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Do electric vehicles need subsidies in the UK?

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Do electric vehicles need subsidies in the UK?

Abstract

We analyse the total cost of ownership of petrol, diesel, hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicles in the UK over 2017-2029. We do this for large, medium and small cars, under assumptions of 0%, 6%, 30% and 60% discount rates. We find that some electric car models from mass market brands are close to reaching cost parity with their petrol, diesel and hybrid counterparts, but subsidies would accelerate their uptake, especially for impatient consumers with high discount rates. Plug-in hybrid electric vehicles are not worth the effort because although relatively low, their CO2 emissions are non-zero, and their purchase price is as high or even higher than that of battery electric vehicles. A subsidy of £4,500 or an exemption from the 20% VAT, perhaps capped at £4,500, would accelerate mass market penetration of battery electric vehicles in the UK. If decarbonising road transport were not as urgent as it is, the market for battery electric vehicles could be left to develop on its own, without government intervention. However, because the cost of batteries is not falling fast enough, subsidies are needed in the short term.

Keywords

Total cost of ownership

Electric vehicles

GHG emissions

CO2 emissions

Transport decarbonisation

Life cycle costs

1. Introduction

In 2017, the transport sector was responsible for 27% of total GHG emissions in Europe, two thirds of which were generated by road transport (European Environment Agency, 2019). The Paris Agreement, which came into effect in November 2016, commits developed and developing countries to keeping global warming below 2°C and aspiring to a target of 1.5°C.

In June 2019, the UK became the first major economy in the world to pass net zero emissions legislation (UK Department for Business, Energy & Industrial Strategy, 2020). The target requires the UK to bring all GHG emissions to net zero by 2050. Since decarbonising aviation and shipping by 2050 would be very challenging, cars and vans will need to be completely decarbonised (Transport and the Environment, 2018, p. 8). Decarbonisation of cars and vans cannot be achieved by improving the efficiency of internal combustion engines or replacing petrol and diesel with advanced biofuels or synthetic fuels (Transport and the Environment, 2018, p. 8).

In July 2017, the British government announced that it would "end the sale of all new conventional petrol and diesel cars and vans by 2040" (UK Department for Environment, Food & Rural Affairs and Department for Transport, 2017, p. 1, point 6). In May 2019, the UK Committee on Climate Change stated that 2040 was too late to phase out petrol and diesel cars and vans and recommended all sales to be pure battery electric by 2035 at the latest (UK Committee on Climate Change, 2019). Following this, the government ran a public consultation between February and July 2020, on moving the deadline forward and ending the sale of new petrol, diesel and hybrid cars and vans by 2035 or earlier (UK Department for Transport and Office for Low Emission Vehicles, 2020a). However, there is no clear plan on how to achieve the 2040 target, let alone the 2035 one, except for 'The Road to Zero: Next steps towards cleaner road transport and delivering our Industrial Strategy' (UK Department for Transport, 2018a), which lists a number of policies in very broad terms, including regulation, affordability and consumer information. The document, published in July 2018, claimed that the government would "continue to bring down the cost of purchasing and owning ultra-low emission vehicles through grants and other incentives" (UK Department for Transport, 2018a, p. 42), but in October that same year, the grants were reduced (UK Office for Low Emission Vehicles, 2018b).

Battery electric vehicles, which as discussed below, are seen as the way forward, have a higher purchase price than conventional vehicles, due to the cost of the battery. This has been a significant hurdle limiting consumer's uptake of electric vehicles (International Energy Agency, 2018, p. 68; Gómez Vilchez et al., 2019). Thanks to the effects of learning and economies of scale, battery costs declined by approximately 14% per year between 2007 and 2014, from above US$1,000 per kWh to around US$410 per kWh (Nykvist and Nilsson, 2015). In the year 2017 the costs varied between US$360 per kWh to US$155 per kWh and the cost forecast for 2030 is US$100 per kWh to US$122 per kWh (International Energy Agency, 2018, pp. 66-67). The reduction in battery costs has helped reduce the initial price tag of electric vehicles somewhat.

Given the commitments made in the Paris Agreement and the UK government announcement to end the sale of all new conventional cars and vans by 2040 (or, pending the results of the 2020 consultation, by 2035), it is surprising that little attention has been devoted to putting together a policy package to ensure consumers in large numbers will be willing (which in economics also means "able to afford") to buy clean vehicles. Even the UK Committee on

Climate Change (2019, p. 11), describes the plans for delivering the 2040 target as “too vague.” Against this backdrop, it is important to understand whether electric vehicles need subsidies in the UK and if so, of how much.

We address this question by comparing the total costs of ownership (TCO) of petrol, diesel, hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicles bought in the UK in 2017. We do this for three different car sizes: large, medium and small. For each car size and propulsion type we use the model with the highest number of registrations in 2017. We find that the lower operating costs of plug-in hybrid and battery electric vehicles do not completely offset their higher purchase price for the car models selected. We then extend the analysis in Appendix B to include lower priced electric vehicles, and find that although some have virtually reached or are close to reaching cost parity, subsidies would accelerate their market penetration. Plug-in hybrid electric vehicles may be not worth the effort, however, because although they cause substantially lower CO2 emissions, they still cause some, and their purchase price is as high or even higher than that of battery electric vehicles.

One important methodological contribution of the present study is that, unlike most previous TCO calculations, it excludes all current taxes and subsidies to start with. This is important because taxes and subsidies distort relative prices, regardless of whether changing relative prices was the objective of the government or not. What matters for policy is how the TCO of cleaner technologies compares with the TCO of conventional ones, and whether lower operating costs compensate for a higher initial purchase price. It is only on the basis of net TCO that a sensible policy package can be put together. After computing the TCO exclusive of taxes and subsidies, current taxes and subsidies are added on to the calculation, to understand whether the current package is helping to narrow or eliminate the gap, which it is. This result, however, is very sensitive to the initial purchase price. The higher the initial price, the higher the subsidy needed to close the TCO gap.

In addition to the above, the study makes two important contributions on the policy front: first, it compares the TCO of small, medium and large cars on different propulsion systems in the UK, and, second, it highlights the importance of subsidies in relation to the initial purchase price.

The paper proceeds as follows. Section 2 critically reviews previous work. Section 3 describes the model and the data. Section 4 presents the results, and Section 5 concludes and provides some policy recommendations. In addition, the paper has three appendices: Appendix A lists the car manufacturers' websites; Appendix B contains an extensive sensitivity analysis and an extended analysis to include six additional car models, and Appendix C contains a comparison of the specific car models used in this study.

2. Previous work

Decarbonising the road transport sector will require mass penetration of alternative technologies, and electric vehicles (EVs) are seen as a very promising option (Diao et al., 2016; Hagman et al., 2016; Andwari et al., 2017; Hardman et al., 2017; Hao et al., 2017; Wang et al., 2017; Cavallaro et al., 2018; Gómez Vilchez et al., 2019; He et al., 2019; Li et al., 2020). However, the price of EVs is high relative to that of conventional petrol and diesel cars. Their running costs, however, are lower.

In 2017, 2018, and 2019, 1.7%, 2.1%, and 2.7% of newly registered vehicles in the UK were either plug-in hybrid or battery electric (UK Department for Transport, 2018c, 2019a, 2020a). Although there is an increasing trend, the numbers are still low. The UK is not the only country with such a low share and the literature has devoted some attention to potential reasons, such as consumers being sceptical about unfamiliar technologies (Carley et al., 2013) or anxious about battery range and charging infrastructure (Sierzchula et al., 2014; Lieven, 2015; Bonges III and Lusk, 2016; Mersky et al., 2016; Egbue et al., 2017; Liao et al., 2017; Wang et al., 2017). Policy can certainly help in those areas (Liao et al., 2017; Santos and Davies, 2020) and there is evidence that it does (Mersky et al., 2016; Rietmann and Lieven, 2019).

Another important possible reason that has also been considered extensively in the literature is that consumers may simply be failing to take operating costs into account altogether. In fact, this issue has been examined for a number of years, not just in relation to EVs but, going further back in time, in relation to vehicles with higher fuel efficiency, and also in relation to appliances more generally, and their energy consumption, with Hausman (1979) starting this tradition. Turrentine and Kurani (2007), Sovacool and Hirsh (2009) and Allcott (2011), for example, argue that consumers do not analyse their fuel costs in a systematic way in their vehicle purchases. For those who do, not much is known about how they estimate the value of improved fuel economy and factor it in their purchasing decisions (Greene et al., 2005, p. 758; Greene, 2010, p. vi).

The sticky issue on which there is much controversy is the implicit discount rate. Gallagher and Muehlegger (2011) compare consumer response to changes in petrol prices and upfront payments, in the form of sales tax waivers, and estimate an implicit discount rate of 14.6%, whilst Busse et al. (2013) analyse the effect of petrol prices on short-run equilibrium prices of cars of different fuel economies and find implicit discount rates under 10%, with some being very small or even negative (!), meaning that future fuel costs are not discounted but compounded. This great variation in estimated implicit discount rates is further evidenced by Greene (2010), who reviews 27 econometric studies that directly or indirectly estimate the value consumers place on fuel economy. The implicit discount rates from those 27 studies vary from 0.2% to over 60% (Greene, 2010, p. xi). The two most important conclusions from Greene (2010) are that (a) some consumers significantly undervalue future fuel savings, some fully value future fuel savings, and some significantly overvalue future fuel savings; and (b) the literature has consistently yielded widely varying estimates of discount rates over a period of more than three decades, and this suggests that there is "either an empirical problem in estimating the value consumers place on fuel economy, or that the presumed theory of consumer behaviour is incorrect, or both" (Greene, 2010, p. vii).

Although Busse et al. (2013) conclude that there is little evidence that consumers are myopic, in a recent and more comprehensive review of the reasons for the (somewhat disappointing) adoption of energy-efficient technologies by individuals and firms, Gerarden et al. (2017) find evidence of inattention and/or myopia. On similar lines, Leard (2018) highlights the issue of inattention, and finds that inattentive consumers make choices as if they undervalued fuel cost savings, or simply as if they did not pay attention to fuel costs, and attentive consumers make choices as if they fully valued these savings. Unsurprisingly, those consumers who do not drive much are less likely to pay attention to fuel costs (Leard, 2018). This is in line with results by Santos and Davies (2020), who find that fleet operators are more attentive than other drivers to fuel costs (and taxes), probably because their businesses revolve around driving long distances. The problem of consumers not realising that in the long run the savings in operating costs may offset at least part of the initial price could potentially be solved by supplying them with information on the TCO in promotional materials or car labels (Dumortier et al., 2015).

The question, however, is, even if all consumers behaved rationally and discounted operating costs at the time of choosing a car to purchase, or were provided with information on the TCO, and even if there were consistency across the literature regarding implicit discount rates, do the lower operating costs of EVs compensate their higher purchase price, within a reasonable period of time? This is by far the most pressing issue at the moment, evidenced by the increasing number of studies, namely under the umbrella of TCO, trying to answer exactly that very question.

Liu and Santos (2015), for example, compare TCO for cars on different propulsion systems in the US and conclude that cleaner technologies are more expensive than conventional ones, a result that also holds after taking into account the climate change costs of CO2 emissions. Using much more detailed data, Breetz and Salon (2018) analyse the five-year TCO for conventional, hybrid, and electric vehicles in 14 US cities from 2011 to 2015. They find that the lower operating costs of battery electric vehicles are not enough to make up for their high purchase price, and conclude that subsidies are needed. Their careful study is city-specific, as incentives vary across cities in the US.

Zhao et al. (2015) compute TCO and conclude that battery electric vehicles are not competitive with conventional vehicles in China even after taking the central government subsidies into account. Diao et al. (2016) also highlight the importance of subsidies to battery electric vehicles in China. The TCO they compute are higher for battery electric vehicles than for conventional ones, even though they include the (monetised) benefits that battery electric vehicles enjoy in the form of exemptions from license plate and driving restrictions.[1] Hao et al. (2017) also find that for the Chinese case, TCO are higher for battery electric vehicles and emphasise the important role of policy, including subsidies.

Palmer et al. (2018) calculate TCO for conventional, hybrid, plug-in hybrid and battery electric vehicles in the UK, in California and Texas for the US, and in Japan, for the period 1997-2015, and find that subsidies are indeed important, and have allowed battery electric vehicles to reach cost parity in the UK, California and Texas, but this is not the case for plug-in hybrid electric vehicles, which have not received as much financial support.

On the same lines, Bubeck et al. (2016) model TCO for Germany, and conclude that plug-in hybrid electric vehicles and battery electric vehicles are not competitive and need substantial subsidies from the government. Danielis et al. (2018) and Scorrano et al. (2020) also estimate TCO, but for Italy, and find that battery electric cars are not cost-competitive with petrol or diesel cars. However, when subsidies are included in the calculations, battery electric cars break even with some diesel cars. Weldon et al. (2018) reach a similar conclusion for Ireland, when comparing TCO of battery electric cars and internal combustion engine ones. Hagman et al. (2016) conduct a similar exercise for Sweden and also find that government subsidies are pivotal in making battery electric vehicles competitive with internal combustion engine and hybrid ones.

[1] Vehicle purchase restrictions are essentially a cap on the total number of vehicles that can be sold in a year, and driving restrictions are bans from circulation in urban areas imposed on certain number plates on some days. These policies are in place in a number of Chinese cities.

In a more sophisticated study, Lévay et al. (2017) estimate TCO for a number of electric vehicle-internal combustion engine vehicle pairs to make cross-segment and cross-country comparisons in France, Germany, Hungary, Italy, Norway, Poland, the Netherlands, and the United Kingdom. They find that subsidies and/or tax breaks are essential in making electric vehicles competitive with internal combustion engine ones, and although they do not have enough observations to conduct a statistical analysis, their descriptive analysis shows that there is an association between fiscal incentives and electric vehicle market share.

The present study applies this well-known TCO technique to the UK case, but, as explained in Section 1, it differs from previous studies in that it excludes all current taxes and subsidies in the baseline calculations, it compares the TCO of small, medium and large cars running on different propulsion systems, and then assesses the impact of current taxes and subsidies on closing the gap in TCO, which is important to accelerate EV market penetration.

3. Model and data

This section details the model that we used, the vehicles that we chose to compare and why, and the data sources.

3.1 Total costs of ownership

We calculate the Total Cost of Ownership (TCO) for a car bought in 2017 with the following standard formula:

$$TCO = \sum_{t=0}^{t=12} \frac{C_t}{(1+r)^t}$$

where *C* is cost and includes the vehicle purchase price, fuel and electricity costs and non-fuel operating costs in the baseline calculations, minus purchase subsidies plus energy and vehicle taxes in an extended model, plus the cost of CO2 emissions in a further extension; *t* indicates the year and varies from year 0 (2017) to year 12 (2029), and *r* is the discount rate, for which we assume four different values (0%, 6%, 30% and 60%). The rationale for choosing these values is that they span the range found in previous work (Greene, 2010, p. xi), as discussed in Section 2. All monetary values are expressed in 2017 prices.[2]

The reason for modelling up to the year 2029 was that we assumed that the lifetime mileage of a battery electric vehicle, defined as the total distance a car is driven during its entire life, was 100,000 miles (or 161,000 kilometres), which considering the annual distances driven, as described below, would make 2029 the year when the car would need to be scrapped/replaced. The assumption of 100,000 miles (or 161,000 kilometres) is in line with the literature. The International Energy Agency (2018, p. 62) estimates battery life at around 175,000 km. Newbery and Strbac (2016, p.3) assume an EV battery life of 170,000 km. However, many of the manufacturers' warranties on batteries are fixed for 100,000 miles or 161,000 kilometres (Safari, 2018, p. 56; Wu et al., 2015, p. 200).

For modelling purposes, the average distance travelled by cars in the UK for 2017, 7,800 miles (or 12,553 km) per car per year, was taken from Table NTS0901 from the National Travel

[2] All relevant conversions were made using the GDP deflator from the UK Office for National Statistics (2020).

Survey (NTS), published by the UK Department for Transport (2018d). This average distance is set to both decrease, due to an increase in the prices of energy (petrol, diesel and electricity), and increase, due to an increase in income per capita. The net increase will depend on both price and income elasticities, as shown in Table 1 and discussed further down.

Income, fuel and electricity price projections were taken from UK government publications, as detailed below. The elasticities of distance travelled with respect to energy prices and with respect to income were used in order to estimate how annual distance travelled will evolve over the years. The elasticity of distance travelled with respect to energy prices was assumed to be -0.10 and the elasticity of distance travelled with respect to income was assumed to be 0.005. The values were taken from Goodwin et al. (2004), Tables 3 (p. 282) and 5 (p. 284), respectively.[3] Table 3 in Goodwin et al. (2004) reports fuel price elasticities rather than electricity price elasticities, so, for this reason, we conducted a sensitivity test by doubling and halving both the elasticity of distance travelled with respect to energy prices and the income elasticity, and these changes made virtually no difference. Although our benchmark model excludes all taxes, we projected distance driven over the period by applying elasticities to fuel and electricity prices with and without taxes, to test for sensitivity. In all six cases cars reach about 100,000 miles in 2029, as Table 1 shows.

[3] The central value of the income elasticity on Table 5 (p. 284) in Goodwin et al. (2004) is actually negative and counter-intuitive, so the highest possible value reported there was used instead.

Table 1: Total distance driven in miles per vehicle in the UK 2017-2029 (projected)

	Total distance driven		
	Central elasticities	Doubled elasticities	Halved elasticities
Without taxes	100,346	99,308	100,871
With taxes	100,553	99,716	100,975

Source: own calculations

Income projections for the period 2017 to 2029 were taken from the Annual Parameters Table of the WebTAG Data Book (UK Department for Transport, 2018e).

The costs included in *C* are purchase price, fuel/electricity costs, and non-fuel operating costs.

In contrast with the United States, where costs vary by state and even city, in the UK, costs are the same throughout the country, as are all taxes and subsidies on vehicles and energy. Also, unlike China, the UK does not have any vehicle purchase restrictions or driving restrictions in place,[4] which Diao et al. (2016) monetise and include in their TCO calculations.

The congestion charge in London, from which plug-in hybrid electric vehicles and battery electric vehicles are exempt, can be ignored in the TCO calculations for two reasons: (a) the exemptions for plug-in hybrid electric vehicles and battery electric vehicles are set to be

[4] Many towns and cities in the UK are considering clean air zones but none have been implemented at the time of writing this paper, except for the London Ultra Low Emission Zone, which only affects petrol cars that do not meet the Euro 4 standard, which became mandatory in 2005, and diesel cars that do not meet the Euro 6 standard, which became mandatory in September 2015.

terminated in 2021 and 2025, respectively (Transport for London, 2020); and (b) only 0.27% of all cars registered in the UK use the congestion charging zone in London.[5]

Finally, there are only a very small number of embryonic schemes in some English towns and cities, and boroughs in London, offering free parking to electric vehicles. We cannot add these to the TCO because such schemes are very few, very small, and there are no data on uptake or savings.

To summarise, the costs included in *C* and discussed below are purchase price, fuel/electricity costs, and non-fuel operating costs. There are clear guidelines from the government on depreciation costs for conventional and electric vehicles, which are embedded in the non-fuel operating costs, as explained in Section 3.1.3.

3.1.1 Purchase price

The purchase price for each of the vehicles we modelled was taken from the manufacturers' websites. The prices are detailed in Table 4 and the manufacturers' websites are listed in Appendix A.

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[5] This was computed as 85,854, the total number of cars using the charging zone daily in September 2019 (Transport for London, 2019, p. 184, Table 10.6), divided by 31.89 million, the total number of cars (of all ages) registered in the UK in 2019 (UK Department for Transport, 2020b, Table VEH0207).

