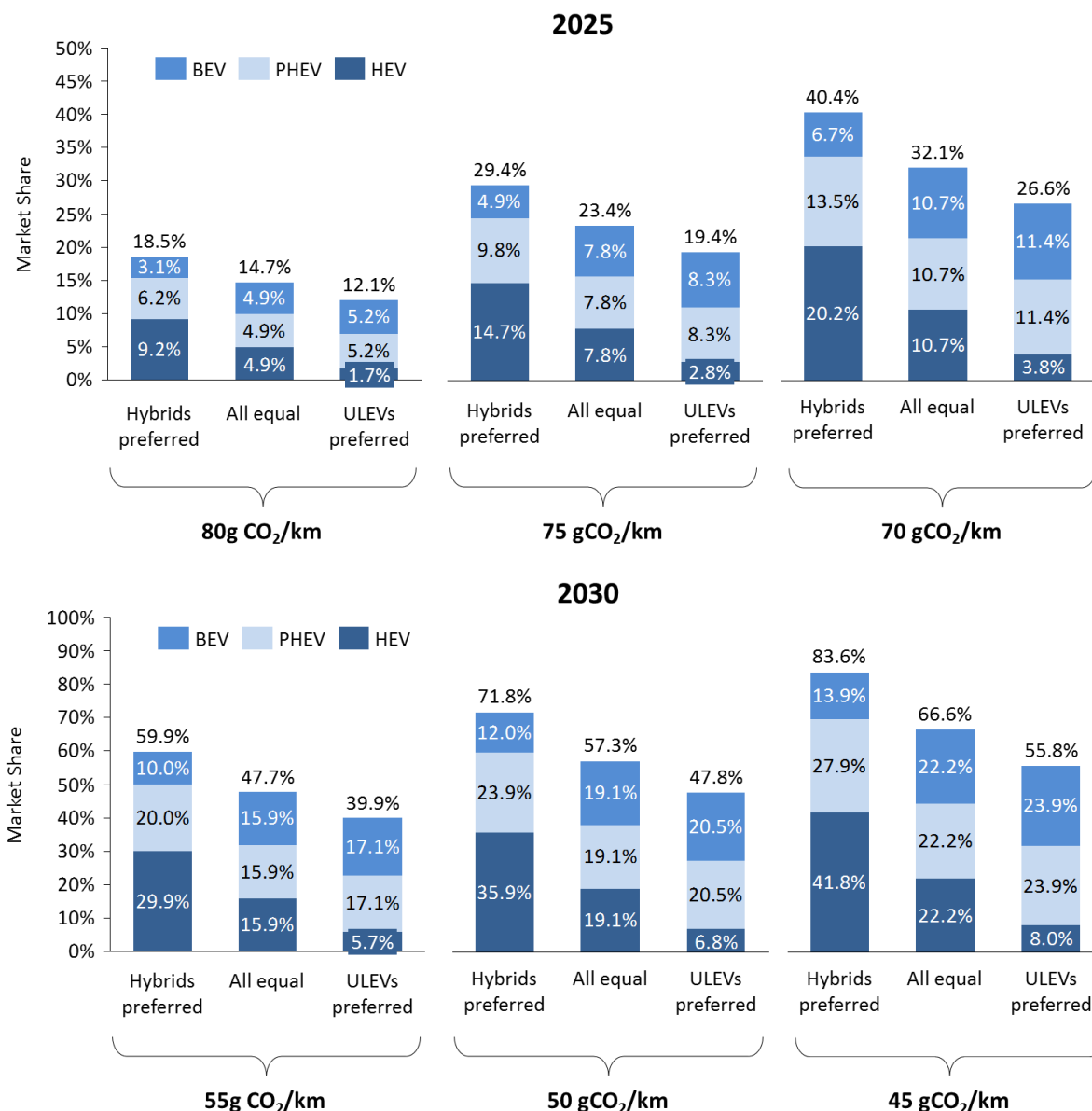

Figure 45: Market shares of HEVs, PHEVs and BEVs required to achieve particular average new car emissions level in 2025 and 2030

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[53] 75 gCO_2/km WLTP target in 2025 equivalent to 65-70 gCO_2/km NEDC, and 50 gCO_2/km WLTP target in 2030 equivalent to 40-45 gCO_2/km NEDC. Exact WLTP to NEDC conversion factor depends on the market share of PHEVs. Large discrepancy between proportion of electric kilometres for PHEVs under NEDC and WLTP adds additional component to NEDC-WLTP gap.