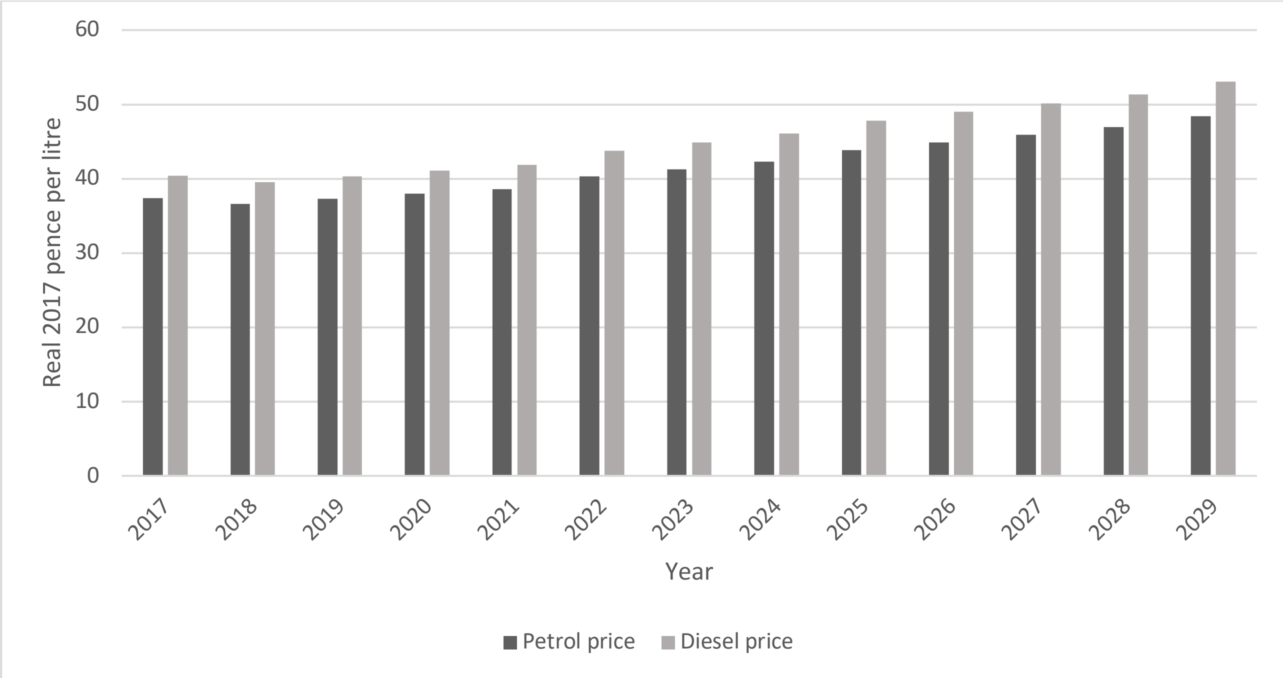
3.1.2 Fuel/energy costs

The fuel and domestic electricity prices for the period 2017-2029 were taken from Table A 1.3.7 of the WebTAG Data Book (UK Department for Transport, 2018e). These are disaggregated by net price, duty and VAT, and correspond to UK government forecasts. Commercial electricity prices were taken from Table 4 of the set of tables supporting the Treasury Green Book Supplementary Appraisal Guidance on Valuing Energy Use and GHG Emissions (UK Department for Business, Energy & Industrial Strategy, 2017). Commercial electricity prices are not subject to VAT but are subject to the Climate Change Levy, which is a tax on energy delivered to non-domestic users, with the aim of providing an incentive to increase energy efficiency and reduce CO2 emissions. The Climate Change Levy was removed from commercial electricity prices. The Climate Change Levy for 2017, 2018 and 2019 is available from HM Revenue & Customs (2016). Since the UK government does not provide any projections for the Climate Change Levy, the 2019 levy was removed from commercial electricity prices for the remaining of the period modelled.

Both commercial and domestic (also known as residential) electricity prices were used because drivers may charge their batteries at home or in a charging station provided by the employer or a charging point in a service station or on the road. Following Liu and Santos (2015), we assumed that 2/3 of charging was done at home and 1/3 of charging was done at work or at commercial stations, but we also tested for sensitivity with respect to this assumption, by re-estimating the results assuming (a) all charging was done at home, and (b) all charging was done at work or commercial stations. The results are virtually the same under any of the assumptions, showing the model is not sensitive to where the batteries are charged, i.e., to domestic versus commercial electricity prices. The results of this sensitivity analysis are presented in Appendix B.

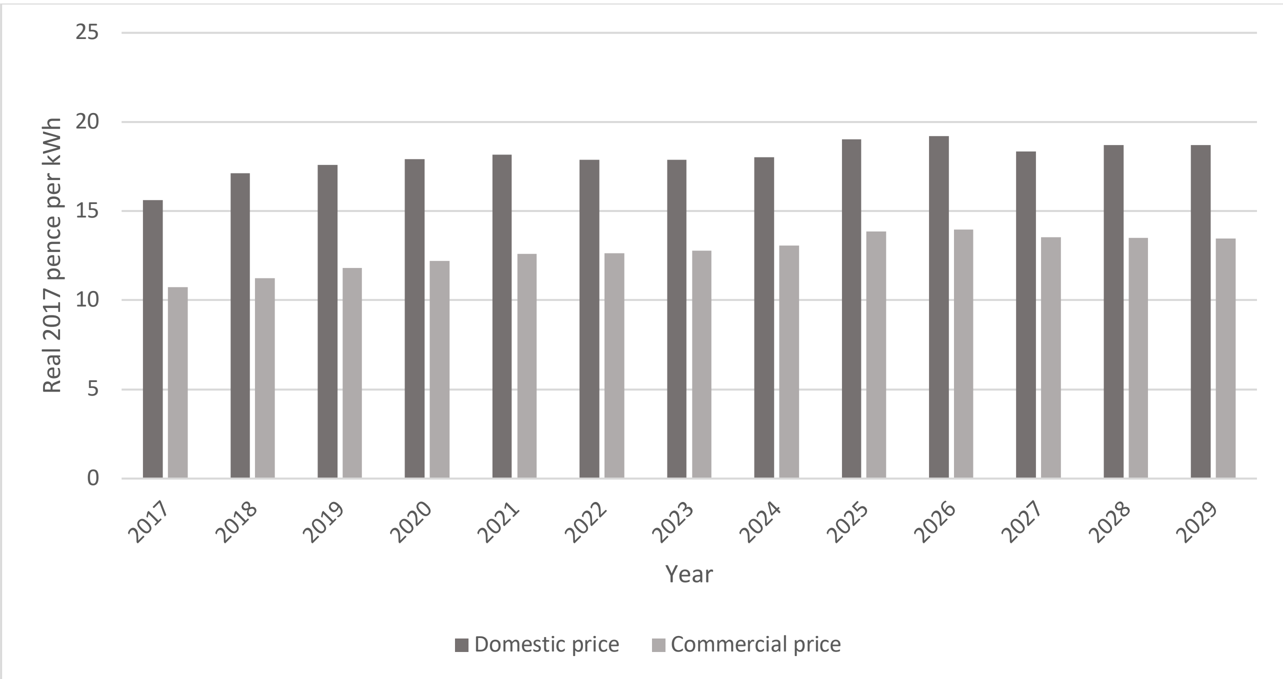
Figures 1 and 2 show fuel and electricity prices, all of which are forecast to increase in real terms over the period modelled.

Figure 1: Petrol and diesel prices 2017-2029, excluding all taxes



Source: UK Department for Transport, 2018e, Table A 1.3.7

Figure 2: Commercial and domestic electricity prices 2017-2029, excluding all taxes



Source: UK Department for Transport, 2018e, Table A 1.3.7 (domestic prices) and UK Department for Business, Energy & Industrial Strategy, 2017, Table 4 (commercial prices)

3.1.3 Non-fuel operating costs

In line with the UK Department for Transport (2018e), non-fuel operating costs were assumed to include oil, tyres, maintenance, depreciation and vehicle capital saving (only for vehicles in working time). We also used the formula proposed by the UK Department for Transport (2018e), as follows:

$$C = a + b/V$$

where C is cost in pence per km, V is average speed in km per hour, a is a parameter for distance related costs, and b is a parameter for vehicle capital saving (only relevant to working vehicles).

The a and b parameters for the period in question were taken from Tables A 1.3.14 and A 1.3.15 of the WebTAG Data Book (UK Department for Transport, 2018e). We also assumed that the percentage of car travel in working time was 12% and the percentage of car travel in non-working time was 88%, in line with Table A 1.3.4 of the WebTAG Data Book (UK Department for Transport, 2018e).

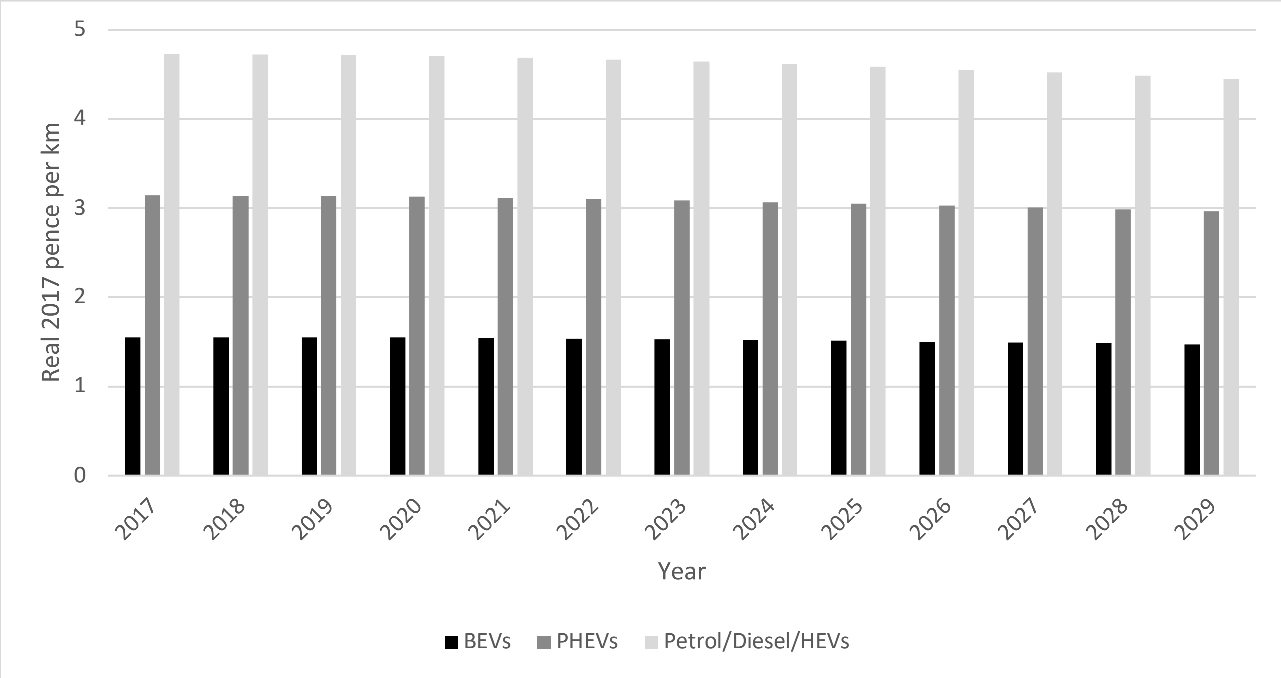
The average speed was estimated as a weighted average of speeds by type of road, taken from Table SPE0112 of speed statistics (UK Department for Transport, 2018f). The share of traffic by road was taken from Table TRA0104 of road traffic statistics (UK Department for Transport, 2018g) and was assumed to be constant throughout the period. We conducted sensitivity tests but the results stay virtually the same when the speed is doubled or halved, as shown in Appendix B.

Table A 1.3.15 of the WebTAG Data Book (UK Department for Transport, 2018e) provides a forecast trend of non-fuel costs for petrol and diesel cars but no such forecast for electric cars. Because of this, we used the base value for 2017 for electric cars, calculated using the parameters from Table A 1.3.14, and then created a series by applying the same annual change of the forecast for petrol and diesel car non-fuel costs.

Non-fuel operating costs for hybrid electric vehicles (HEVs) were assumed to be the same as those for petrol and diesel because they produce electricity whilst running on petrol and diesel. Non-fuel operating costs for plug-in hybrid electric vehicles (PHEVs) were assumed to be an average of non-fuel operating costs for conventional cars and non-fuel operating costs for battery electric vehicles (BEVs) because PHEVs have a dual powertrain.

Figure 3 shows non-fuel operating costs for the cars modelled over 2017-2029.

Figure 3: Non-fuel operating costs



Source: estimated by the authors, as explained in the text, using data from the UK Department for Transport, 2018e (Tables A 1.3.14, A 1.3.15 and A 1.3.4), UK Department for Transport, 2018f (Table SPE0112) and UK Department for Transport, 2018g (Table TRA0104)

3.1.4 Taxes and subsidies

All taxes and subsidies were excluded from our baseline calculations and only included at a later stage to check whether they help and whether any changes are needed.

As explained in Section 3.1.2, petrol and diesel taxes and domestic electricity taxes for the period 2017-2029 were taken from Table A 1.3.7 of the WebTAG Data Book (UK Department for Transport, 2018e), and the Climate Change Levy, from HM Revenue & Customs (2016), which only contains the levy up to 2019. Since the UK government has not published its planned Climate Change Levy up to 2029, the 2019 amount was assumed for 2020-2029. Table 2 presents all petrol, diesel and electricity taxes.

Table 2: Petrol, diesel and electricity taxes, in 2017 prices

Year	Petrol and diesel duty (pence/litre)	Petrol and diesel VAT %	Domestic electricity duty (pence/kWh)	Commercial electricity duty (pence/kWh)	Domestic electricity VAT %	Commercial electricity VAT %	Domestic electricity CCL (pence/kWh)	Commercial electricity CCL (pence/kWh)
2017	58.15	20	0	0	5	0	0	0.568
2018	58.73	20	0	0	5	0	0	0.583
2019	59.84	20	0	0	5	0	0	0.847
2020	60.68	20	0	0	5	0	0	0.847
2021	61.38	20	0	0	5	0	0	0.847
2022	62.17	20	0	0	5	0	0	0.847
2023	62.75	20	0	0	5	0	0	0.847
2024	63.35	20	0	0	5	0	0	0.847
2025	63.96	20	0	0	5	0	0	0.847
2026	64.57	20	0	0	5	0	0	0.847
2027	65.19	20	0	0	5	0	0	0.847
2028	65.82	20	0	0	5	0	0	0.847
2029	66.46	20	0	0	5	0	0	0.847

Source: UK Department for Transport (2018e, Table A 1.3.7) and HM Revenue & Customs (2016)

Purchase subsidies for PHEVs and BEVs in 2017, known as plug-in grants, were taken from the UK Office for Low Emission Vehicles (2016, p.1). These government grants were based on the environmental performance of the vehicle, defined as CO2 emissions and their zero emission range. These grants, however, were reduced in October 2018, and then again, in March 2020, as shown on Table 3. In March 2020 zero emission cars priced over £50,000 ceased to be eligible to receive a grant.

The Vehicle Excise Duty (VED) is “a tax applicable to all vehicles driving on UK roads” (UK Office for Low Emission Vehicles, 2018a, p. 2). The VED depends on the car CO2 emissions and varies between the first and subsequent years. In addition, diesel vehicles, which cause substantially more air pollution than all other powertrains, pay a higher rate. The VED rates for each of the cars modelled in this study are presented on Table 4.

All cars with a list price above £40,000 are also levied a supplement of £310 in addition to the standard VED rate for the first five years in which the standard rate is paid (UK Office for Low Emission Vehicles, 2018a, point 2.5 and Table 4). The 2020 Budget, however, introduced an exemption from the supplement for new and existing zero emission cars (HM Treasury, 2020, point 1.245, p. 63). This means that the Tesla X modelled in the present study, which paid the supplement in 2018 and 2019, will not pay the supplement in 2020, 2021 or 2022.

3.1.5 Cost of CO2 emissions

The cost of CO2 emissions for each vehicle modelled was simply estimated as the quantity of CO2 emitted multiplied by the central value of the non-traded price of CO2, which was taken from Table A 3.4 of the WebTAG Data Book (UK Department for Transport, 2018e). The higher values of the non-traded price of CO_2 were used for the sensitivity analysis presented in Appendix B, as was the double of these higher values.

We should highlight, however, that the debate over the Social Cost of Carbon, which is based on a valuation of the damages associated with climate change, is far from settled in academic and policy-making circles. Social Cost of Carbon estimates span a very wide range, depending on the model used and the assumptions made. It has been estimated hundreds of times since the early 1990s, with estimates varying from US$10 per tCO_2 to US$1,000 per tCO_2 (Ricke et al., 2018). Following a comprehensive review in 2009, the UK government adopted an approach that moved away from the Social Cost of Carbon (Santos, 2017a, p. 123). Instead, the values are now based on the UK government reduction targets and their corresponding abatement costs (UK Department for Business, Energy & Industrial Strategy, 2019, p. 14, point 3.42). Because in the EU there are separate emission reduction targets for the traded sector (where emissions are covered by the EU Emission Trading Scheme, EU ETS) and for the non-traded sector (where emissions are not covered by the EU ETS), the UK government treats emissions in the two sectors as different commodities and values them differently: CO_2 emissions which occur in the traded sector are valued at the Traded Price of Carbon, whereas CO_2 emissions in the non-traded sector are valued at the Non-Traded Price of Carbon (UK Department for Business, Energy & Industrial Strategy, 2019, p. 15, point 3.45).

Although drivers in the UK already internalise the cost of CO_2 emissions by paying the fuel duty (Santos, 2017a, p. 124) and VED, it is nonetheless interesting to explore whether including CO_2 emissions in the model significantly changes the present value of the TCO for the different vehicles.

3.2 Vehicles

As explained above, five propulsion types were modelled: petrol, diesel, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).[6] Within these propulsion types, there are small, medium and large cars, and so the most popular models within each size category were identified. In order to do this, we used the database of cars registered for the first time in the UK by make and model, collected by the UK Driver and Licensing Agency and published by the UK Department for Transport (2018b).

Once all 15 cars were selected, their fuel and/or electricity consumption and CO2 emissions were taken directly from the manufacturers' websites.[7]

Table 4 presents all models and their characteristics, along with all the taxes and subsidies applicable on the cars modelled in the UK in 2017. Taxes and subsidies were excluded from benchmark calculations, so that the true gap in TCO could be estimated.

[6] HEVs are relatively common now. They use two different forms of power: an electric motor and an internal combustion engine. They are grid-independent because the electricity is produced by the regenerative braking system when the vehicle is running on petrol/diesel, and stored in the battery for use later on. PHEVs also run on two forms of power, but they source the electricity from the grid. Finally, BEVs rely on a battery, which stores electricity and needs to be charged regularly. Both PEHVs and BEVs are grid-dependent or plug-in vehicles.

[7] It is worth noting, however, that the data concerning the vehicles' energy consumption and CO2 emissions reported by manufacturers may differ from actual usage.