BEVs and PHEVs have a much stronger potential to reduce fleet average emissions compared with HEVs. Introducing HEVs alone can reduce fleet average emissions by only ~15 gCO₂/km in both 2025 and 2030, which it can be seen is insufficient to bring about the level of decarbonisation highlighted. The actual target levels for 2025 and 2030 will depend largely on the how big a share of the EU's 2030 Climate and Energy Package is assigned to the light duty vehicle (LDV) sector. Although a 30% reduction from 2005 levels would represent an equal share with the other non-ETS sectors, the availability of ultra-low and zero emission vehicles may result in LDVs being apportioned a greater requirement to decarbonise. Figure 46 shows the HEV, PHEV and BEV market shares, under different uptake scenarios, that would be required to meet both higher and lower emission levels in 2025 and 2030.

Figure 46: Market shares for HEVs, PHEVs and BEVs required to meet 2025 and 2030 WLTP emissions targets, under different uptake scenarios (Hybrids preferred = 1.5 HEV:1 PHEV: 0.5 BEV; All equal = 1 HEV : 1 PHEV : 1 BEV; ULEVs preferred = 0.5 HEV : 1.5 PHEV : 1.5 BEV)

Achieving lower fleet average CO₂ emissions needs considerably more ultra-low emission vehicles to be sold. For example, in 2030 decreasing emissions by 5 gCO₂/km results in the required market share of a 1:1:1 mixture of HEVs, PHEVs and BEVs increasing by ~10 percentage points. However, the

requirement decreases the more BEVs and PHEVs contribute to this mix and HEV uptake makes only a small difference to the numbers of BEVs and PHEVs needed. For example, for an average of 45 gCO_2/km in 2030, reducing the number of HEVs by a factor of 3 can be compensated for by increasing the market share of BEVs and PHEVs by only 2 percentage points each.

The cost analysis in this study suggests that that the deployment levels of advanced powertrains needed to meet low CO_2 target levels could be achieved based on the relatively small differences in ownership costs. Sales would be more likely determined by other factors such as the availability of models in all vehicle segments and access to a charging infrastructure to provide convenient mobility to ULEV users. If these potential barriers can be addressed, then seeking deep reductions in new car CO_2 emissions is feasible while bringing net financial benefits to car users.

It is clear that in both 2025 and 2030, HEVs do relatively little to lower emissions, relative to the partial hybridisation in future ICEs, and should not be considered an effective tool in achieving aggressive CO_2 reduction in the long term. For the average emissions ranges highlighted (70-80 gCO_2/km in 2025, and 45-55 gCO_2/km in 2030), HEVs alone become insufficient by 2030.

BEVs are unsurprisingly the most effective at reducing emissions and, given their TCO savings compared with PHEVs, deserve the most financial support should it be deemed necessary. Not only do they become highly cost competitive with diesel ICEs on a per vehicle basis, but fewer are needed to reduce fleet average emissions to a particular level. Focussing subsidies that encourage ULEV uptake on BEVs therefore offers the most cost effective strategy.

8 Conclusions and implications

This study has assessed in detail the probable costs of ownership of low and ultra-low emission cars likely to be on the market in Europe in the 2020s. It has used the latest evidence on the trends in technology costs and the potential efficiency improvements of future new cars, as well as realistic scenarios for a range of other ownership costs such as depreciation rates, servicing costs and fuel prices. The results have implications for European consumers as well as policymakers, and the main findings are set out in turn below:

1. Continued improvement in vehicle efficiency makes vehicle ownership cheaper for the consumer.

The total costs of ownership for first, second and third owners are forecast to decrease in the 2020s for all powertrains, even under a backdrop of rising fuel and electricity prices, and stricter air quality standards, particularly for diesel cars. In all years, fuel savings from additional efficiency measures more than offset the higher upfront cost within at least the first four years of ownership. For example, in 2030 a C-segment Petrol ICE with a 2020 technology package is €400 more expensive on a 4-year TCO basis compared with a vehicle with continued technology deployment, even under a best case scenario in which technology costs and efficiency gains improve at the same rates in both vehicles. A summary of the benefits provided by continued efficiency improvements to 2025 is shown in Table 9. The payback period of additional technology deployed between 2015 and 2025 is predicted to be on average 0.7 – 1.7 years, and provide average lifetime fuel savings of €4,410 - €9,360. The exact payback depends on the fuel, segment and extent to which vehicle manufacturers improve already deployed technology. Similarly, the technology deployed between 2020 and 2025 alone offers a payback of 2.0 – 4.3 years on average, saving €910 - €2,510 over the lifetime of the vehicle. This highlights the benefit of continued efficiency improvements into the 2020s.

Table 9: Ranges of costs and benefits of additional efficiency technology in 2025 baseline vehicle relative to no further deployment from 2015 and 2020. Range bounded by scenarios where 1) efficiency gains of already deployed technology improves at rate observed in baseline vehicle, 2) fuel consumption remains constant when further deployment stopped. All values presented are a weighted average across all segments.

Baseline 2025 vehicle relative to:	Powertrain	Additional Purchase Price	First Year Fuel Cost Saving	Payback Period, years	Lifetime (16yr) Fuel Cost Savings
Deployment kept at 2015 level	Petrol ICE	€710	€450 - €712	1.1 - 1.7	€5,914 - €9,362
	Diesel ICE	€310	€332 - €504	0.7 - 1.0	€4,409 - €6,700
	Average	€510	€499	1.1	€6,596
Deployment kept at 2020 level	Petrol ICE	€380	€101 - €191	2.1 - 4.3	€1,322 - €2,506
	Diesel ICE	€232	€68 - €126	2.0 - 3.8	€906 - €1,679
	Average	€306	€121	3.1	€1,603

2. The total costs of ownership for conventional and ultra-low emission powertrains continue to converge in the 2020s, with BEVs becoming highly competitive with all other powertrains when considered over the vehicle lifetime.

Ownership costs for different powertrains are expected to converge in the 2020s, driven primarily by strong falls in the purchase price of ultra-low emission models such as plug-in hybrids and battery electric vehicles. The average 4-year TCO for a battery electric car relative to diesel ICE decreases

from €4,100 in 2015 to €600 in 2025 and €100 in 2030. However, this does not include the potential cost of a residential charge point, estimated at €600-€1,000. The strong potential for improvements in petrol and diesel car efficiency at relatively low cost makes TCO parity challenging on a first owner basis for ultra-low emission powertrains since the advantage of lower running cost from BEVs/PHEVs or fuel cell vehicles is reduced.

However, when taken over the European average vehicle life of 16 years, ultra-low emission vehicles are highly competitive with conventional powertrains. BEVs on average offer a compelling ownership cost, which in 2020 is €7,400 cheaper than a petrol ICE cars and €3,600 cheaper than a diesel ICE. By 2030 this gap has grown to €4,400 for diesel ICEs, and for petrol ICEs stands at €6,900 (however, these values do not include the cost of charge points for each owner or battery replacement). Since depreciation makes a smaller contribution to TCO for second and third owners compared to new vehicle buyers, the low running costs of electrified vehicles could provide significant benefits to lower income citizens who often buy pre-owned vehicles.

The running cost advantage of ultra-low emissions vehicles is also amplified among high mileage users. For example, at 20,000 km the 4 year TCO of a Segment C BEV in 2025 becomes €800 cheaper than a petrol ICE and almost cost equal with diesel ICEs. For PHEVs, maximising the proportion of driving distance covered in 'electric mode' also has a strong impact on ownership costs. Driving c.70% of total kilometres in electric mode compared with 35% (for example if users can charge at a workplace or non-home destination during the day), reduces the 4-year ownership costs by €1,500 in 2015, and €1,000 even in 2030 when overall vehicle energy consumption has declined.

3. Battery costs have a strong impact on the cost of BEVs, while improved efficiency of conventional powertrains reduces exposure to oil price volatility.