Table 3: Eligible emission categories and levels of subsidies for different types of grid-dependent vehicles in the UK in 2017, 2018 and 2020

Emission category	CO_2 emissions	Zero emissions range	Level of subsidy in £, 2017 prices			Vehicles under the study eligible for grant		
			2017	2018	2020	2017	2018	2020
Category 1	<50g/km	>70 miles	4500	3500	3000	BMW i3 Nissan Leaf Tesla X	BMW i3 Nissan Leaf Tesla X	BMW i3 Nissan Leaf
Category 2	<50g/km	10-69 miles	2500	0	0	BMW 330e PHEV Mitsubishi Outlander PHEV		
Category 3	50-75g/km	>20 miles	2500	0	0	Mini Countryman PHEV		

Source: UK Office for Low Emission Vehicles (2016, p. 1; 2018) and UK Department for Transport and Office for Low Emission Vehicles (2020b)

Table 4: Vehicles modelled

	Small cars					Medium cars					Large cars				
Propulsion type	Petrol	Diesel	HEV	PHEV	BEV	Petrol	Diesel	HEV	PHEV	BEV	Petrol	Diesel	HEV	PHEV	BEV
Make	Ford	Ford	Toyota	Mini	BMW	Ford	VW	Toyota	BMW	Nissan	Nissan	Nissan	Toyota	Mitsu-bishi	Tesla
Model	Fiesta Turbo	Fiesta TDCi	Yaris	Coun-tryman Cooper	i3	Focus	Golf TDi	Auris Hybrid	330e	Leaf	Qash-qai DiG	Qash-qai dCi	C-HR HEV	Outla-nder	Model X
Reference	Fiesta petrol	Fiesta diesel	Yaris hybrid	Mini PHEV	i3 EV	Focus petrol	Golf diesel	Auris Hybrid	BMW PHEV	Leaf EV	Qash-qai petrol	Qash-qai diesel	C-HR Hybrid	Outla-nder PHEV	Tesla EV
Base price £ (no tax)	11,225	12,991	13,082	25,833	27,783	16,595	16,404	18,011	29,916	22,696	15,900	17,392	19,453	30,583	61,650
VAT 20% (£)	2,245	2,598.3	2,616.5	5,166.6	5,556.6	3,319.1	3,280.8	3,602.3	5,983.3	4,539.2	3,180	3,478.3	3,890.6	6,116.6	12,330
Price inc. VAT (£)	13,470	15,590	15,699	31,000	33,340	19,915	19,685	21,614	35,900	27,235	19,080	20,870	23,344	36,700	73,980
Subsidy as of 2017 (£)	NA	NA	NA	2,500	4,500	NA	NA	NA	2,500	4,500	NA	NA	NA	2,500	4,500
VED 1st year (£)	165	145	95	0	0	145	165	115	0	0	165	145	95	0	0
VED remaining years (£)	140	140	130	130	0	140	140	130	130	0	140	140	130	130	310*
Fuel consumption l/100km	5.1	3.80	3.7	2.10	0	4.60	4.10	3.90	1.90	0	5.60	3.80	3.80	1.70	0
Electricity consumption kWh/100km	0	0	0	13.20	13.10	0	0	0	11.90	19.40	0	0	0	13.40	21.40
CO2 emissions g/km as indicated by manufacturer	115	96	84	49	0	105	106	91	44	0	129	99	86	41	0

Source: Car prices, energy consumption, CO2 emissions (manufacturers' websites); VED rates and subsidies (UK Office for Low Emission Vehicles, 2018a). All monetary values expressed in 2017 prices.
* Only payable in 2018 and 2019.

The different cars in each size category may offer different features. For example, some consumers may be especially interested in achieving high speeds, whilst others may especially value the maximum power the engine can put. Using the methodology proposed by Nieuwenhuis (2014), we compare the different cars in each size category in relation to a number of features. We present the methodology and results in Appendix C. The main conclusion from this comparison is that none of the cars modelled in this study outperforms all others in its own size category, at least for the features modelled.

Another interesting issue is that the car models with the highest number of registrations in each car size category/propulsion type combination have different market positioning. For example, for small cars, the BMW i3 and the Mini Countryman Cooper have a higher market positioning than the Ford Fiesta. For medium cars, the BMW 330e has a higher market positioning than the Ford Focus. For large cars, Tesla X is a luxury car, that targets more high-end consumers, and is positioned differently from the Nissan Qashqai dci. BMW is typically perceived as a brand of cars with high performance but also high price, whereas Ford, Mitsubishi, Nissan, Volkswgen, and Toyota, are perceived as mass-market brands (Hirsh et al., 2003).

The high initial price attached to cars with high market positioning has not prevented some of them from achieving the highest number of registrations in their size category/propulsion type, which was the criterion used to select the specific models in this study. In order to compare car models with similar market positioning an additional six car models are introduced in Appendix B.

4. Results and discussion

In this section we present our results and discuss them. The two areas where we focus are TCO and breakeven points. The present value of TCO, which we defined in Section 3, includes the purchase price, fuel/electricity costs, and non-fuel operating costs over the lifetime of the vehicle, discounted to the value of the base year, which in this study is 2017, using four different discount rates (0%, 6%, 30%, and 60%). Breakeven point is defined as the point in time at which the TCO of two different technologies break even, or in other words, the point in time at which the owner of the vehicle has recovered the initial higher purchase price thanks to the lower operating costs.

4.1 Baseline model

Our baseline model excludes all taxes and subsides, so that we can get a clear idea of where the actual TCO of the different technologies stand in the UK, in order to later estimate what taxes and subsidies are needed in order to achieve cost parity.

4.1.1 Present value of TCO

Table 5 shows the TCO discounted to the base year, 2017, for all the cars modelled, under the four discount rates assumed. Table 6 shows the ratio of TCO using the petrol car in each size category as the reference.

Table 5: Total Costs of Ownership, in £, 2017 prices, excluding any taxes or subsidies

Vehicles		0%	6%	30%	60%
Small	Fiesta petrol	22,125	19,082	14,720	13,440
	Fiesta diesel	23,017	20,228	16,223	15,043
	Yaris Hybrid	23,041	20,271	16,293	15,121
	Mini PHEV	31,970	30,228	27,745	27,026
	i3 EV	33,682	32,029	29,656	28,959
Medium	Focus petrol	27,159	24,214	19,989	18,748
	Golf diesel	26,631	23,784	19,696	18,493
	Auris Hybrid	28,104	25,296	21,263	20,076
	BMW PHEV	35,578	33,972	31,683	31,019
	Leaf EV	30,248	28,125	25,080	24,188
Large	Qashqai petrol	27,136	23,995	19,496	18,178
	Qashqai diesel	27,417	24,628	20,623	19,443
	C-HR Hybrid	29,479	26,690	22,684	21,505
	Outlander PHEV	36,504	34,825	32,430	31,736
	Tesla EV	69,727	67,454	64,196	63,243

Note: Base year: 2017. Period modelled: 2017-2029
Source: Own calculations

Table 6: Total Costs of Ownership ratios excluding any taxes or subsidies, with petrol car as the reference

Vehicles		0%	6%	30%	60%
Small	Fiesta petrol	1.00	1.00	1.00	1.00
	Fiesta diesel	1.04	1.06	1.10	1.12
	Yaris Hybrid	1.04	1.06	1.11	1.13
	Mini PHEV	1.44	1.58	1.88	2.01
	i3 EV	1.52	1.68	2.01	2.15
Medium	Focus petrol	1.00	1.00	1.00	1.00
	Golf diesel	0.98	0.98	0.99	0.99
	Auris Hybrid	1.03	1.04	1.06	1.07
	BMW PHEV	1.31	1.40	1.58	1.65
	Leaf EV	1.11	1.16	1.25	1.29
Large	Qashqai petrol	1.00	1.00	1.00	1.00
	Qashqai diesel	1.01	1.03	1.06	1.07
	C-HR Hybrid	1.09	1.11	1.16	1.18
	Outlander PHEV	1.35	1.45	1.66	1.75
	Tesla EV	2.57	2.81	3.29	3.48

Note: Base year: 2017. Period modelled: 2017-2029
Source: Table 5

Tables 5 and 6 show that, not surprisingly, higher discount rates play against vehicles that are more expensive to buy but cheaper to operate. The 0% discount rate is only presented to illustrate that even in the case when consumers attach the same weight to present and future disbursements, cleaner cars have, in general, higher TCO. Tables 5 and 6 also show that TCO for petrol and diesel cars, and HEVs are very similar within each car size category and discount rate, with diesel cars having slightly lower TCO in the medium size category. They also show that TCO are higher, and in some cases, substantially higher, for PHEVs and BEVs, with BEVs exhibiting the highest TCO in the small and large size categories. In all cases, the higher purchase price of PHEVs and BEVs outweighs the potential savings in the operating costs over the vehicle's lifetime. This means that at no point in time do PHEVs or BEVs break even with petrol cars, diesel cars, or HEVs, in the absence of taxes and subsidies, as we show graphically in Section 4.1.2.

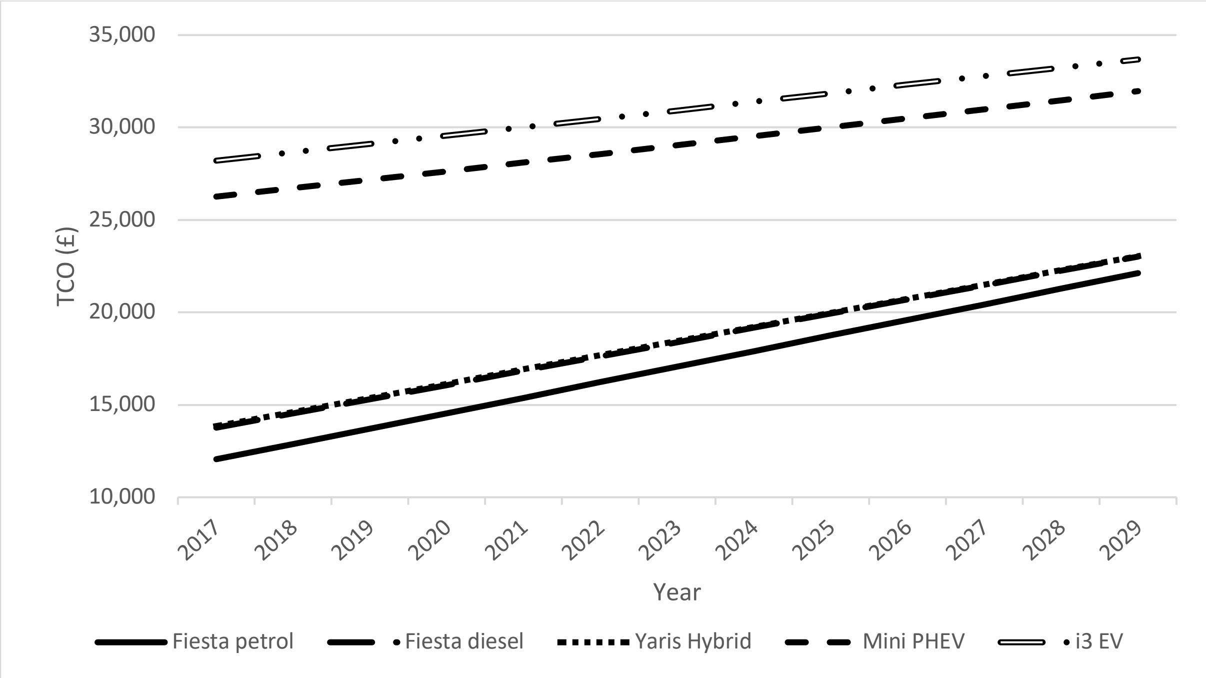
4.1.2 Breakeven points

When cleaner, more expensive cars, have lower operating costs, the owner might recover the initial higher purchase costs before the end of the vehicle life. Without taxes or subsidies this is completely impossible for the car models included in this study, as would have been evident from Tables 5 and 6.

Figures 4 to 7 illustrate the year-on-year trajectory of the TCO for the vehicles modelled. The TCO curves never cross within the period modelled. Figure 4 shows the TCO trajectories under a 0% discount rate. This is essentially a benchmark, as it is very unlikely that anyone would attach the same weight to present and future costs. Consumers typically prefer to defer costs in time. A 0% discount rate provides the most favourable platform for clean technologies, with a higher purchase price but lower operating costs. Figures 4a-4c show that even under this unrealistic 0% discount rate assumption, PHEVs and BEVs are more expensive throughout the period modelled. In other words, the higher initial cost is never recovered. The picture only gets worse with higher discount rates. Figures 5a-5c and 6a-6c show the TCO trajectories under a 6% discount rate and under a 30% discount rate, respectively. Finally, Figures 7a-7c show the TCO trajectories under a 60% discount rate, representing consumers who place a much higher weight on costs incurred today relative to costs incurred in the future. Any future savings from cleaner vehicles are of little interest to these consumers so the gap between TCO is even larger, as would have also been evident from Tables 5 and 6.

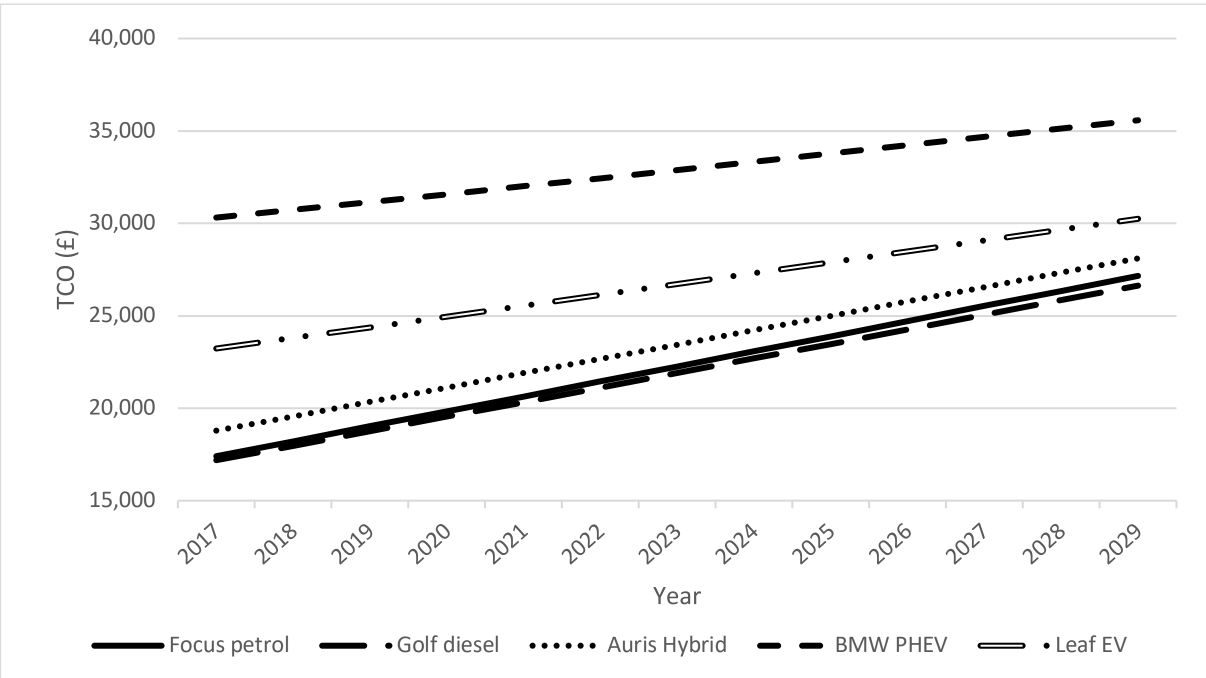
The effect of the very low and very high discount rates used can be seen by comparing Figures 4a-c with Figures 7a-c. The TCO curves in Figures 4a-c get closer over time, although they never cross each other within the period modelled. The TCO curves in Figures 7a-c are virtually parallel. Although the actual discount rates of car buyers in the UK are not known, the main finding from the analysis so far is that PHEVs and BEVs never break even with petrol cars, diesel cars or HEVs during the period modelled, and this applies not only to any possible discount rate but also to the unrealistic 0% discount rate, where consumers place the same emphasis to present and future costs. Prolonging the lines in Figures 4a-c yields breakeven points between grid-dependent and petrol cars that fall beyond any reasonable payback period, as in many cases the vehicles would have been scrapped by then.

Figure 4a: Small cars TCO 2017-2029, excluding any taxes or subsidies, under a 0% discount rate



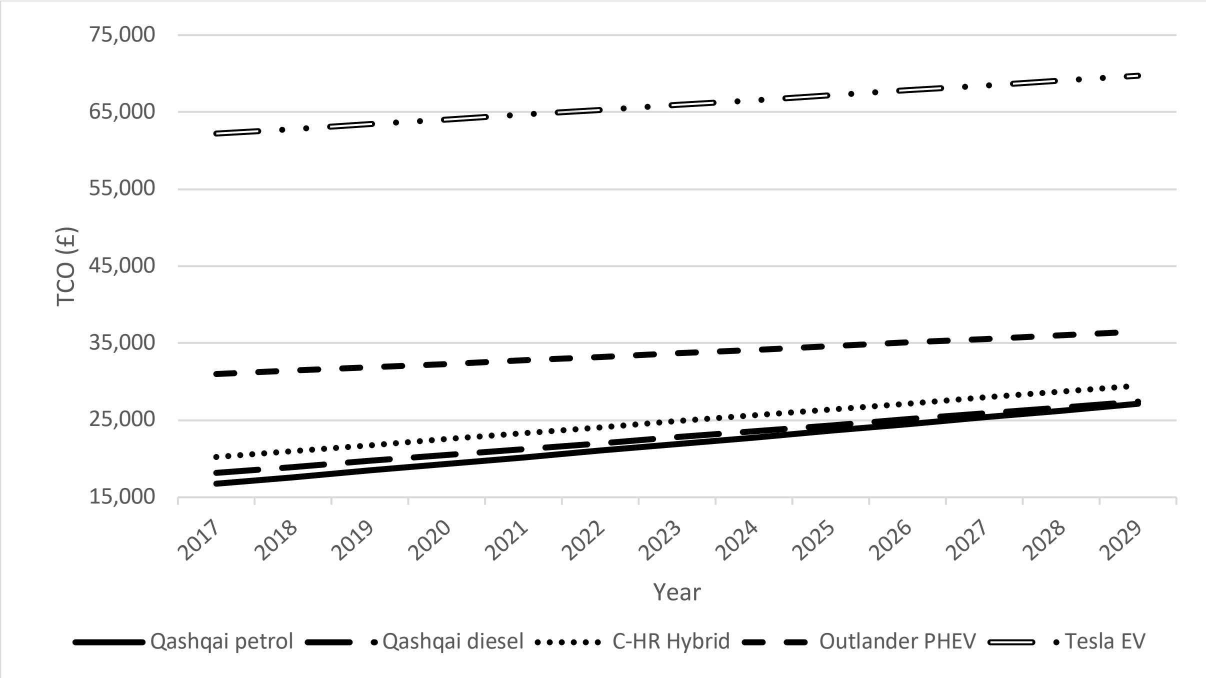
Source: Own calculations

Figure 4b: Medium cars TCO 2017-2029, excluding any taxes or subsidies, under a 0% discount rate