Batteries are currently responsible for ~40% of the cost of a medium sized BEV. The TCO results are therefore sensitive to battery cost assumption. If batteries were to become available at a cost similar to the most bullish forecasts by, for example, Tesla and General Motors, BEVs would reach TCO parity with petrol ICEs over the first 4 years of ownership before 2020, although this excludes the cost of a charge point which delays the parity date to between 2020 and 2025. OEMs could instead choose to take advantage of lower battery costs by offering BEVs with higher range, which also offers them a handle through which they can adjust vehicle cost. However, uncertainty still exists over the requirement for battery replacement for BEVs, and work to reduce this risk through ensuring maximum longevity of batteries through more sophisticated battery management systems, designs allowing replacement of modules rather than whole packs, and developing second life applications for used batteries will reduce this cost.

Conversely, the TCO results are relatively insensitive to changes in future oil prices. This is partly due to high European fuel taxes observed in many Member States (compared to the USA, for example) reducing the impact of crude oil price increases, but mainly because of the low fuel consumption of future petrol and diesel cars. This highlights the wider consumer benefits of efficient conventional cars independent of other more advanced powertrains.

4. Efficiency led reductions in vehicle ownership costs provide a low risk environment for ambitious policies to decarbonise light vehicles after 2020.

This analysis suggests that efficient conventional petrol or diesel cars continue to have lower ownership costs than current models even down to CO_2 emissions levels of 70-80g/km on an NEDC basis, as the fuel savings continue to offset any increases in upfront costs. Meanwhile, cost convergence between conventional and ultra-low emission cars for the first owner implies a transition will be possible, allowing a move away from the current relatively high up-front purchase grants or exemption from purchase taxes (e.g. in Scandinavia), and instead towards lower cost measures such as discounts on circulation taxes to offset the remaining TCO gap in the early 2020s. Some of this TCO gap could be covered by

consumers' willingness to pay for the features of electrified vehicles such as reduced vehicle noise, and improved driving performance. Adjusting the fuel duty rates offers a further method to close the TCO gap to EVs and reclaim some of the lost tax revenue which results from fuel efficiency improvements. This is of particular relevance to diesel which, although currently benefits from a European average fuel duty of 43 ¢/litre compared with 55 ¢/litre for petrol. Concerns over air quality may see this trend reverse in favour of petrol or equal taxation on the basis of CO_2 or energy content.

However, ownership costs are only one aspect in the decision making process for new car buyers, and continued effort is also required to address other barriers to electric mobility. This includes increasing coverage of rapid charging stations on major roads (or hydrogen refuelling stations for fuel cell vehicles), working at a city level to find charging solutions for drivers without access to off-street parking, and ensuring convenient roaming access and payment options for charging infrastructure for drivers moving between cities and countries.

Policy makers at every level should recognise the relationship between decarbonisation, local level efforts to improve air quality (e.g. urban area 'low emissions zones'), and reducing European dependence on imported oil which results in more value from consumer spending being retained within the Europe economy.[43] A strong decarbonisation strategy, which necessitates the deployment of ultra-low carbon technology, therefore offers a mutual benefit to both car owners and wider European society.

9   Appendix

9.1   2015 Segment Shares

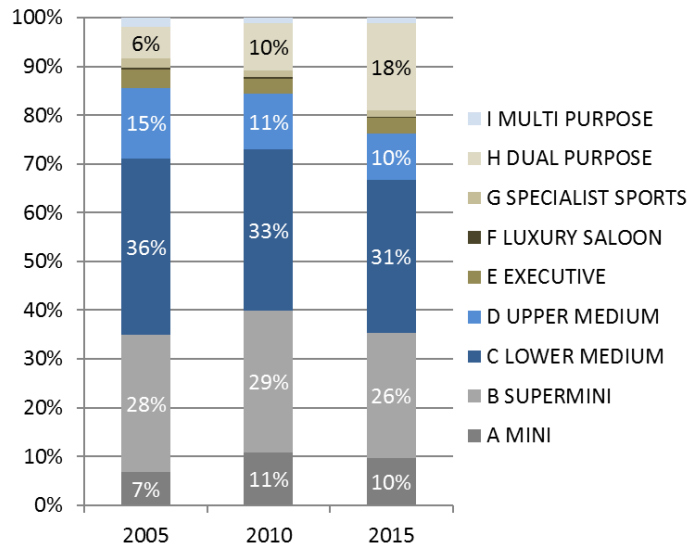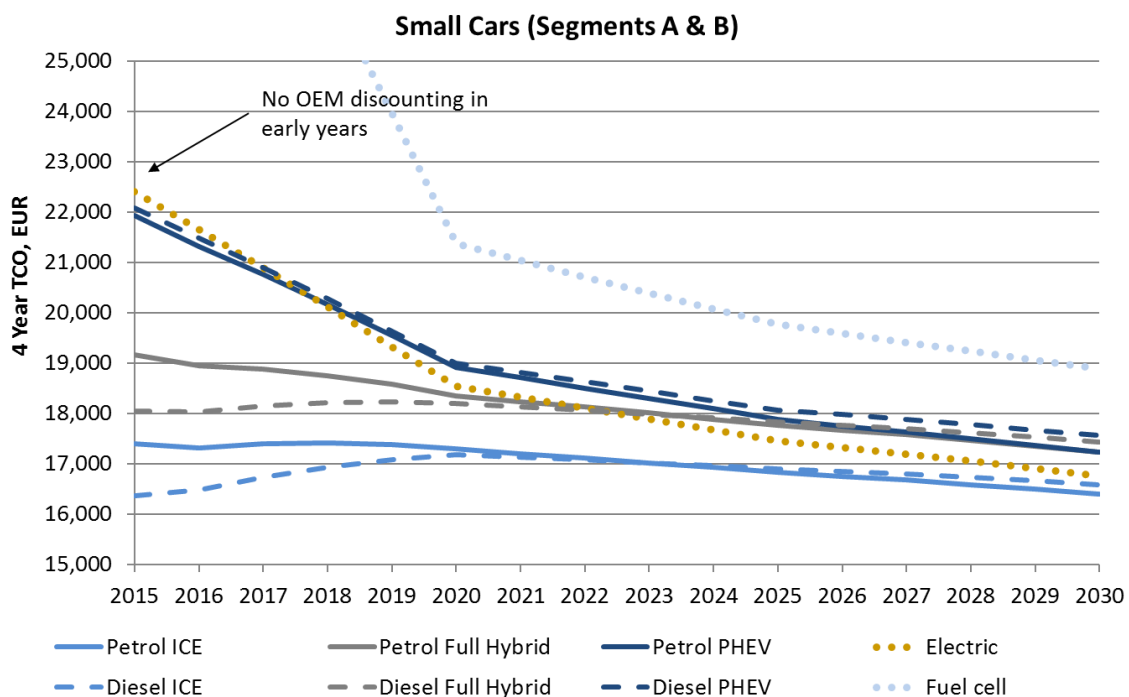Average TCOs for each powertrain are generated by weighting by the 2015 market shares for each segment.

Figure 47: EU-28 Car Segment Shares 2005-2015. Data provided by ICCT

9.2   Change in average 4-year TCOs for small, medium and large cars

As discussed in Section 7.2.1-7.2.2, small cars are relatively more expensive to electrify, and large cars are cheaper. Consequently, the premium of BEVs on a 4-year TCO basis decreases with increasing vehicle size.

Medium Cars (Segments C, D & I)

Legend:
- Petrol ICE
- Diesel ICE
- Petrol Full Hybrid
- Diesel Full Hybrid
- Petrol PHEV
- Diesel PHEV
- Electric
- Fuel cell

Large Cars (Segments E, F, G & H)