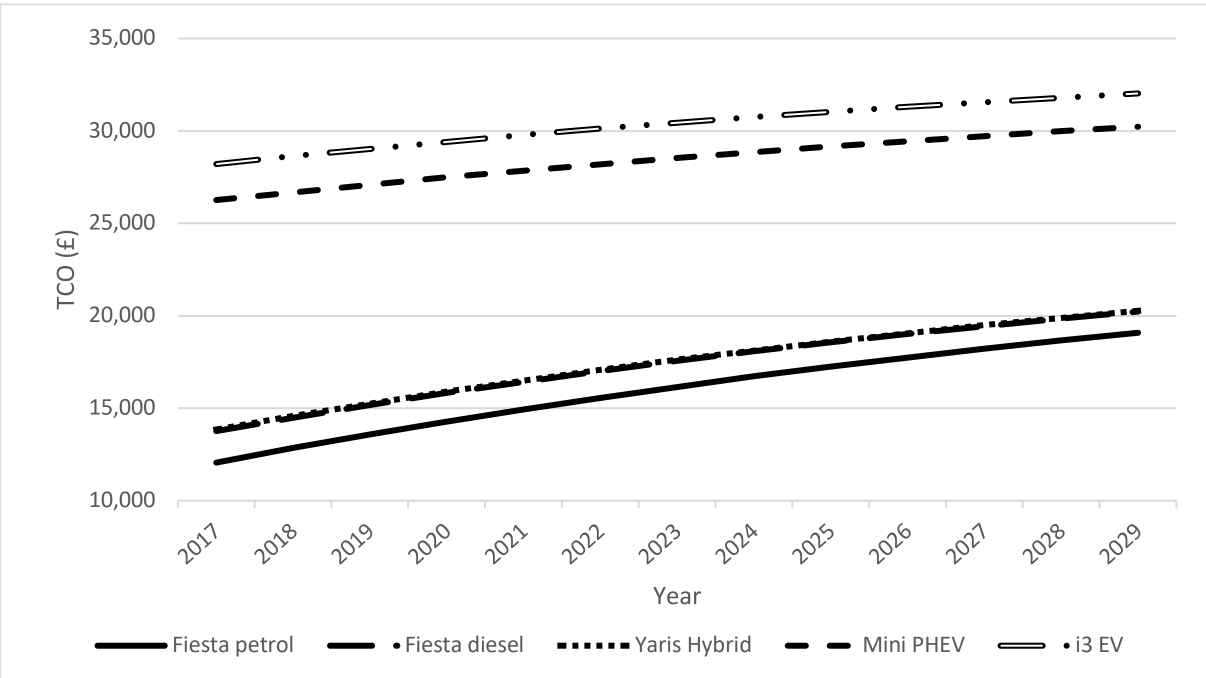
Source: Own calculations

Figure 4c: Large cars TCO 2017-2029, excluding any taxes or subsidies, under a 0% discount rate



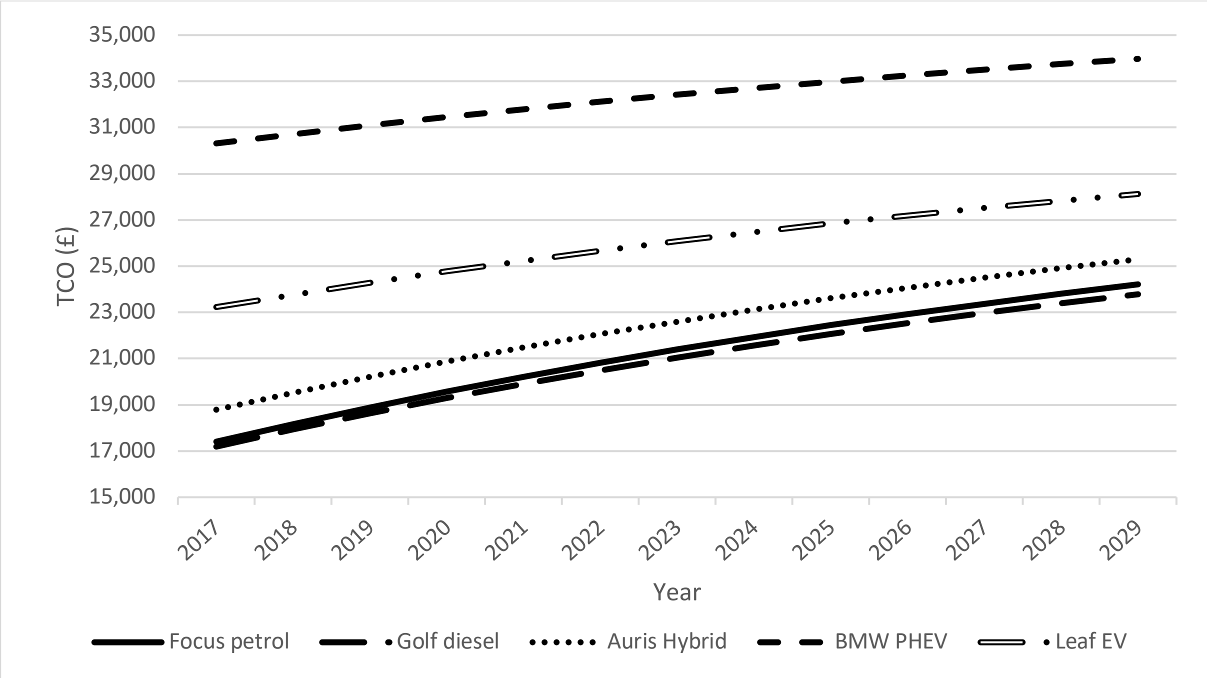
Source: Own calculations

Figure 5a: Small cars TCO 2017-2029, excluding any taxes or subsidies, under a 6% discount rate



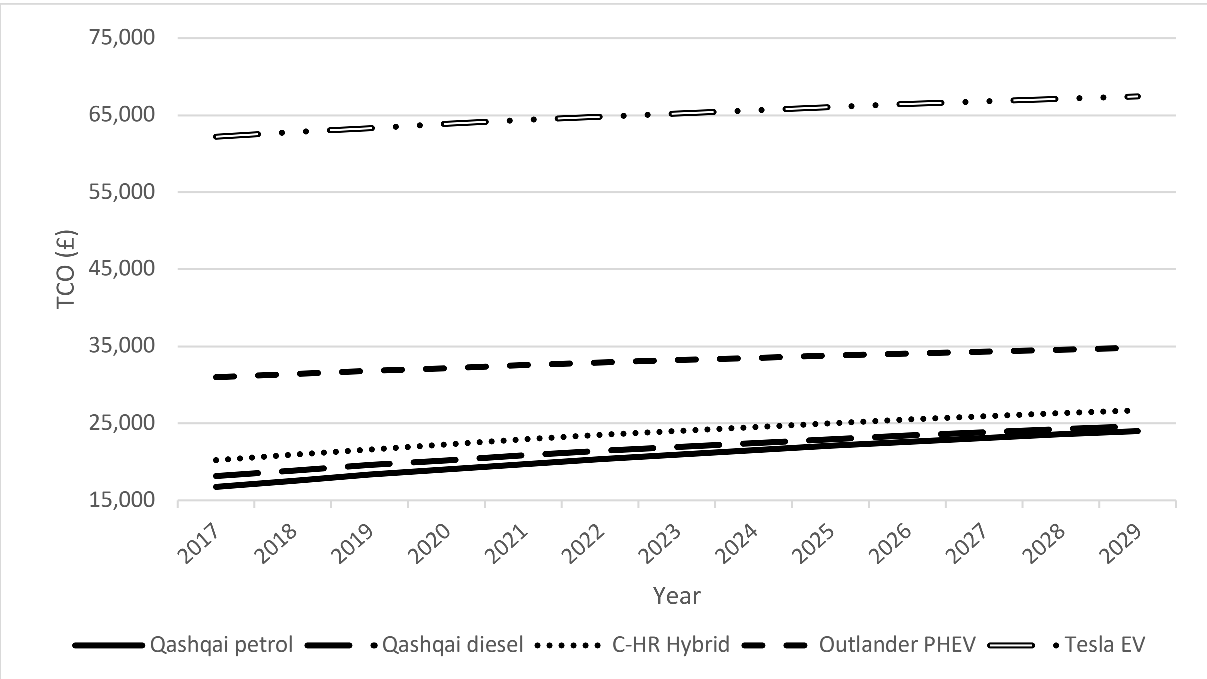
Source: Own calculations

Figure 5b: Medium cars TCO 2017-2029, excluding any taxes or subsidies, under a 6% discount rate



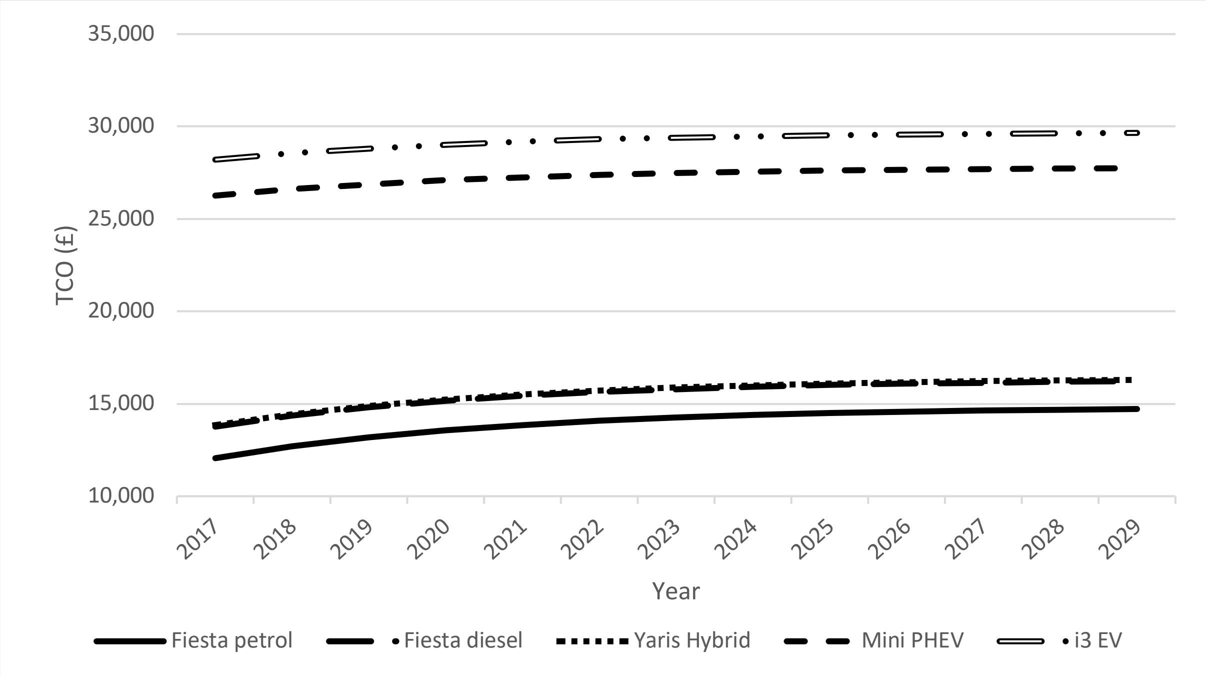
Source: Own calculations

Figure 5c: Large cars TCO 2017-2029, excluding any taxes or subsidies, under a 6% discount rate



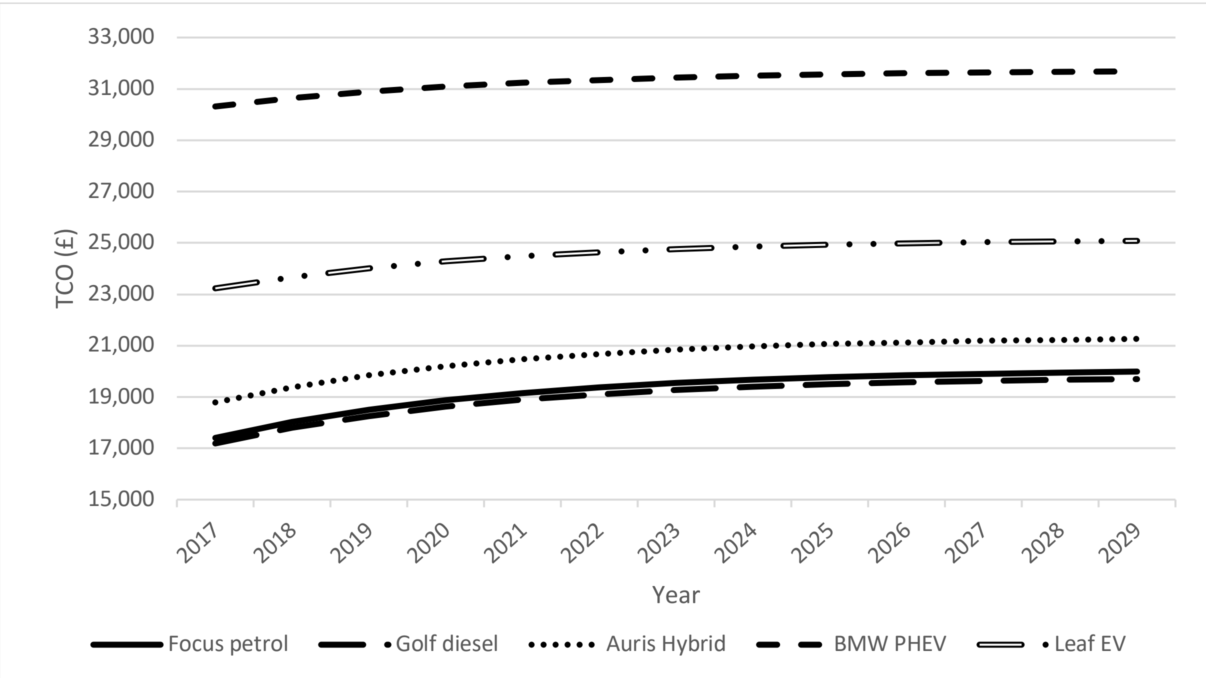
Source: Own calculations

Figure 6a: Small cars TCO 2017-2029, excluding any taxes or subsidies, under a 30% discount rate



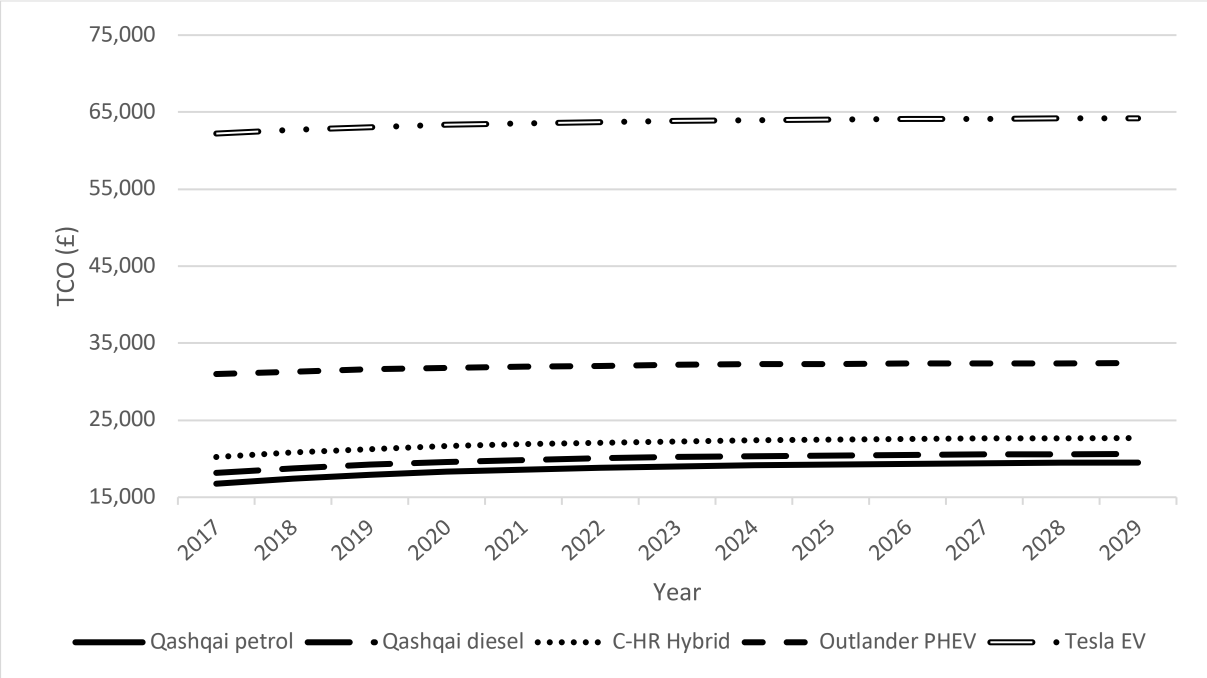
Source: Own calculations

Figure 6b: Medium cars TCO 2017-2029, excluding any taxes or subsidies, under a 30% discount rate



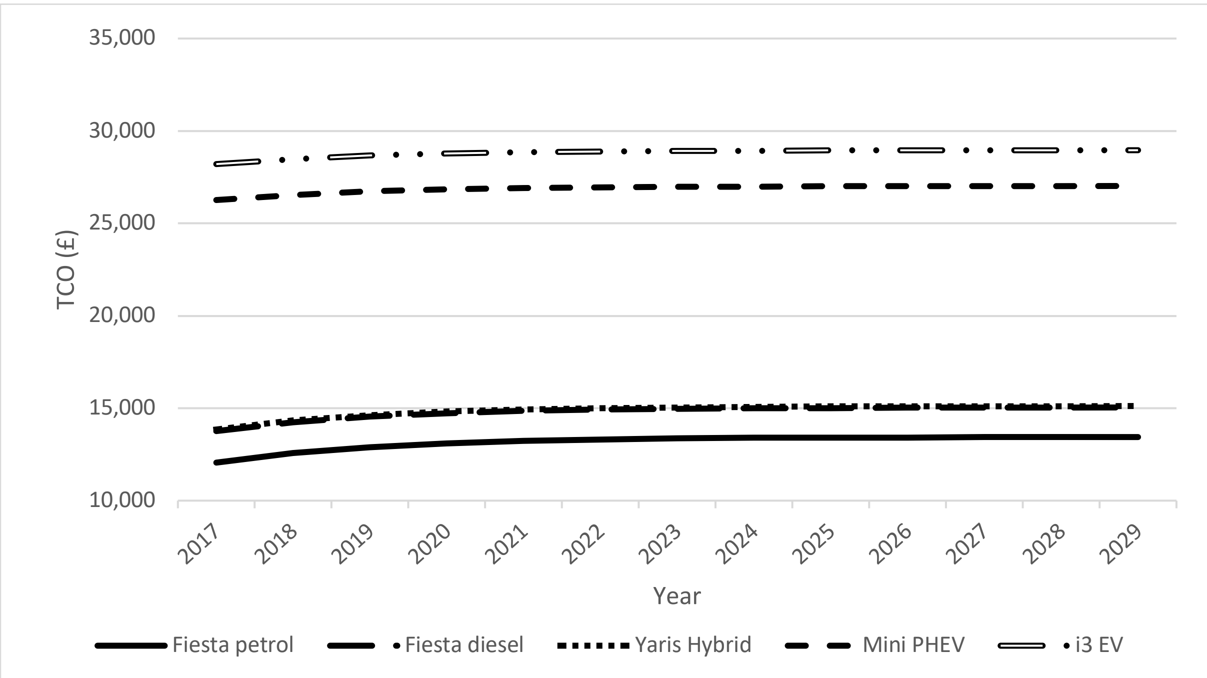
Source: Own calculations

Figure 6c: Large cars TCO 2017-2029, excluding any taxes or subsidies, under a 30% discount rate



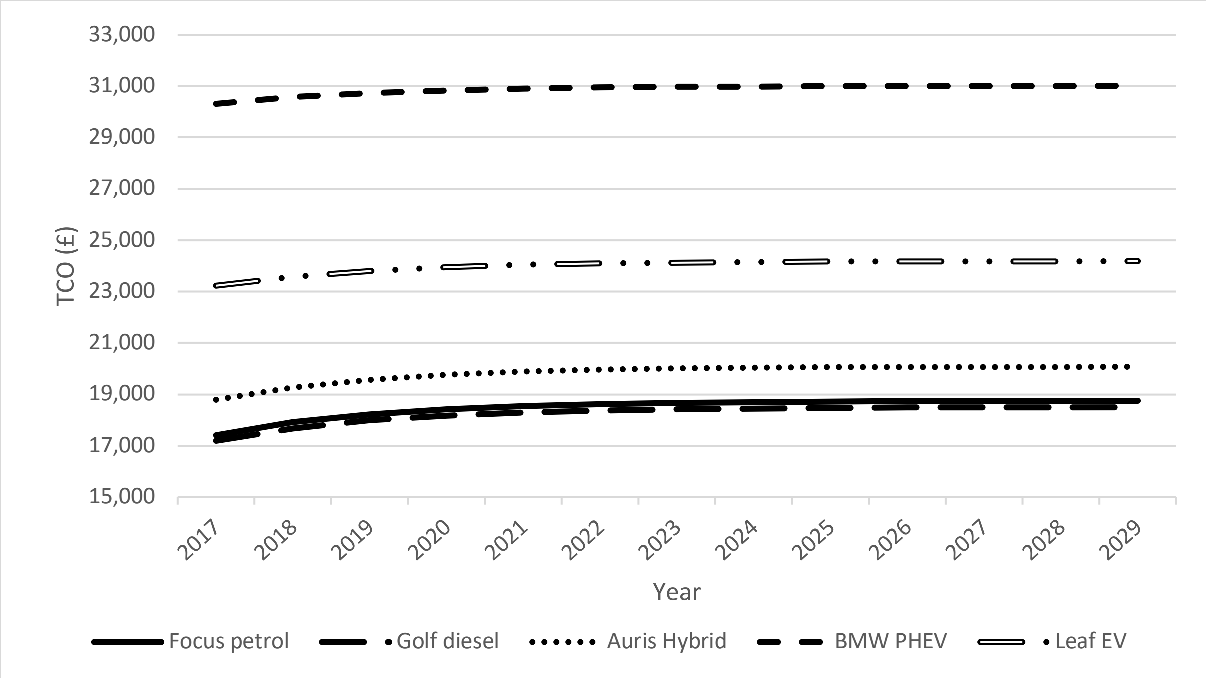
Source: Own calculations

Figure 7a: Small cars TCO 2017-2029, excluding any taxes or subsidies, under a 60% discount rate



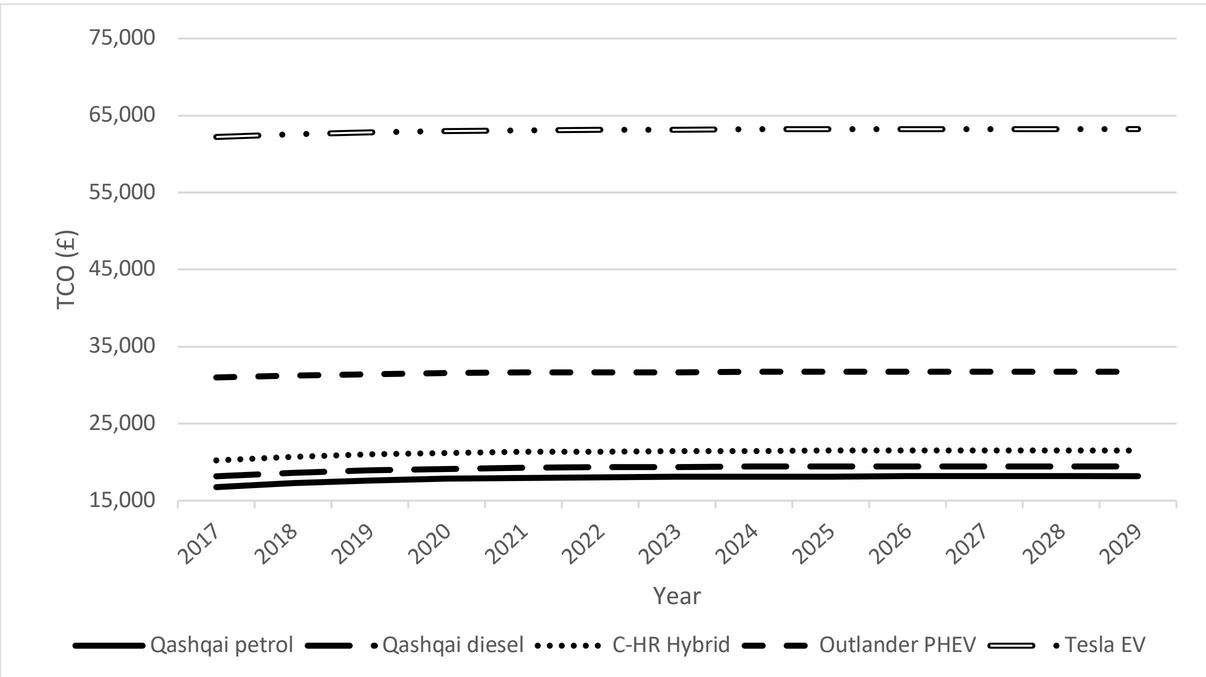
Source: Own calculations

Figure 7b: Medium cars TCO 2017-2029, excluding any taxes or subsidies, under a 60% discount rate



Source: Own calculations

Figure 7c: Large cars TCO 2017-2029, excluding any taxes or subsidies, under a 60% discount rate



Source: Own calculations

4.1.3 Baseline model: final thoughts

Although the price of PHEVs and BEVs has fallen over the last decade, the initial price of the vehicles modelled in this study is still relatively high and is never recovered over the vehicle lifetime in the absence of any taxes or subsidies. Until these technologies become fully competitive with petrol, diesel and HEVs, government intervention is needed. The UK government has a set of energy taxes and vehicle subsidies and taxes in place. The following section concentrates on whether these taxes and subsidies make grid-dependent vehicles more attractive to car buyers.

4.2 TCO including taxes and subsidies

In this section we add all taxes and subsidies to the analysis in order to understand if they change relative TCO enough to make grid-dependent vehicles competitive.

4.2.1 Present value of TCO

Table 7 shows the TCO discounted to the base year, 2017, for all the cars modelled, under the four discount rates assumed, including all energy taxes and vehicle subsidies and taxes. Table 8 shows the ratio of TCO using the petrol car in each size category as the reference. The main conclusion is that energy taxes and vehicle subsidies and taxes go some way towards making cleaner cars more competitive, when these results are compared to those presented in Section 4.1. However, the effects vary by vehicle model, with the Leaf EV, being the only grid-dependent car amongst the cars included in this study, that becomes competitive with the petrol car (in the medium size category) under all discount rates, except for the 60% discount rate.[8] Focusing on the 6% and 30% discount rates, which span the range in which actual (implicit) discount rates are likely to fall, we note that the Leaf EV, which was borderline competitive with its petrol counterpart under no government intervention (i.e., no taxes or subsidies), is now fully competitive, with TCO ratios of 0.88 and 1 under the 6% and 30% assumptions, respectively.

The main problem with most of the grid-dependent cars included in this study, which were selected because they were the vehicles with the highest number of registrations in the UK in 2017 in their size category/propulsion type combination, is that they have a substantially higher initial purchase price and market positioning. TCO are very sensitive to purchase price, as shown by the sensitivity analysis presented in Appendix B. For that reason, an extended analysis is presented in that appendix, to include BEVs of similar market positioning to the petrol reference in the problematic small and large size categories.

[8] It also becomes competitive with the HEV under all discount rates, and with the diesel car under all discount rates, except for the 60% one.

Table 7: Total Costs of Ownership, in £, 2017 prices, including all current taxes and subsidies

Vehicles		0%	6%	30%	60%
Small	Fiesta petrol	33,299	27,738	19,787	17,467
	Fiesta diesel	32,719	27,925	21,060	19,050
	Yaris Hybrid	32,452	27,753	21,023	19,053
	Mini PHEV	39,287	36,197	31,790	30,511
	i3 EV	34,911	33,209	30,765	30,048
Medium	Focus petrol	36,868	32,108	25,302	23,315
	Golf diesel	37,454	32,482	25,367	23,285
	Auris Hybrid	38,800	33,983	27,087	25,068
	BMW PHEV	43,419	40,548	36,454	35,265
	Leaf EV	30,544	28,347	25,199	24,276
Large	Qashqai petrol	39,941	34,084	25,716	23,276
	Qashqai diesel	38,000	33,206	26,341	24,331
	C-HR Hybrid	40,304	35,546	28,733	26,739
	Outlander PHEV	44,220	41,350	37,254	36,064
	Tesla EV	78,462	76,057	72,538	71,444

Note: Base year: 2017. Period modelled: 2017-2029
Source: Own calculations

Table 8: Total Costs of Ownership ratios including all current taxes and subsidies, with petrol car as the reference

Vehicles		0%	6%	30%	60%
Small	Fiesta petrol	1.00	1.00	1.00	1.00
	Fiesta diesel	0.98	1.01	1.06	1.09
	Yaris Hybrid	0.97	1.00	1.06	1.09
	Mini PHEV	1.18	1.30	1.61	1.75
	i3 EV	1.05	1.20	1.55	1.72
Medium	Focus petrol	1.00	1.00	1.00	1.00
	Golf diesel	1.02	1.01	1.00	1.00
	Auris Hybrid	1.05	1.06	1.07	1.08
	BMW PHEV	1.18	1.26	1.44	1.51
	Leaf EV	0.83	0.88	1.00	1.04
Large	Qashqai petrol	1.00	1.00	1.00	1.00
	Qashqai diesel	0.95	0.97	1.02	1.05
	C-HR Hybrid	1.01	1.04	1.12	1.15
	Outlander PHEV	1.11	1.21	1.45	1.55
	Tesla EV	1.96	2.23	2.82	3.07

Note: Base year: 2017. Period modelled: 2017-2029
Source: Table 7

4.2.2 Breakeven points

Although the Leaf EV has a similar present value of TCO to that of its petrol, diesel and HEV counterparts, the present value is calculated over the period 2017-2029 and car owners will typically want to offset the initial higher purchase price before the end of the vehicle's lifetime. Therefore, the breakeven points need to be identified. Figures 8 and 9 show the TCO trajectories when energy taxes and vehicle subsidies and taxes are included, under the 6% and 30% discount rate assumptions, which are the most realistic.

Under a 6% discount rate, the Leaf EV breaks even with both the petrol and diesel cars in the medium size category in 2021, so the car owner has to wait four years to recover the difference in higher purchase price. This may be an acceptable payback period for some prospective car buyers but not for others.[9] The payback period under a 30% discount rate is, of course, longer. Under a 30% discount rate, the Leaf EV breaks even with the petrol car in the medium size category in 2029, and with the diesel car, in 2027. Interestingly, the Leaf EV breaks even with the Auris Hybrid in the second year, under both a 6% and a 30% discount rate assumption.[10] [11]

Although including all taxes and subsidies makes the grid-dependent vehicles modelled in this study more competitive, except for the Leaf EV discussed above, none of them breaks even with petrol cars, diesel cars or HEVs under any discount rate.

In the small size category, the Fiesta petrol is the vehicle with the lowest TCO, closely followed by the Fiesta diesel and the Yaris Hybrid. Although the i3 EV has lower TCO than the Mini

[9] In the US, for example, car buyers expect payback in 2.8 years if they are to pay more for increased fuel economy (Greene et al., 2005).

[10] Furthermore, the Leaf EV breaks even with the Auris Hybrid in the third year under a 60% discount rate.

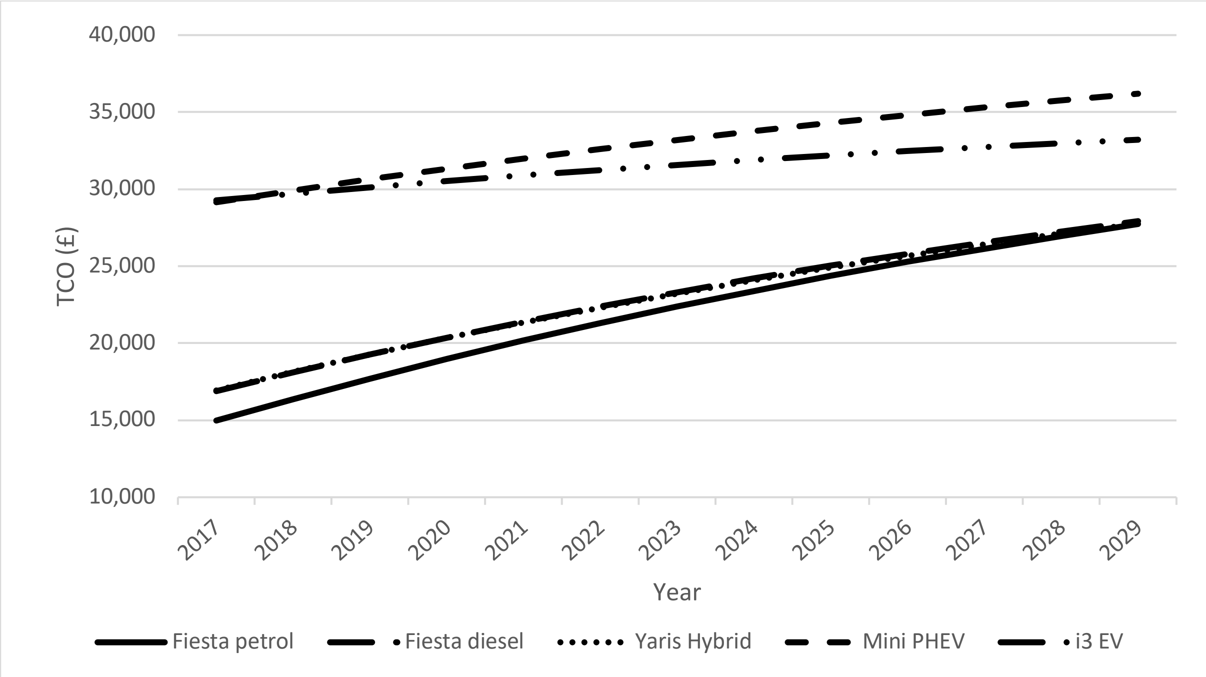
[11] According to the database from the UK Department for Transport (2018b), in 2017 the total first registrations of Auris Hybrid were 10,704 and the total first registrations of the Leaf EV were 5,665. It is difficult to assert the reasons behind this preference. It could be linked to the specific features the two cars offer, as discussed in Appendix C, or to issues of range anxiety, as suggested by Sierzchula et al. (2014), Lieven (2015), Bonges III and Lusk (2016), Mersky et al. (2016), Egbue et al. (2017), Liao et al. (2017), and Wang et al. (2017). It could also be the result of many consumers ignoring the TCO when choosing what car to buy, or being myopic/inattentive, as postulated by Gerarden et al. (2017) and Leard (2018), which would reinforce the need for labelling, as proposed by Dumortier et al. (2015). In any case, this pair-wise comparison is somewhat limited as there are a range of makes, models and propulsion types consumers can choose from.

PHEV from the second year onwards, both cars have substantially higher TCO than petrol, diesel or HEVs throughout the period modelled.

In the large size category, the petrol and diesel cars are the options with the lowest present value of TCO over the period modelled. Like in the other groups, the grid-independent HEV is only slightly more expensive over its lifetime than the petrol and diesel vehicles. Turning to the PHEV, the Outlander has a higher present value of TCO than all the other vehicles, except for the Tesla EV, whose TCO are by far the highest.

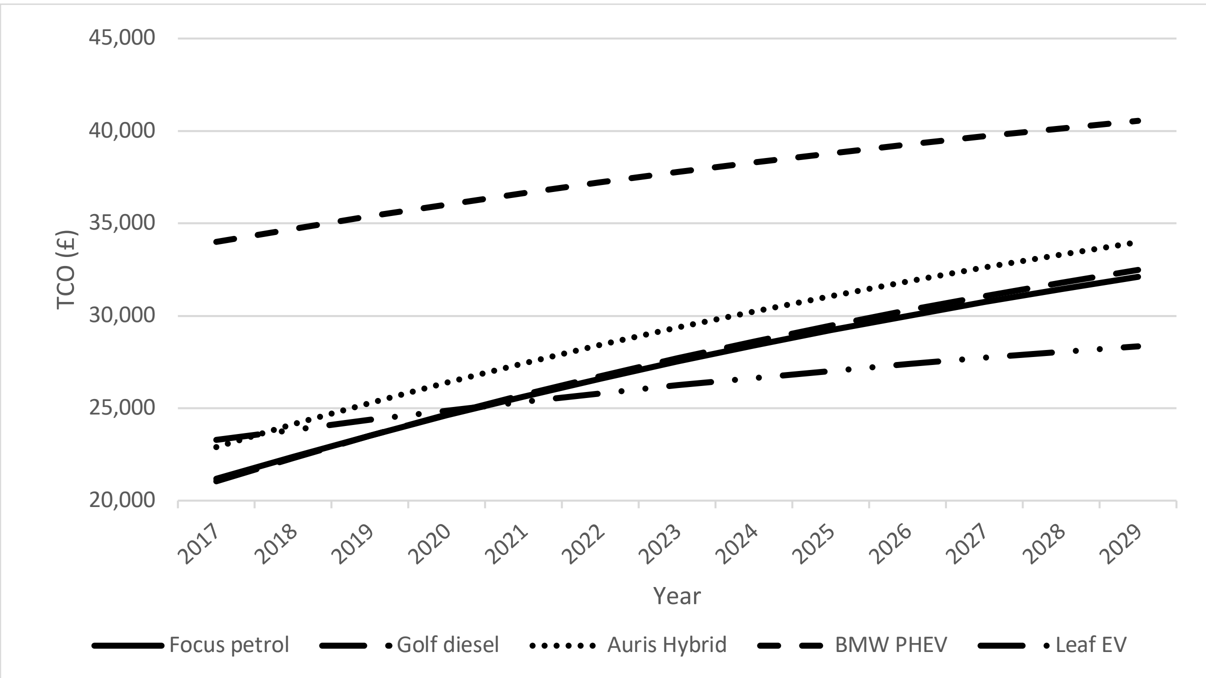
The caveat in this analysis is that, as advanced in Section 3.2, the BMW i3 and the Mini Countryman Cooper have a higher market positioning than the Ford Fiesta. Similarly, the Tesla X is a luxury car. These cars attract a different group of consumers. They had the highest number of new registrations in their size category/propulsion type in 2017, despite the insufficient subsidy, which supports the idea of market segmentation. Other BEV models with lower purchase prices are included in an extended analysis in Appendix B, for comparison purposes. When energy taxes and vehicle subsidies and taxes are included in the calculations, these lower priced BEVs either break even with their petrol reference within a reasonable period of time, or have only slightly higher TCO. Some are close to reaching cost parity even without any fuel taxes or vehicle subsidies or taxes.