Legend:
- Petrol ICE
- Diesel ICE
- Petrol Full Hybrid
- Diesel Full Hybrid
- Petrol PHEV
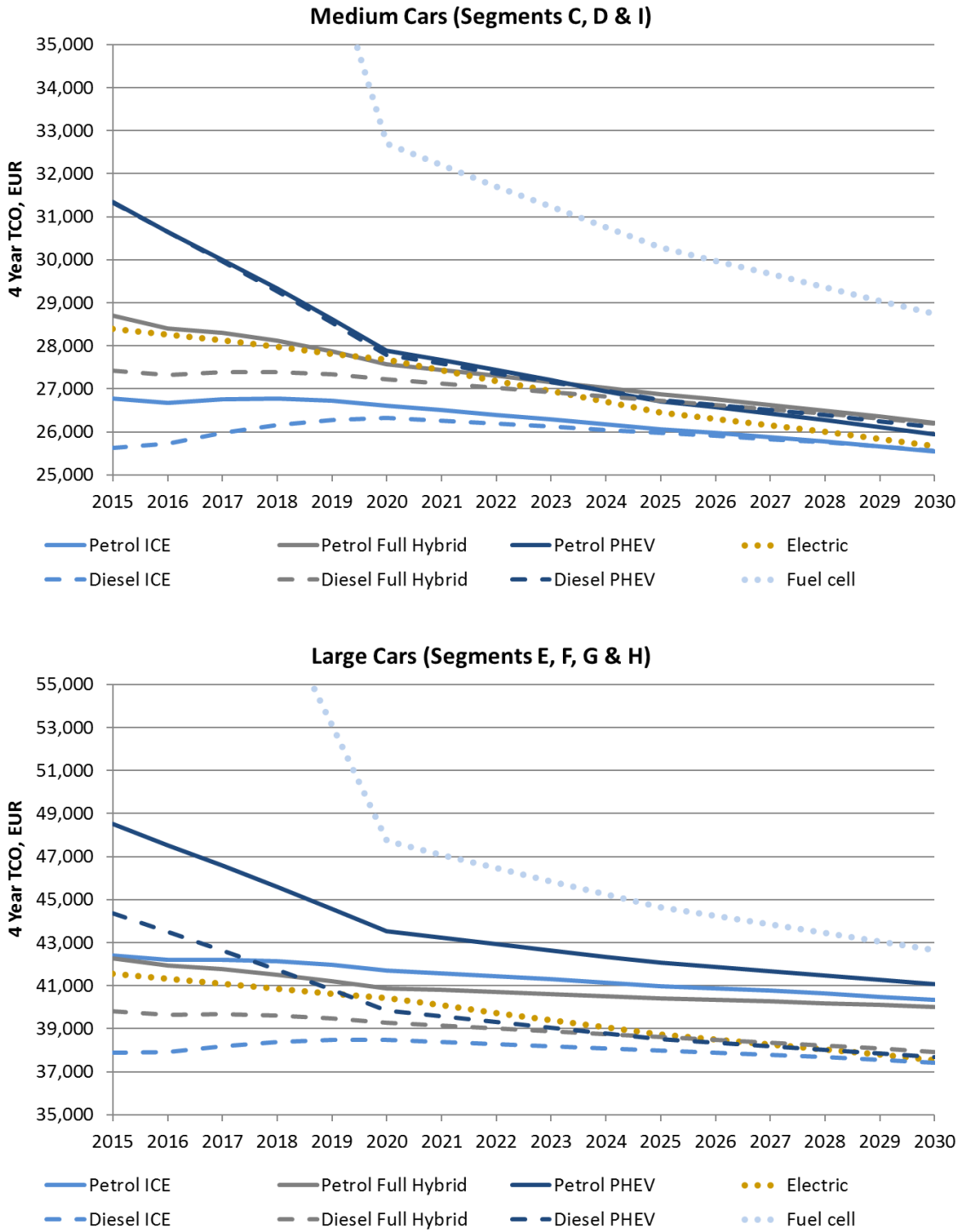