Figure 8a: Small cars TCO 2017-2029, including current taxes and subsidies, under a 6% discount rate



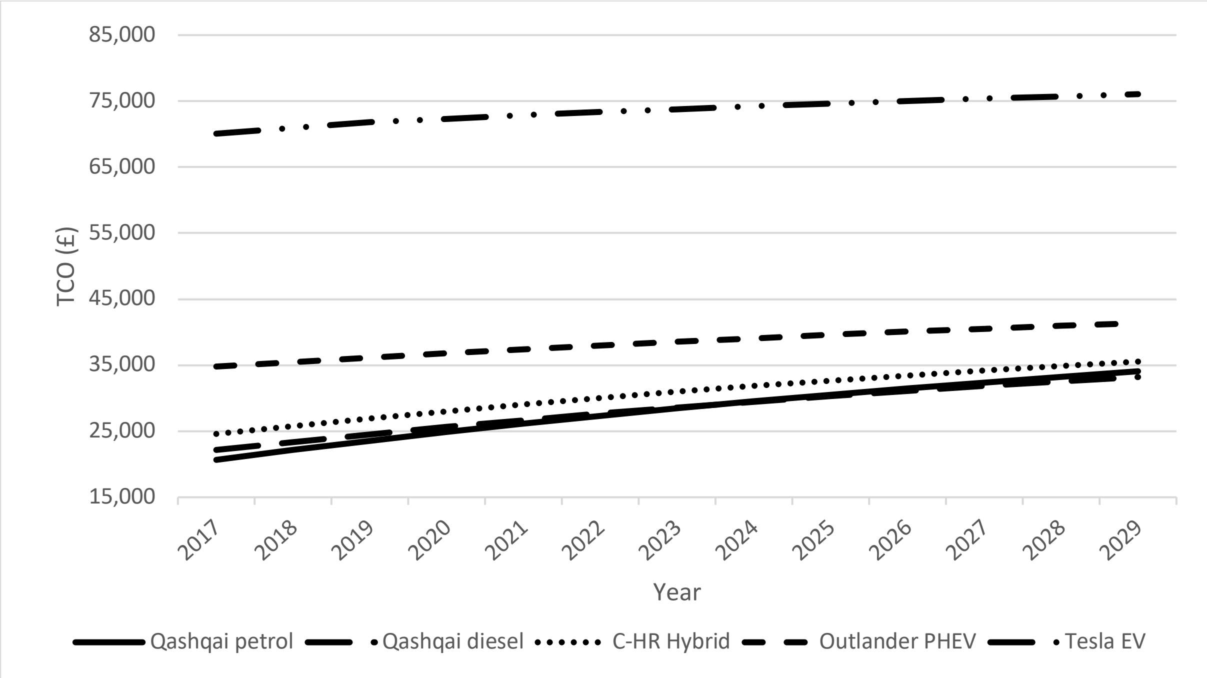
Source: Own calculations

Figure 8b: Medium cars TCO 2017-2029, including current taxes and subsidies, under a 6% discount rate



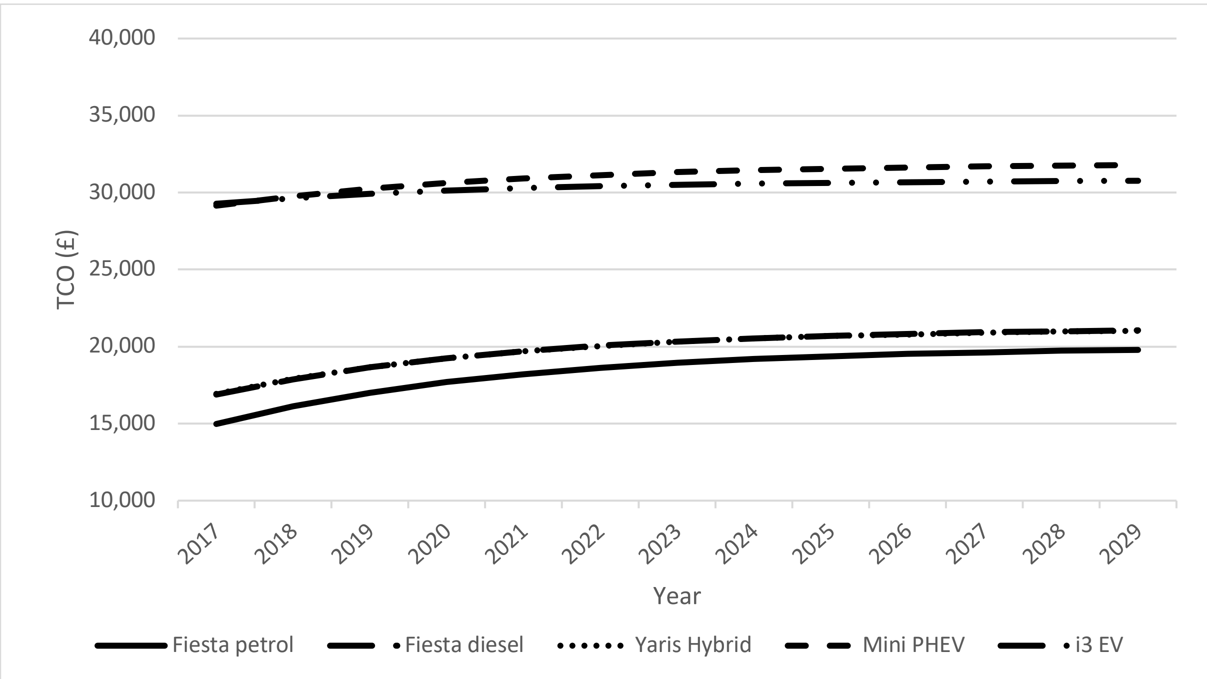
Source: own calculations

Figure 8c: Large cars TCO 2017-2029, including current taxes and subsidies, under a 6% discount rate



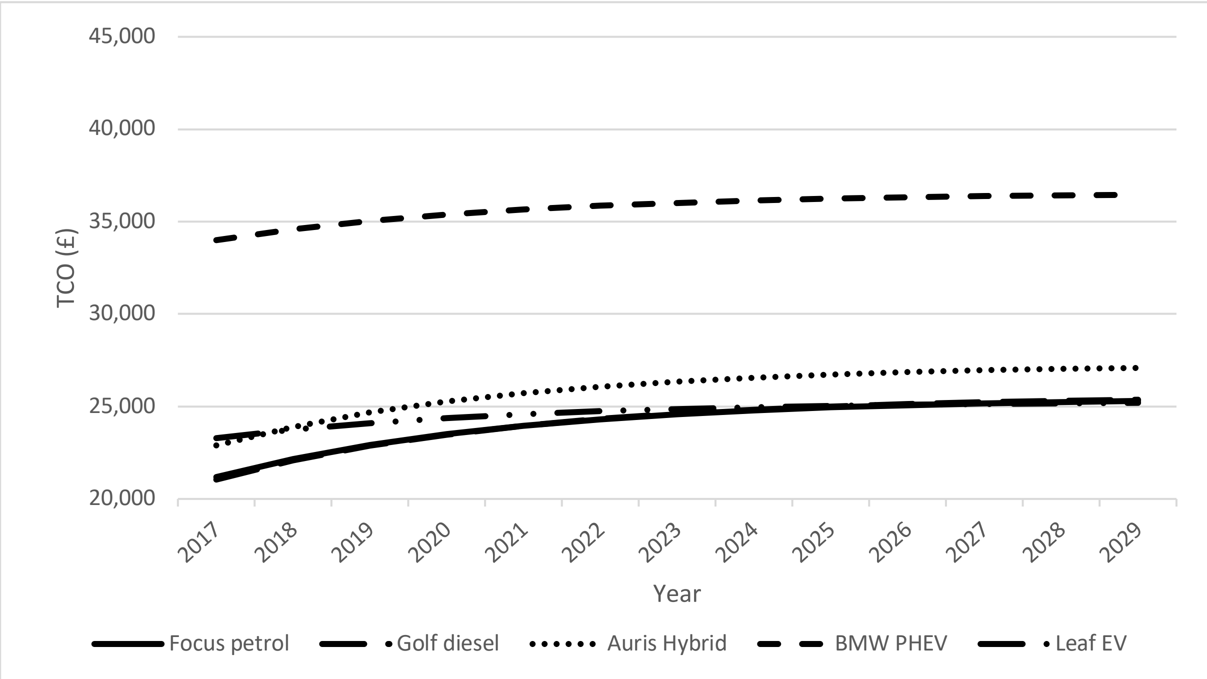
Source: own calculations

Figure 9a: Small cars TCO 2017-2029, including current taxes and subsidies, under a 30% discount rate



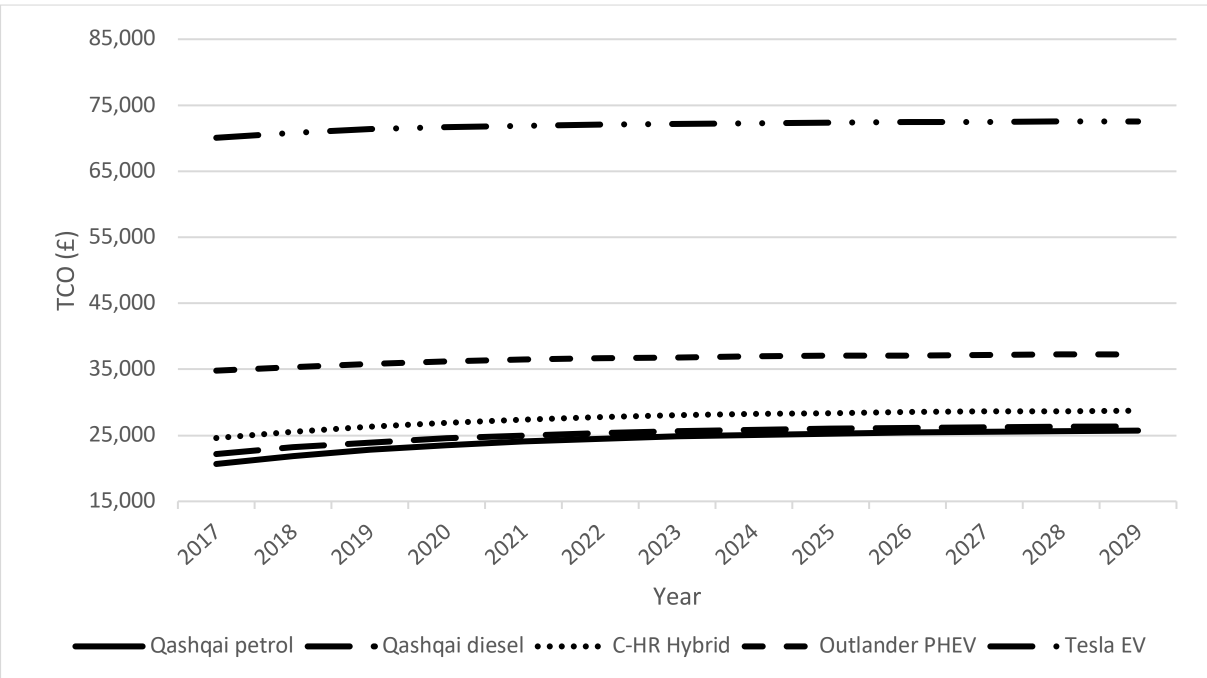
Source: own calculations

Figure 9b: Medium cars TCO 2017-2029, including current taxes and subsidies, under a 30% discount rate



Source: own calculations

Figure 9c: Large cars TCO 2017-2029, including current taxes and subsidies, under a 30% discount rate



Source: Own calculations

4.2.3 Taxes and subsidies: final thoughts

Energy taxes and vehicle subsidies and taxes change relative TCO, making grid-dependent vehicles somewhat more attractive than if there were no taxes or subsidies. From the PHEVs and BEVs with the highest number of registrations in the UK in 2017 for each car size category/propulsion type combination, only the Leaf EV breaks even with petrol, diesel and HEV, with all other grid-dependent cars still having higher TCO than petrol, diesel and HEVs, when taxes and subsidies are included in the calculations.

However, the initial purchase price is of fundamental importance, as shown by the sensitivity analysis presented in Appendix B. An extended analysis in the same appendix shows that when BEVs with lower price tags and comparable market positioning to their petrol reference are considered, taxes and subsidies change relative TCO enough for them to either break even within a reasonable period of time, or have only slightly higher TCO.

It is interesting that the petrol, diesel and HEVs within each car size category, show similar overall TCO. Nonetheless, HEVs do not offer zero emissions and therefore cannot be regarded as a long-term solution for decarbonising road transport.

We now turn our attention to an extremely important related topic: CO2 emissions and their inclusion in the model. After all, the whole point of accelerating electric vehicle market penetration is to reduce CO2 emissions from road transport.

4.3 Model including CO_2 emissions

Adding the cost of CO2 emissions to the TCO plays in favour of cleaner technologies, but only marginally. The problem here is that the cost per tonne of CO2 recommended by the UK government is too low to make any difference. In fact, the costs per tonne of CO2 recommended by most governments and accepted in the academic literature are, in general, low, as previously found by Liu and Santos (2015) for the US case, Olson (2015) for the Norwegian case, and Zhao et al. (2015) for the Chinese case. All three papers argue that subsidies are not efficient from an economic point of view, mainly because of the low values of CO2 costs assumed.

The ratios of TCO taking petrol as the reference barely change when the central values of non-traded CO2 emissions (UK Department for Transport, 2018e, Table A 3.4) are added to the model. This applies to all car size categories, all discount rates, and for the model with and the one without taxes and subsidies. Adding the cost of CO2 emissions to the model that includes all current taxes and subsidies is essentially double counting, because energy taxes and vehicle subsidies and taxes are already designed with CO2 emissions in mind. Nonetheless, the exercise was conducted to illustrate that the current CO2 values recommended by the UK government make no difference to the results. Table 9 shows the TCO ratios once the costs of CO2 are taken into account.

Testing for sensitivity, the results stay virtually unchanged when the high non-traded values (UK Department for Transport, 2018e, Table A 3.4), instead of the central ones, are used. Furthermore, doubling these high non-traded values changes TCO ratios only slightly, and does not affect the conclusions. These results are shown in Appendix B.

The cost of carbon would need to take much higher values than those generally accepted by the scientific community in order to trigger any change leading to substantial emission reductions (Santos, 2017b, p. 73).

Table 9: Total Costs of Ownership ratios, including CO2 costs, with petrol car as the reference

Vehicles		Without taxes or subsidies				With taxes and subsidies			
		0%	6%	30%	60%	0%	6%	30%	60%
Small	Fiesta petrol	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Fiesta diesel	1.03	1.05	1.09	1.11	0.98	1.00	1.06	1.09
	Yaris Hybrid	1.02	1.05	1.10	1.12	0.97	0.99	1.06	1.09
	Mini PHEV	1.39	1.53	1.85	1.98	1.15	1.28	1.58	1.73
	i3 EV	1.44	1.60	1.96	2.11	1.01	1.16	1.52	1.70
Medium	Focus petrol	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Golf diesel	0.98	0.98	0.99	0.99	1.02	1.01	1.00	1.00
	Auris Hybrid	1.03	1.04	1.06	1.07	1.05	1.05	1.07	1.07
	BMW PHEV	1.27	1.37	1.56	1.64	1.15	1.24	1.43	1.50
	Leaf EV	1.07	1.12	1.23	1.27	0.80	0.86	0.98	1.03
Large	Qashqai petrol	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Qashqai diesel	1.00	1.02	1.05	1.06	0.94	0.97	1.02	1.04
	C-HR Hybrid	1.06	1.09	1.15	1.17	1.00	1.03	1.11	1.14
	Outlander PHEV	1.29	1.40	1.63	1.72	1.08	1.19	1.43	1.53
	Tesla EV	2.44	2.69	3.22	3.42	1.89	2.16	2.77	3.03

Note: Base year: 2017. Period modelled: 2017-2029
Source: Own calculations

Given that CO_2 emissions from road transport need to be drastically reduced and eventually brought down to zero, and that the time window is rapidly closing, the obvious question is what financial incentives would make cleaner technologies competitive, and what cleaner technologies should be favoured.

Within each size category, CO_2 emissions are highest for petrol cars, followed by diesel vehicles, HEVs, PHEVs and BEVs, in that order. Because of the models that made it to the medium size category, our medium diesel car emits slightly higher CO_2 per km than the petrol car in that size category. This, however, is a feature specific to the two models in question: the Focus petrol and the Golf diesel. In general, however, diesel cars tend to emit less CO_2 because although emissions per litre are higher for diesel than for petrol, emissions per km are lower due to the higher fuel efficiency of diesel relative to petrol. Because of this, diesel in Europe, including the UK, was perceived as an easy and quick way of reducing CO_2 emissions from road transport, and this opportunity was seized by car manufacturers, who managed to comply with CO_2 targets with little effort (Transport and Environment, 2018). Leaving to one side that CO_2 emissions per km from diesel are no more than 25% to 30% lower than those from petrol, and this is nowhere enough to decarbonise road transport, diesel was classified as 'carcinogenic' by the World Health Organization in 2012 (International Agency for Research on Cancer, 2012) so this in itself constitutes a good reason to phase it out. In addition, there is ample evidence that diesel vehicles produce disproportionally more air pollution than other vehicles, and that air pollution has negative impacts on the respiratory, cardiovascular and neurological systems (Liu and Grigg, 2018). That is why diesel vehicles in the UK pay a higher VED rate, as shown in Table 4, and discussed in Section 3.1.4.

The Clean Air Strategy 2019 (UK Department for Environment, Food and Rural Affairs, 2019) also sets very ambitious targets for cleaning the air in the UK, partly banking on the sales ban of (petrol and) diesel cars by 2040, or potentially, 2035, pending the results of the 2020 consultation discussed in Section 1. Last but not least, the diesel emissions scandal that broke in September 2015 has made it difficult to promote the idea that diesel can be reconciled with reductions in air pollution (Schiermeier, 2015).

The emissions from PHEVs are between 40% and 50% lower than those from HEVs, depending on the car make and model. The present value of the total costs of CO2 emissions of all the vehicles modelled under the four discount rates is shown in Table 10.

Table 10: Present value of costs of CO2 emitted, in £, 2017 prices

	Vehicles	0%	6%	30%	60%
Small	Fiesta petrol	1,335	953	413	257
	Fiesta diesel	1,114	796	344	215
	Yaris Hybrid	975	696	301	188
	Mini PHEV	569	406	176	110
	i3 EV	0	0	0	0
Medium	Focus petrol	1,218	870	377	235
	Golf diesel	1,230	879	380	237
	Auris Hybrid	1,056	754	327	204
	BMW PHEV	511	365	158	99
	Leaf EV	0	0	0	0
Large	Qashqai petrol	1,497	1,069	463	289
	Qashqai diesel	1,149	821	355	222
	C-HR Hybrid	998	713	309	193
	Outlander PHEV	476	340	147	92
	Tesla EV	0	0	0	0

Note: Base year: 2017. Period modelled: 2017-2029
Source: Own calculations

Table 10 confirms that the UK government is thinking in the right direction, as the financial incentives in place impact vehicles according to their CO2 emissions. For example, VED rates vary according to the car CO2 emissions. Also, petrol and diesel are heavily taxed, affecting not just petrol and diesel cars, but also HEVs and PHEVs.

It is also worth noting that the PHEVs and BEVs modelled in this study benefited from the subsidies that were in place in 2017, shown on Table 3 in Section 3. However, in October 2018, the PHEV subsidies, which were £2,500, were terminated, and the BEV subsidies were reduced from £4,500 to £3,500, to "ensure that the grant remains sustainable" (UK Office for Low

Emission Vehicles, 2018b). The BEV subsidies were then further reduced in March 2020, from £3,500 to £3,000, and cars costing £50,000 or more were excluded (UK Department for Transport and Office for Low Emission Vehicles, 2020b).

Given that PHEVs are not zero emission vehicles, eliminating PHEV subsidies, as the UK government has done, makes sense. However, reducing BEV subsidies, when purchase prices have not decreased, is debatable. With a subsidy of £3,000, the Leaf EV, for example, breaks even with the Focus petrol and the Golf diesel under a 6% discount rate but not under a 30% discount rate. The extended analysis in Appendix B shows that, as subsidies decrease, fewer BEVs are fully competitive with their petrol counterparts, and are only so at lower discount rates.

The following section reflects on potential policies that would help make BEVs more competitive.

4.4 Policies

Policies to accelerate electric vehicle market penetration can include a range of interventions that do not entail any financial incentives, such as use of bus lanes and low emission zones, or information campaigns, or actions that include some relatively minor financial incentives, such as free parking on public roads and exemption from charging in congestion charging zones or low emission zones.