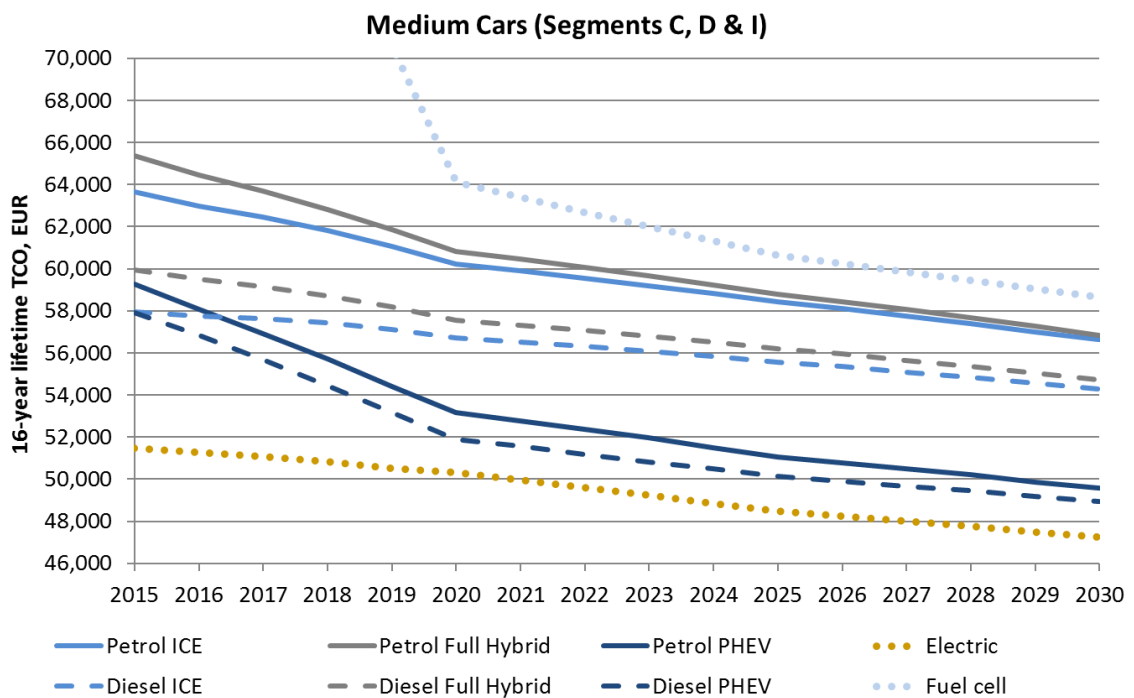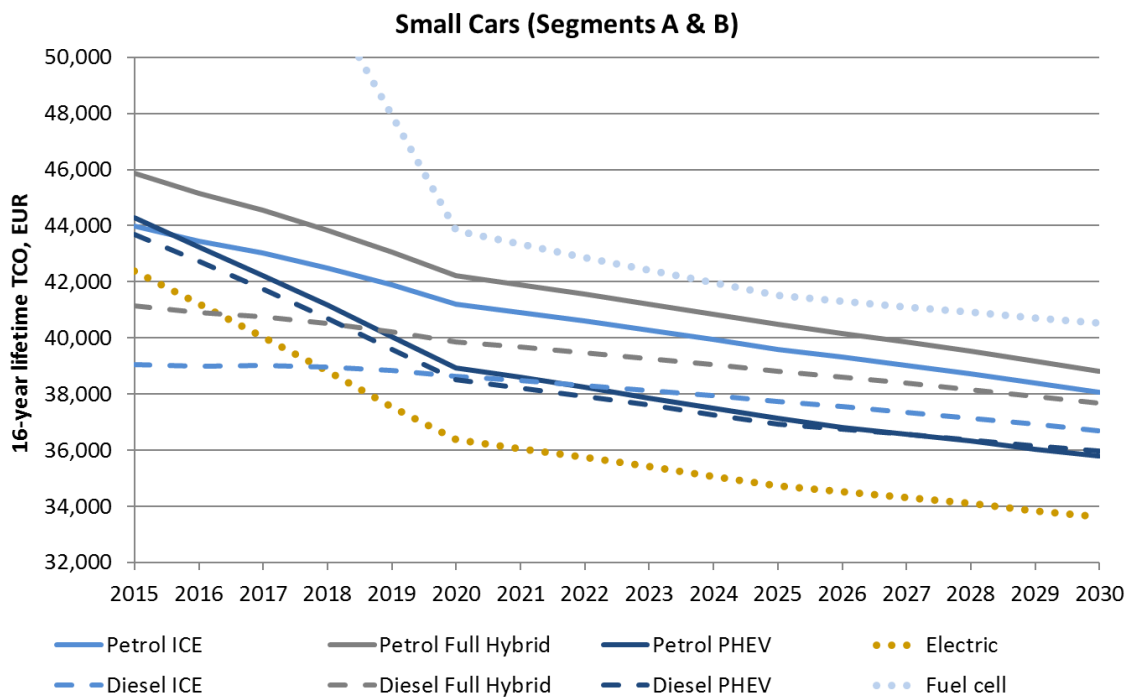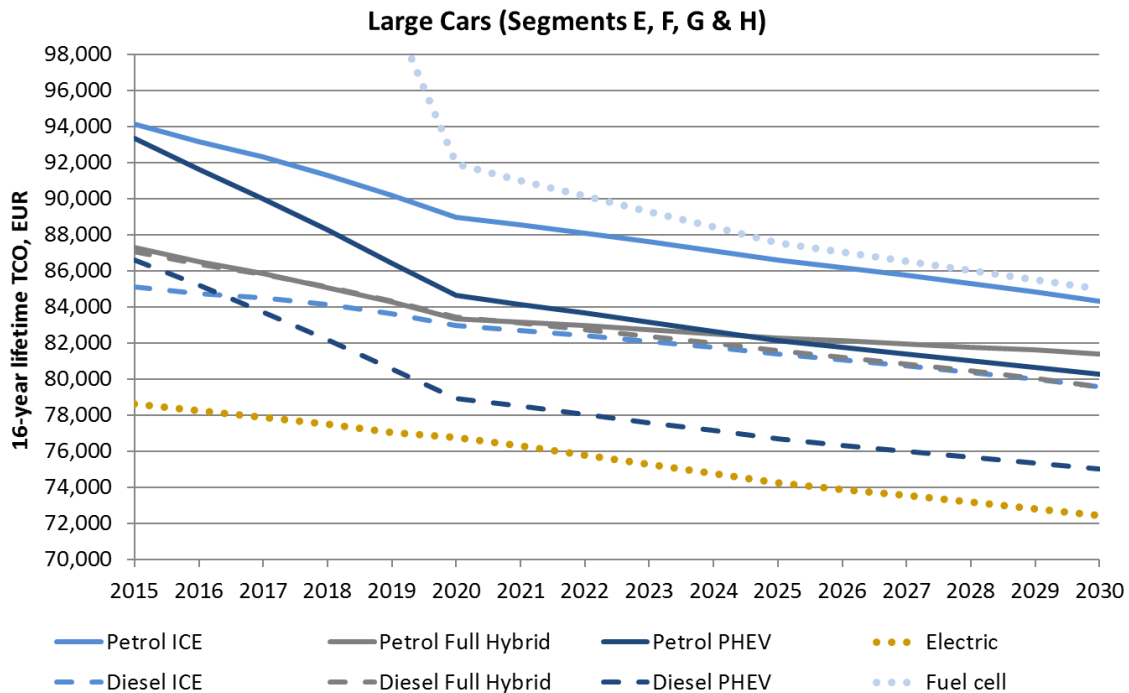- Diesel PHEV
- Electric
- Fuel cell

Figure 48: Average 4-year TCO of each powertrain, weighted by 2015 segment shares, for small, medium and large cars (baseline conditions)

9.3 Change in average lifetime (16-year) TCOs for small, medium and large cars

Small Cars (Segments A & B)

Legend: Petrol ICE, Petrol Full Hybrid, Petrol PHEV, Electric, Diesel ICE, Diesel Full Hybrid, Diesel PHEV, Fuel cell

Medium Cars (Segments C, D & I)

Legend: Petrol ICE, Petrol Full Hybrid, Petrol PHEV, Electric, Diesel ICE, Diesel Full Hybrid, Diesel PHEV, Fuel cell

Large Cars (Segments E, F, G & H)

Figure 49: Average lifetime (16-year) TCO of each powertrain, weighted by 2015 segment shares, for small, medium and large cars (baseline conditions)

Large cars are dominated by Segment H which accounted for 79% of sales in 2015. Segment H has seen significant growth over the last 10 years, from 6% of all sales in 2005 to 18% in 2015, due primarily to the introduction of more compact SUVs. Unlike many large SUVs and Segment E, F and G cars, these are not considered premium cars and are priced more similarly to Segment C and D. Consequently, the same OEM discounting has been applied to Segment H BEVs between 2015 and 2020, and this is largely responsible for the highly competitive lifetime TCO of large BEVs in the early years. However, as major OEMs are yet to bring these vehicles to market it remains to be seen what pricing strategy they employ. The comparatively low lifetime TCO is then sustained throughout the 2020s, despite OEM discounting being removed. This is due to the assumed range of Segment H cars rising to only 300 km in 2025, as per medium sized cars, as opposed to >400 km for the other large segments. Consequently, a smaller and cheaper battery is sufficient.