In the present study, however, we concentrate on relative TCO and how these can be changed with taxes and subsidies.[12] From the environmental model in Section 4.3, it is clear that PHEVs, which are relatively very expensive and rely on fossil fuels to some extent, are clean*er* rather than clean. For that reason, and bearing in mind that the ultimate aim should be to completely decarbonise road transport, the removal of PHEV subsidies from October 2018 can be considered a step in the right direction. Policy efforts should concentrate on BEVs, which are zero emission.

If relative TCO are to be changed, the two potential avenues are subsidies and tax exemptions. We explore these options and discuss them below.

4.4.1 Subsidies

Subsidies for BEVs typically take the form of a one-off disbursement by the government, as is the case of plug-in grants in the UK. The actual amount will not only have an impact on TCO but will also have an impact on when the BEV breaks even with its petrol, diesel and HEV counterparts. If the present value of TCO is the same for BEVs and conventional technologies but the break-even point occurs far in the future, the attractiveness of BEVs is jeopardised.

The BMW i3 and the Tesla X sit at the high end of the market and attract consumers willing to pay higher TCO. The Tesla X is a luxury car, and because its price exceeds £50,000, it ceased

[12] We are not arguing that additional policies are not worth pursuing, and there is evidence that in some contexts they can work (Langbroek et al., 2016; Figenbaum, 2017; Li et al., 2020; Wang et al., 2019; Yu et al., 2018; Wang et al., 2017). In addition, some authors suggest that the development of a fast and reliable charging infrastructure is the most effective policy any government could implement (Bakker and Trip, 2013; Sierzchula et al., 2014; Lieven, 2015; Bonges III and Lusk, 2016; Mersky et al., 2016; Egbue et al., 2017; Wang et al., 2017; Santos and Davies, 2020).

to be eligible for a plug-in grant in March 2020. This seems reasonable, and in line with the recommendation by Hardman et al. (2017) that incentives should not be available on high-end BEVs. Although Tesla X buyers are typically high-end consumers, Clinton and Steinberg (2019) find that the statistically significant positive impact from electric vehicle purchase rebates in the US does not vary significantly by the make of the vehicle purchased, such as a Tesla versus a non-Tesla. Despite that result, it can be argued that helping mass penetration of BEVs in the UK is not about subsidising very expensive cars but about subsidising BEVs from mass market brands. Mass market BEVs have the potential of breaking even with their petrol counterparts, provided they receive some help, at least in the short to medium term.

The extended analysis in Appendix B shows that the subsidy reductions implemented in 2018 and 2020 are likely to delay rather than accelerate BEV market penetration in the UK. BEVs are more likely to break even with the petrol reference in their size category when subsidies are higher. Higher subsidies also move breakeven points forward in time, and this is especially important for impatient consumers with high discount rates.

Registrations of new grid-dependent vehicles represent under 3% of total new registrations (UK Department for Transport, 2020a). Reinstating the £4,500 subsidy would boost BEV sales. The subsidies would only be needed for a few years, until BEVs are competitive, or until a predetermined market share has been reached. With the generally accepted values of CO2, these subsidies would not be efficient from an economic point of view. They would, however, make much sense from an environmental perspective, and would help decarbonise road transport.

4.4.2 Tax exemptions

Breetz and Salon (2018) note that an 8% sales tax in the US applied to a car with a relatively high purchase price can cancel out years of fuel savings. Plug-in grants in the UK could be replaced with an exemption from VAT.

Exempting BEVs from VAT would effectively be equivalent to a subsidy of 20% of the cost of the car. Such a policy would make lower priced BEVs, such as those modelled in Appendix B, more competitive and attractive to mass market consumers. The VAT applicable to these cars is, in all cases, higher than the £3,000 plug-in grant offered by the government as of 2020. Given the high cost to the Treasury in terms of foregone tax revenue, especially in the case of expensive cars, a compromise could entail capping the VAT exemption at £4,500, which was the plug-in grant offered by the government until October 2018. In addition, cars with price tags in excess of 50,000 could be excluded from the VAT exemption, just like they are from the plug-in grant.

4.4.3 Final thoughts on financial incentives

Excluding ultra-low emission vehicles that are non-zero emission and cars with price tags in excess of £50,000 from the plug-in grant, as the UK government has done, is sensible. However, reducing the plug-in grant from £4,500 in 2017 to £3,000 in 2020 is not. Reinstating the £4,500 plug-in grant or replacing it with VAT exemptions for battery electric vehicles, capped at £4,500, are financial incentives likely to be effective, as there is evidence showing that buyers are especially sensitive to incentives that affect the initial cost (Hardman et al., 2017; Ghasri et al., 2019). Subsidies have also been found to have a statistically significant positive impact on the number of new EV registrations in the US (Wee et al., 2018; Clinton and Steinberg, 2019).

5. Conclusions and policy implications

In this study we have assessed whether electric vehicles need subsidies in the UK by comparing the TCO of petrol, diesel, hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicles bought in the UK in 2017, for three different size categories of cars: large, medium and small. For each size category and propulsion type we used the model with the highest number of first-time registrations in 2017. We then extended the analysis to include lower priced battery electric vehicles.

One methodological contribution of the present study is that, unlike most previous TCO calculations, our baseline model excludes all taxes and subsidies. This helps understand where the different TCO stand relative to one another. We then added all taxes and subsidies applicable to the period 2017-2029, and conducted an extensive sensitivity analysis.

Our findings show that TCO are very sensitive to the initial car price. Lower priced electric vehicles are not far from reaching cost parity, but they still need subsidies if mass market penetration of electric vehicles is to be accelerated, as subsidies help bring breakeven points forward in time.

Given that plug-in hybrids are not zero emission, the government’s scrappage of subsidies for this propulsion type is a sensible step. The reduction of the plug-in grant for zero emission cars from £4,500 in 2017 to £3,000 in 2020, however, does not seem warranted, given the government target to end the sale of all new conventional petrol and diesel cars and vans by 2040, or 2035, pending the results of the 2020 consultation.

Battery electric vehicles in the UK need subsidies. This result is in line with findings for other countries (Liu and Santos, 2015; Zhao et al., 2015; Bubeck et al., 2016; Diao et al., 2016; Hagman et al., 2016; Hao et al., 2017; Lévay et al., 2017; Breetz and Salon, 2018; Palmer et al., 2018; Danielis et al., 2018; Weldon et al., 2018; Scorrano et al., 2020). Increasing the plug-in grant back to £4,500 for zero emission cars or replacing it with VAT exemptions, perhaps capped at £4,500, is likely to boost the sale of battery electric vehicles.

One important caveat to this policy recommendation, however, is that, as already highlighted, there is the possibility that consumers may ignore TCO when choosing what car to buy, or they may be myopic/inattentive, or they may be reluctant to buy battery electric vehicles due to range anxiety. Having said that, it is reasonable to assume that if (higher) subsidies were in place, consumers that in the absence of (or the presence of lower) subsidies would have not even considered buying a battery electric vehicle, would at least consider the idea. Purchase subsidies can be very effective (Hardman et al., 2017; Ghasri et al., 2019, Wee et al., 2018; Clinton and Steinberg, 2019) and this would be especially the case if, as proposed by Dumortier et al. (2015), consumers were provided with information on TCO in promotional materials or car labels.

Once battery prices have fallen enough to make battery electric vehicles competitive, or a predetermined market share has been reached, subsidies will no longer be needed. A large share of battery electric vehicles will also result in substantially lower revenues from fuel duties, which represented 5.5% of total tax revenue in 2018/19.[13] This is a problem that will need to be addressed, but falls outside the scope of the present study.

[13] This is exclusive of VAT receipts, and was computed as revenues from fuel and vehicle duties, £34.4 billion (UK Department for Transport, 2019b, Table TSGB1311/RDE0103), divided by total tax revenues, £620.3 billion, for 2018/19 (HM Revenue & Customs, 2020, p. 6, Table 1).

Appendix A: Car manufacturers' websites

Audi e-tron Quattro pricing and electricity consumption ⟨https://www.audi.co.uk⟩

BMW i3 and BMW 330e pricing, fuel and electricity consumption and emissions information. ⟨https://www.bmw.co.uk/⟩

Ford Fiesta and Ford Focus pricing, fuel consumption and emissions information. ⟨https://www.ford.co.uk/⟩

Hyundai Kona Electric pricing and electricity consumption ⟨https://www.hyundai.co.uk⟩

Kia e-Niro pricing and electricity consumption ⟨https://www.kia.com⟩

Mini Countryman PHEV pricing, fuel consumption and emissions information. ⟨https://www.mini.co.uk/en_GB/home.html⟩

Mitsubishi Outlander pricing, fuel consumption and emissions information. ⟨http://www.mitsubishi-cars.co.uk/⟩

Nissan Leaf and Nissan Qashqai pricing, fuel and electricity consumption and emissions information. ⟨https://www.nissan.co.uk/⟩

Renault ZOE pricing and electricity consumption ⟨https://www.renault.co.uk⟩

Skoda CitiGoE pricing ⟨https://www.skoda.co.uk/⟩ and electricity consumption ⟨https://www.electrive.com/2019/11/21/skoda-begins-manufacturing-the-citigo-e-iv/⟩

Tesla Model X electricity consumption information. ⟨https://www.fueleconomy.gov/feg/PowerSearch.do?action=noform&path=1&year1=2017&year2=2018&make=Tesla&baseModel=Model%20X&srchtyp=ymm⟩

Tesla Model X pricing information. ⟨https://www.tesla.com/en_GB/⟩

Toyota Yaris, Toyota Auris and Toyota CH-R pricing, fuel consumption and emissions information. ⟨https://www.toyota.co.uk/⟩

Volkswagen Golf and e-up! pricing, fuel and electricity consumption and emissions information. ⟨https://www.volkswagen.co.uk/⟩

Appendix B: Sensitivity analysis

In this Appendix we conduct an extensive sensitivity analysis of the model with respect to fuel consumption, fuel prices, place of battery charging (home versus work/commercial points), average speed, cost of CO2, and car purchase price. We do this for the model without any taxes or subsidies.

The findings of this sensitivity analysis are that the conclusions of the model remain the same under all discount rates, except, as could have been expected, when the purchase price of PHEVs and BEVs is changed.

Sensitivity of the model with respect to fuel consumption

The fuel consumption of petrol and diesel cars and HEVs was doubled and halved, to substantially increase and decrease their costs of operation, and in so doing, to decrease and increase the difference in TCO with respect to their PHEV and BEV counterparts.

As it can be seen on Table B1, halving or doubling fuel consumption makes virtually no difference to the TCO ratios, regardless of the discount rate used.

Sensitivity of the model with respect to fuel prices

Petrol and diesel prices fell in 2020 due to exceptional and unprecedented circumstances, caused by a dual shock in both demand and supply of oil. Demand for oil worldwide was drastically reduced due to COVID-19, a Pandemic that caused virtually all the countries in the world to introduce restrictions on the movement of people, bringing mobility “almost to a halt” (International Energy Agency, 2020). The problem was exacerbated by the breakdown in negotiations between the Organization of the Petroleum Exporting Countries (OPEC) and Russia, which led to an over-supply of oil (Arezki and Nguyen, 2020), a problem that was only partly tackled in April that year when they agreed to cut production. In the UK, for example, the pre-tax price of petrol and diesel fell by 33% and 27%, respectively, over the first four months of 2020.

In order to test for sensitivity, we reduced pre-tax fuel prices for all years by 50%, which is exactly equivalent to halving fuel consumption. Even under this extreme assumption, the model conclusions do not change, as can be seen from the TCO ratios in Table B1.

Sensitivity of the model with respect to place of battery charging

The assumption of 2/3 of charging done at home and 1/3 of charging done at work or at commercial stations is arbitrary, so we tested for sensitivity of results by assuming that all the charging was done at home, or all the charging was done at work. The change makes no difference to the conclusions, as can be seen from Table B1.

Sensitivity of the model with respect to speed

We doubled and halved the average speed assumed and the TCO ratios remain virtually unchanged, as Table B1 shows.

Sensitivity of the model with respect to costs of CO2

The central non-traded values of CO_2, from Table A 3.4 of the WebTAG Data Book (UK Department for Transport, 2018e) were used in all the calculations reported in the body of the paper. In order to test for sensitivity of TCO with respect to costs of CO_2, the higher non-traded values of CO_2 from the same table were used, and a further test was done by doubling the higher values. The TCO ratios yield the same conclusions, regardless of the CO_2 value used.

Sensitivity of the model with respect to PHEV and BEV purchase price

One of the most important parameters for the calculation of TCO is the purchase price. In order to test for sensitivity, we halved the purchase price of PHEVs and BEVs and, as expected, this changed the results, as it can be seen on Table B1. This is not a weakness of our model but a strength, as it shows that the initial price is of fundamental importance for TCO.

Table B1: Sensitivity analysis

	Vehicle size	Small					Medium					Large				
	Propulsion type	Petrol	Diesel	Hybrid	PHEV	EV	Petrol	Diesel	Hybrid	PHEV	EV	Petrol	Diesel	Hybrid	PHEV	EV
	Reference	Fiesta petrol	Fiesta diesel	Yaris Hybrid	Mini PHEV	i3 EV	Focus petrol	Golf diesel	Auris Hybrid	BMW PHEV	Leaf EV	Qashqai petrol	Qashqai diesel	C-HR Hybrid	Outlander PHEV	Tesla EV
0%	**Baseline**	**1.00**	**1.04**	**1.04**	**1.44**	**1.52**	**1.00**	**0.98**	**1.03**	**1.31**	**1.11**	**1.00**	**1.01**	**1.09**	**1.35**	**2.57**
	Half fuel consumption	1.00	1.07	1.07	1.57	1.65	1.00	0.99	1.05	1.39	1.18	1.00	1.04	1.12	1.45	2.76
	Double fuel consumption	1.00	1.00	1.00	1.25	1.32	1.00	0.97	1.02	1.18	1.00	1.00	0.97	1.04	1.18	2.26
	Half fuel prices	1.00	1.07	1.07	1.53	1.65	1.00	0.99	1.05	1.36	1.18	1.00	1.04	1.12	1.42	2.76
	Double fuel prices	1.00	1.00	1.00	1.31	1.32	1.00	0.97	1.02	1.22	1.00	1.00	0.97	1.04	1.22	2.26
	100% of battery charging done at home	1.00	1.04	1.04	1.46	1.54	1.00	0.98	1.03	1.32	1.13	1.00	1.01	1.09	1.36	2.59
	100% of battery charging done at work or at commercial stations	1.00	1.04	1.04	1.41	1.49	1.00	0.98	1.03	1.28	1.07	1.00	1.01	1.09	1.32	2.52
	Half speed	1.00	1.04	1.04	1.43	1.51	1.00	0.98	1.03	1.30	1.11	1.00	1.01	1.09	1.33	2.55
	Double speed	1.00	1.04	1.04	1.45	1.53	1.00	0.98	1.04	1.32	1.11	1.00	1.01	1.09	1.35	2.58
	With CO2 non-traded values	1.00	1.03	1.02	1.39	1.44	1.00	0.98	1.03	1.27	1.07	1.00	1.00	1.06	1.29	2.44
	With CO2 non-traded values (high estimates)	1.00	1.02	1.02	1.36	1.40	1.00	0.98	1.02	1.25	1.04	1.00	0.99	1.05	1.27	2.37
	With CO2 non-traded values (twice the high estimates)	1.00	1.01	0.99	1.29	1.29	1.00	0.98	1.01	1.20	0.98	1.00	0.98	1.03	1.20	2.20
	Purchase price halved for PHEVs and BEVs	1.00	1.04	1.04	0.86	0.89	1.00	0.98	1.03	0.76	0.70	1.00	1.01	1.09	0.78	1.43
6%	**Baseline**	**1.00**	**1.06**	**1.06**	**1.58**	**1.68**	**1.00**	**0.98**	**1.04**	**1.40**	**1.16**	**1.00**	**1.03**	**1.11**	**1.45**	**2.81**
	Half fuel consumption	1.00	1.08	1.09	1.69	1.79	1.00	0.99	1.05	1.47	1.22	1.00	1.05	1.14	1.54	2.98
	Double fuel consumption	1.00	1.02	1.02	1.41	1.49	1.00	0.97	1.03	1.29	1.07	1.00	0.99	1.07	1.31	2.53

	Half fuel prices	1.00	1.08	1.09	1.66	1.79	1.00	0.99	1.05	1.45	1.22	1.00	1.05	1.14	1.52	2.98
	Double fuel prices	1.00	1.02	1.02	1.45	1.49	1.00	0.97	1.03	1.32	1.07	1.00	0.99	1.07	1.34	2.53
	100% of battery charging done at home	1.00	1.06	1.06	1.60	1.69	1.00	0.98	1.04	1.41	1.18	1.00	1.03	1.11	1.46	2.83
	100% of battery charging done at work or at commercial stations	1.00	1.06	1.06	1.56	1.65	1.00	0.98	1.04	1.38	1.13	1.00	1.03	1.11	1.43	2.77
	Half speed	1.00	1.06	1.06	1.57	1.67	1.00	0.98	1.04	1.39	1.16	1.00	1.03	1.11	1.44	2.79
	Double speed	1.00	1.06	1.06	1.59	1.68	1.00	0.98	1.04	1.41	1.16	1.00	1.03	1.11	1.46	2.82
	With CO2 non-traded values	1.00	1.05	1.05	1.53	1.60	1.00	0.98	1.04	1.37	1.12	1.00	1.02	1.09	1.40	2.69
	With CO2 non-traded values (high estimates)	1.00	1.04	1.04	1.50	1.56	1.00	0.98	1.04	1.35	1.10	1.00	1.01	1.08	1.38	2.64
	With CO2 non-traded values (twice the high estimates)	1.00	1.03	1.02	1.43	1.46	1.00	0.98	1.03	1.31	1.05	1.00	1.00	1.06	1.32	2.48
	Purchase price halved for PHEVs and BEVs	1.00	1.06	1.06	0.91	0.95	1.00	0.98	1.04	0.79	0.69	1.00	1.03	1.11	0.81	1.53
30%	**Baseline**	**1.00**	**1.10**	**1.11**	**1.88**	**2.01**	**1.00**	**0.99**	**1.06**	**1.58**	**1.25**	**1.00**	**1.06**	**1.16**	**1.66**	**3.29**
	Half fuel consumption	1.00	1.12	1.12	1.95	2.09	1.00	0.99	1.07	1.62	1.28	1.00	1.07	1.18	1.71	3.39
	Double fuel consumption	1.00	1.08	1.08	1.76	1.88	1.00	0.98	1.05	1.51	1.20	1.00	1.04	1.14	1.57	3.11
	Half fuel prices	1.00	1.12	1.12	1.94	2.09	1.00	0.99	1.07	1.61	1.28	1.00	1.07	1.18	1.70	3.39
	Double fuel prices	1.00	1.08	1.08	1.79	1.88	1.00	0.98	1.05	1.53	1.20	1.00	1.04	1.14	1.59	3.11
	100% of battery charging done at home	1.00	1.10	1.11	1.89	2.02	1.00	0.99	1.06	1.59	1.26	1.00	1.06	1.16	1.67	3.30
	100% of battery charging done at work or at commercial stations	1.00	1.10	1.11	1.87	2.00	1.00	0.99	1.06	1.57	1.24	1.00	1.06	1.16	1.65	3.27
	Half speed	1.00	1.10	1.11	1.87	2.01	1.00	0.99	1.06	1.58	1.25	1.00	1.06	1.16	1.66	3.28
	Double speed	1.00	1.10	1.11	1.89	2.02	1.00	0.99	1.06	1.59	1.26	1.00	1.06	1.16	1.67	3.30
	With CO2 non-traded values	1.00	1.09	1.10	1.85	1.96	1.00	0.99	1.06	1.56	1.23	1.00	1.05	1.15	1.63	3.22

	With CO2 non-traded values (high estimates)	1.00	1.09	1.09	1.83	1.93	1.00	0.99	1.06	1.55	1.22	1.00	1.05	1.15	1.62	3.18
	With CO2 non-traded values (twice the high estimates)	1.00	1.08	1.08	1.77	1.86	1.00	0.99	1.05	1.52	1.19	1.00	1.04	1.13	1.57	3.07
	Purchase price halved for PHEVs and BEVs	1.00	1.10	1.11	1.01	1.07	1.00	0.99	1.06	0.84	0.69	1.00	1.06	1.16	0.88	1.71
60%	**Baseline**	**1.00**	**1.12**	**1.13**	**2.01**	**2.15**	**1.00**	**0.99**	**1.07**	**1.65**	**1.29**	**1.00**	**1.07**	**1.18**	**1.75**	**3.48**
	Half fuel consumption	1.00	1.13	1.13	2.06	2.21	1.00	0.99	1.07	1.68	1.31	1.00	1.08	1.19	1.78	3.55
	Double fuel consumption	1.00	1.10	1.11	1.92	2.06	1.00	0.98	1.06	1.60	1.25	1.00	1.05	1.16	1.68	3.35
	Half fuel prices	1.00	1.13	1.13	2.05	2.21	1.00	0.99	1.07	1.67	1.31	1.00	1.08	1.19	1.77	3.55
	Double fuel prices	1.00	1.10	1.11	1.94	2.06	1.00	0.98	1.06	1.62	1.25	1.00	1.05	1.16	1.69	3.35
	100% of battery charging done at home	1.00	1.12	1.13	2.02	2.16	1.00	0.99	1.07	1.66	1.30	1.00	1.07	1.18	1.75	3.49
	100% of battery charging done at work or at commercial stations	1.00	1.12	1.13	2.00	2.14	1.00	0.99	1.07	1.65	1.28	1.00	1.07	1.18	1.74	3.46
	Half speed	1.00	1.12	1.12	2.00	2.15	1.00	0.99	1.07	1.65	1.29	1.00	1.07	1.18	1.74	3.47
	Double speed	1.00	1.12	1.13	2.02	2.16	1.00	0.99	1.07	1.66	1.29	1.00	1.07	1.18	1.75	3.48
	With CO2 non-traded values	1.00	1.11	1.12	1.98	2.11	1.00	0.99	1.07	1.64	1.27	1.00	1.06	1.17	1.72	3.42
	With CO2 non-traded values (high estimates)	1.00	1.11	1.11	1.97	2.09	1.00	0.99	1.07	1.63	1.27	1.00	1.06	1.17	1.71	3.40
	With CO2 non-traded values (twice the high estimates)	1.00	1.10	1.10	1.92	2.04	1.00	0.99	1.06	1.61	1.24	1.00	1.06	1.16	1.68	3.32
	Purchase price halved for PHEVs and BEVs	1.00	1.12	1.13	1.05	1.12	1.00	0.99	1.07	0.86	0.68	1.00	1.07	1.18	0.90	1.78

Source: own calculations

Lower priced BEV models

The price of the specific plug-in models chosen for analysis did not change between 2017 and 2020, after adjusting for inflation. However, the question that arises from the results of halving their initial purchase price, is whether there are any plug-in vehicles in the market that have a price which is around 50% of the prices of the cars modelled in this study for the small and large size categories, and would therefore comfortably break even with their petrol counterparts, just like the Nissan Leaf in the medium size category does.

Concentrating on BEVs, which are zero emission, examples in the small size category include the Skoda CitiGoE and the Volkswagen e-up!, with price tags which are 56% and 65% that of the BMW i3, respectively. The Renault ZOE has an initial purchase price which is 81% that of the BMW i3. In the large size category, the Hyundai Kona Electric and the Kia e-Niro have purchase prices which are 41% and 49% that of the Tesla X, respectively, and the Audi e-tron Quattro has a purchase price which is 75% that of the Tesla X.

Table B2 breaks down the prices of these BEVs and Table B3 shows the TCO ratios, with and without taxes and subsidies, with the petrol car as the reference. One important feature of the TCO ratios of these cars is that some of them are not far from reaching cost parity, even when taxes and subsidies are excluded from the calculations. The Skoda CitiGoE, in particular, has a TCO ratio of 0.99 under a 0% discount rate.

For comparison purposes, the calculations are done including the 2017 subsidies, but also the reduced subsidies that came into effect in October 2018 and March 2020. As expected, the lower the initial purchase price, and the higher the subsidy, the more likely these BEVs are to break even with the petrol reference in their size category.

In addition, although not shown on the table, the breakeven point for those BEVs that have lower TCO than their petrol reference, occurs earlier in time when the subsidy is higher, and this is important for impatient consumers with high discount rates.

Table B2: Examples of lower priced BEV models available in 2020

	Small BEVs			Large BEVs		
Make and model	Skoda CitiGoE	Volkswagen e-UP	Renault ZOE	Hyundai Kona Electric	Kia e-Niro	Audi e-tron Quattro
Base price £ (no tax)	15533	17946	22601	25321	30214	46454
VAT 20%	3107	3589	4520	5064	6043	9291
Price inc. VAT (£)	18640	21536	27121	30386	36257	55744
Electricity consumption kWh/100km	14.8	14.5	17.3	15.0	15.9	24.4

Source: Car prices and energy consumption from manufacturers' websites (listed in Appendix A), except for Skoda CitiGoE, whose energy consumption was taken from Randall (2019). All monetary values expressed in 2017 prices.

Table B3: Total Costs of Ownership ratios, with petrol car as the reference

		No taxes or subsidies				**2017 taxes and subsidies**				**2018 taxes and subsidies**				**2020 taxes and subsidies**			
		0%	6%	30%	60%	0%	6%	30%	60%	0%	6%	30%	60%	0%	6%	30%	60%
	Skoda CitiGoE	0.99	1.05	1.19	1.25	0.62	0.68	0.82	0.88	0.65	0.72	0.87	0.94	0.67	0.73	0.90	0.97
Small	Volkswagen e-UP	1.09	1.18	1.35	1.43	0.71	0.78	0.96	1.05	0.74	0.82	1.01	1.11	0.75	0.84	1.04	1.13
	Renault ZOE	1.34	1.45	1.69	1.78	0.90	1.00	1.26	1.38	0.93	1.04	1.31	1.43	0.94	1.06	1.33	1.46
	Hyundai Kona Electric	1.17	1.25	1.40	1.46	0.83	0.90	1.10	1.18	0.84	0.93	1.13	1.21	0.85	0.94	1.15	1.23
Large	Kia e-Niro	1.36	1.46	1.66	1.73	0.98	1.08	1.34	1.44	0.99	1.11	1.36	1.47	1.00	1.12	1.38	1.49
	Audi e-tron Quattro	2.04	2.20	2.53	2.65	1.53	1.70	2.12	2.29	1.54	1.73	2.14	2.32	1.55	1.74	2.16	2.34

Note: The reference for the small size category is the Ford Fiesta Turbo and the reference for the large size category is the Nissan Qashqai DiG
Source: own calculations

Appendix C: Car comparisons

In this appendix, we systematically compare the five specific cars modelled within each size category in relation to the following features:

- Power in kW, which is the maximum power that the engine can put out;
- Acceleration, expressed as the number of seconds it takes for the vehicle to go from 0 to 100 km per hour;
- Weight, expressed in kg;
- Top speed, in km per hour;
- Fuel consumption in litres per 100 km, and for vehicles that combine fossil fuels and electricity or run on electricity only, an 'equivalent' fuel consumption;[14]

One additional feature we also use for a second set of comparisons is the purchase price including VAT.

We follow Nieuwenhuis (2014) and produce spider webs for each car. There are, however, two problems with Nieuwenhuis' graphs, as follows: (a) it is difficult to interpret them because some features, such as power, are desirable, whilst others, such as CO_2 emissions, are not desirable, yet they are all measured with positive numbers on the spider web; and (b) the units are different throughout (grams per km is different from km per hour, etc.).

[14] This number was taken from the manufacturer's technical specifications for the Tesla X. The manufacturer's technical specifications for the BMW i3 and the Leaf EV did not include any 'equivalent' fuel consumption, so this was computed using the standard conversion formula to convert kWh/100 miles to miles per US gallon equivalent, MPGe = 3370.5 ÷ kWh/100 miles, and then converted to litres per 100 km.

We therefore adapt Nieuwenhuis' method by first producing an index for each feature, defined as the actual value the feature takes for that particular car model, minus the minimum value the feature takes for that car category, all divided by the difference between the maximum and minimum values that the feature takes within that car category:

$$Feature\ index = \frac{actual\ value - minimum\ value}{maximum\ value - minimum\ value}$$

For the features which are not desirable, we compute $1 - feature\ index$. In this way, we solve the problem of units, and we make the indices comparable, as the most desirable values are those approaching 1.

Tables C1 shows the values for each feature and Table C2 shows the indices. Figure C1 shows the spider webs for the 15 cars modelled in this study.

Table C1: Car features

	Small cars					Medium cars					Large cars				
Propulsion type	Petrol	Diesel	HEV	PHEV	BEV	Petrol	Diesel	HEV	PHEV	BEV	Petrol	Diesel	HEVd	PHEV	BEV
Make	Ford	Ford	Toyota	Mini	BMW	Ford	VW	Toyota	BMW	Nissan	Nissan	Nissan	Toyota	Mitsu-bishi	Tesla
Model	Fiesta Turbo	Fiesta TDCi	Yaris	Coun-tryman Cooper	i3	Focus	Golf TDi	Auris Hybrid	330e	Leaf	Qash-qai DiG	Qash-qai dCi	C-HR HEV	Outla-nder	Model X
Reference	Fiesta petrol	Fiesta diesel	Yaris hybrid	Mini PHEV	i3 EV	Focus petrol	Golf diesel	Auris Hybrid	BMW PHEV	Leaf EV	Qash-qai petrol	Qash-qai diesel	C-HR Hybrid	Outla-nder PHEV	Tesla EV
Power in kW	63	85	74	165	75	74	85	73	185	110	85	81	90	89	245
Acceleration (0-100 kph in seconds)	13.8	12.4	11.8	6.8	7.3	12.5	10.2	10.9	6.1	7.9	10.6	11.9	11	11	5.2
Weight (kg)	1,113	1,191	1,127.5	1,635	1,270	1,313	1,301	1,310	1,769	1,530	1,331	1,393	1,380	1,860	2,352
Top speed (km per hour)	169	174	165	198	150	185	198	180	225	144	185	182	169	170	209
Fuel consumption l/100km combined (for electric an equivalent is given)	5.1	3.8	3.7	2.1	1.5	4.6	4.1	3.9	1.9	2.2	5.6	3.8	3.8	1.7	2.4
CO2 emissions mixed g/km	115	96	84	49	0	105	106	91	44	0	129	99	86	41	0
Price inc. VAT (£)	13470	15590	15699	31000	33340	19915	19686	21615	35902	27237	19081	20871	23345	36702	73984

Note: The Power in kW in the manufacturer's specifications of the Mini Countryman Cooper and the BMW 330e is the sum of the power of the electric motor and that of the internal combustion engine.
Source: Manufacturers' websites and https://ev-database.uk/

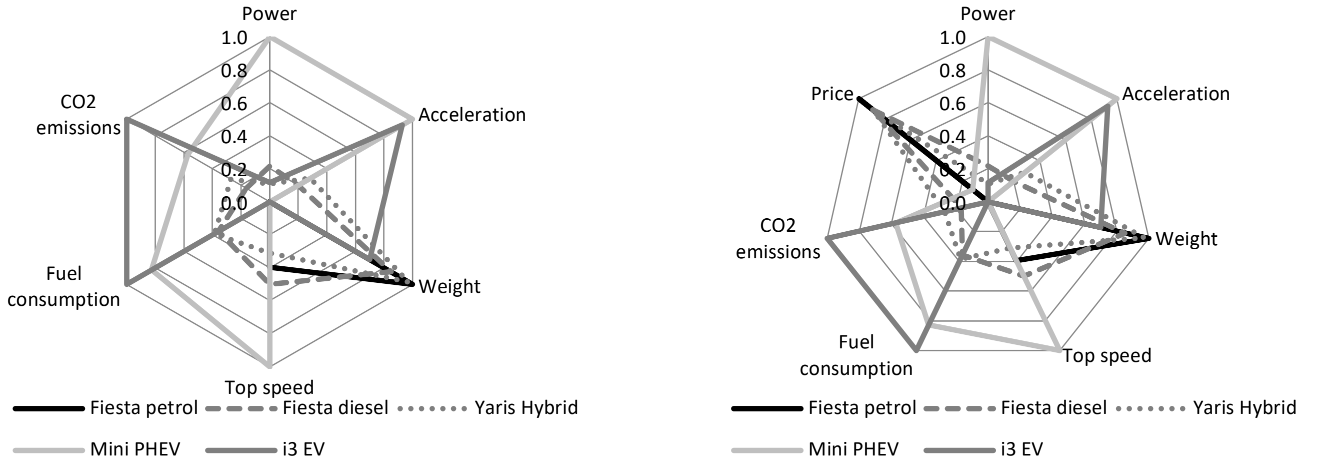
Table C2: Car feature indices

	Small cars					Medium cars					Large cars				
Propulsion type	Petrol	Diesel	HEV	PHEV	BEV	Petrol	Diesel	HEV	PHEV	BEV	Petrol	Diesel	HEVd	PHEV	BEV
Make	Ford	Ford	Toyota	Mini	BMW	Ford	VW	Toyota	BMW	Nissan	Nissan	Nissan	Toyota	Mitsu-bishi	Tesla
Model	Fiesta Turbo	Fiesta TDCi	Yaris	Coun-tryman Cooper	i3	Focus	Golf TDi	Auris Hybrid	330e	Leaf	Qash-qai DiG	Qash-qai dCi	C-HR HEV	Outla-nder	Model X
Reference	Fiesta petrol	Fiesta diesel	Yaris hybrid	Mini PHEV	i3 EV	Focus petrol	Golf diesel	Auris Hybrid	BMW PHEV	Leaf EV	Qash-qai petrol	Qash-qai diesel	C-HR Hybrid	Outla-nder PHEV	Tesla EV
Power	0	0.22	0.11	1	0.12	0.01	0.11	0	1	0.33	0.02	0	0.05	0.05	1
Acceleration	0	0.20	0.29	1	0.93	0	0.36	0.25	1	0.72	0.19	0	0.13	0.13	1
Weight	1	0.85	0.97	0	0.70	0.97	1.00	0.98	0	0.51	1.00	0.94	0.95	0.48	0
Top speed	0.40	0.50	0.31	1	0	0.51	0.67	0.44	1	0	0.40	0.33	0	0.03	1
Fuel consumption	0	0.36	0.39	0.83	1	0	0.19	0.26	1	0.90	0	0.46	0.46	1	0.82
CO2 emissions mixed	0	0.17	0.27	0.57	1	0.01	0	0.14	0.58	1	0	0.23	0.33	0.68	1
Price inc. VAT	1	0.89	0.89	0.12	0	0.99	1	0.88	0	0.53	1	0.97	0.92	0.68	0

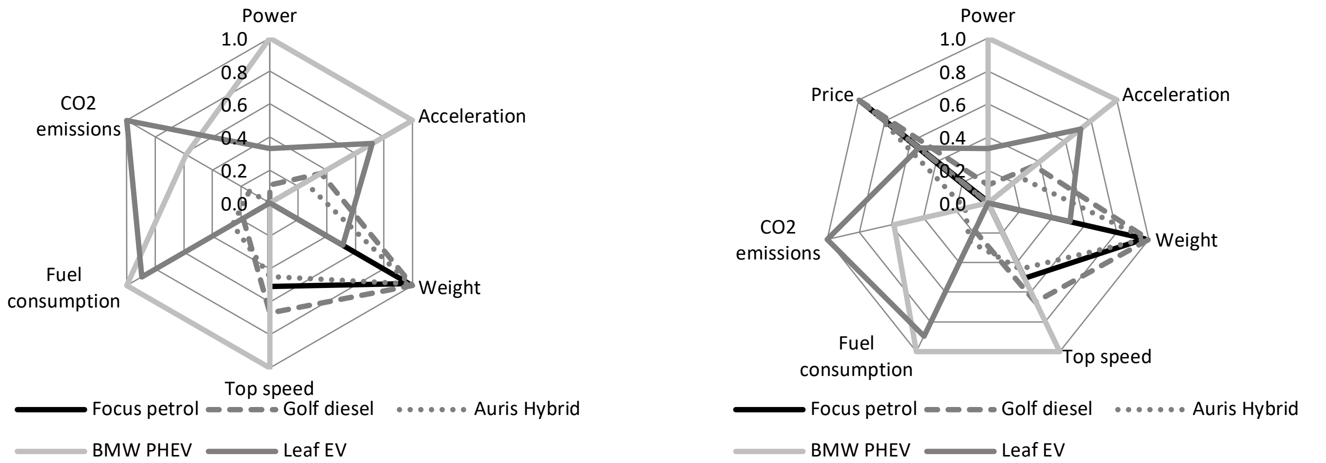
Source: Table C1

Figure C1: Spider webs for comparison of car features

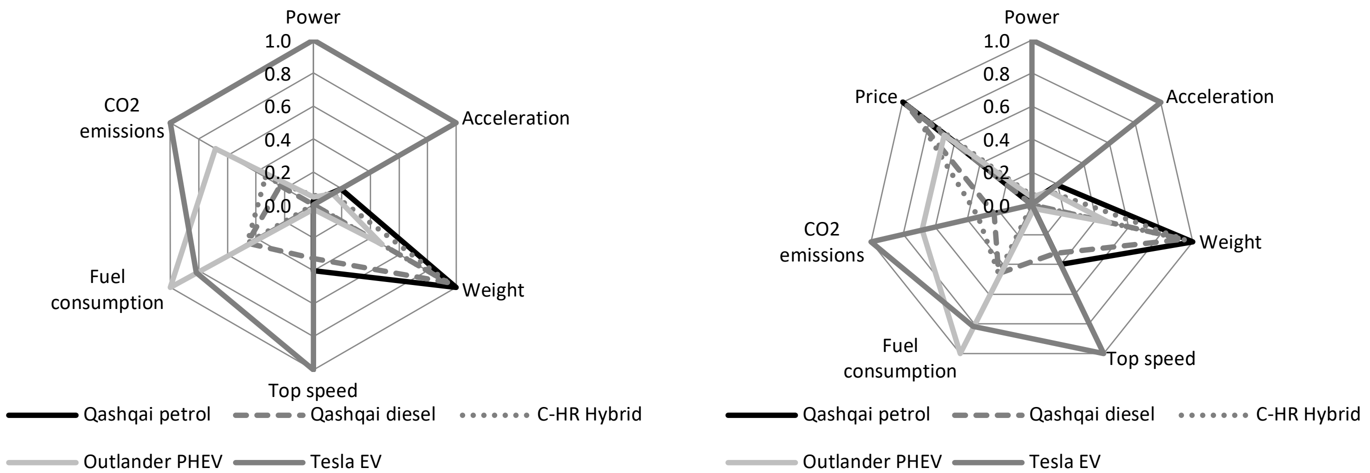
Small category



Medium category



Large category



Source: Table C1

What is crystal clear from all six graphs is that there is no single car that outperforms all others in terms of all features. A point worth noting, however, is that PHEVs and BEVs, which, unsurprisingly, have the best fuel economy and lowest CO2 emissions in each category, often score better than other cars in terms of power, or acceleration, or top speed, or even weight. There are always trade-offs and the final decision will depend on consumer's preferences, and importantly, budget constraints.

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