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Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan

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HIGHLIGHTS

- Ownership costs are compared for Electric, Hybrid, petrol and diesel vehicles.
- Total Cost of Ownership (TCO) is compared for UK, USA and Japan from 1997 to 2015.
- Hybrids are relatively cheaper in 2015 than the year of introduction.
- Market share of hybrids is strongly correlated with their relative TCO.
- At current low fuel prices in the UK, hybrids reach cost parity at 16,000 miles.

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ABSTRACT

New powertrain technologies, such as Hybrid Electric Vehicles, have a price premium which can often be offset by lower running costs. Total Cost of Ownership combines these purchase and operating expenses to identify the most economical choice of vehicle. This is a valuable assessment for private and fleet purchasers alike. Studies to date have not compared Total Cost of Ownership across more than two vehicle markets or analysed historic costs. To address this gap, this research provides a more extensive Total Cost of Ownership assessment of conventional, Hybrid, Plug-in Hybrid and Battery Electric Vehicles in three industrialized countries – the UK, USA (using California and Texas as case studies) and Japan – for the time period 1997–2015. Finally, the link between Hybrid Electric Vehicle Total Cost of Ownership and market share is analysed with a panel regression model.

In all regions the incremental Total Cost of Ownership of hybrid and electric vehicles compared to conventional vehicles has reduced from the year of introduction and 2015. Year on year Hybrid Electric Vehicles Total Cost of Ownership was found to vary least in the UK due to the absence of subsidies. Market share was found to be strongly linked to Hybrid Electric Vehicle Total Cost of Ownership through a panel regression analysis. Financial subsidies have enabled 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 haven't received as much financial backing. This research has implications for fleet purchasers and private owners who are considering switching to a low-emission vehicle. The findings are also of interest to policymakers that are keen to develop effective measures to stimulate decarbonisation of the fleet and improve air quality.

1. Introduction

Electrification of the transport sector offers the opportunity to utilise the increasing share of renewable energy generation whilst reducing national oil dependency. Urban air pollution is also a serious concern for residents in many cities across the world. Poor air quality claims the lives of over seven million people annually worldwide [1]. Different types of electric vehicles such as Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs) emit lower levels of carbon dioxide and air pollutants than conventional petrol and diesel vehicles [2,3], contributing to the decarbonisation of road transport and improving urban air quality. Growing the fleet share of these low-emission vehicles is therefore of interest to policymakers.

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With a larger battery and features such as regenerative braking, engine stop-start and a novel transmission system [4], hybrid and electric vehicles have a higher manufacturing cost than conventional vehicles [5]. Conversely, running costs are often lower stemming from cheaper annual fuel costs, taxes and maintenance. Many countries have offered subsidies or reduced taxes for low-emission vehicles to stimulate adoption: for example the Plug-in vehicle grant in the UK [6], the Clean vehicle rebate project in California [7] and the Green vehicle purchasing promotion measures in Japan [8]. Total Cost of Ownership (TCO) calculations can determine whether subsidies and lower running costs can offset this price premium. Vehicle ownership costs are important in vehicle adoption choice for both private and business purchases. This is evidenced by stated and revealed preference surveys (for example see Ozaki et al. [9]). Over the past decade there has been a rise in the number of vehicles bought through finance especially in the UK [10], however, the amount paid through a typical three year finance model is comparable to the vehicle depreciation (see Section 3.2).

The Toyota Prius was one of the first hybrid cars developed. It was released exclusively to the Japanese market in 1997 [11]. The diversity of the hybrid market has grown such that nearly fifty different models are available in the US vehicle market from a range of brands [12]. In countries such as the UK and Japan, plateauing Prius market share may be attributed to the greater availability of different hybrid models such as the Auris, Yaris and Aqua. Evidence for this is the success of the Toyota Aqua in the Japanese market [13].

This study contributes to the literature in three key areas: investigating how TCO has changed historically, examining how TCO varies across different geographic regions and analytically assessing the relationship between hybrid vehicle TCO and adoption. By building a comprehensive TCO model for several different geographic periods over a time period of 16 years (the period when data was available for all geographic areas), a panel regression model is used to assess the effect of changing ownership costs on market share. The conclusions from the HEV TCO/market share analysis aim to inform how policies can be introduced to stimulate HEV, PHEV and BEV uptake. To assess the robustness of the cost model a sensitivity analysis is conducted for variation in mileage, fuel price, depreciation rate, ownership period and discount rate.

2. Literature review

Many TCO calculations have been published to assess the cost effectiveness of new vehicle technologies such as electric commercial vehicles (e.g. Falcão et al. [14]), electric buses (e.g. Li et al. [15]), plug-in hybrid trucks (e.g. Vora et al. [16]) and vehicle automation (e.g. Wadud [17]). As early as 2001 Lipman & Delucchi [18] compared the cost of different degrees of hybridizations across multiple vehicle segments. Since then, many other publications (see Table 1 for review of key studies in TCO literature) have compared the ownership costs of battery and hybrid electric vehicles. Many of the studies focus on a full spectrum of PHEVs with different battery sizes; to assess whether the cheaper costs of running a PHEV with a higher battery storage capacity offsets the larger initial battery price (for example Al-Alawi and Bradley [19] and Hutchinson et al. [4]). The studies in the literature largely conclude that without government support hybrid and electric vehicles are still more expensive than petrol or diesel cars.

Previous published TCO calculations usually only consider vehicle ownership costs in one country of geographic region (e.g. Gilmore and Patwardhan [23] considers passenger vehicle TCO in India, and Diao et al. [24] consider private car TCO in China). Hutchinson et al. [4] is the only study which compares hybrid vehicle TCO across more than one geographic region concluding that the high fuel price leads to a shorter pay back of less than 2.6 years for HEVs in the UK compared to 6.7 years in California. HEV TCO can vary substantially over different countries and American states as a result of varying fuel price, availability of low-emission vehicle incentives and region dependent

Table 1
Total cost of ownership literature summary.

	Lipman & Delucchi [20]	Thiel et al. [21]	Al-Alawi & Bradley [19]	Hutchinson et al. [4]	Wu et al. [22]	This paper
Vehicle class	Compact or mid-sized large car, pickup, minivan, SUV	Compact car	Compact car, Mid-sized car, Mid-sized SUV, Large SUV	Mid-sized car	Small, Medium and Large cars	Mid –sized car
Powertrain type	Five degrees of hybridization	BEV, PHEV, HEV	HEV, PHEV 5–60	Mild, HSD, Two-Mode, Inline Full, Plug-in HSD, Plug-in Series	BEV, PHEV, HEV	BEV, PHEV, HEV
Purchase year	2000	2010	2010	2013	2015	1997/2000–2015
Economic yr	2000$	2010€	2010$	2013$	2015€	2015£
Economic country	USA	Europe	USA	USA and UK	Germany	UK, USA (California, Texas), Japan
Annual vehicle miles travelled	Not specified -decreasing with age	15,000 km	12,000 miles/yr for cars decreasing with age	130 000 miles over lifetime	Three cases: 7484 km, 15 184 km and 28 434 km	10,400, 11,071, 15,641, 6213 miles/yr for UK, California, Texas and Japan.
Vehicle life	15 years	(payback time)	5 and 13 years	130,000 miles	6 years	3 years (ownership period)
Fuel economy	EPA adjusted	NEDC European average	EPA adjusted	Fuel saving tests for urban and highway	Literature.	Spritmoniter
Gasoline price model	1.46 ($/gallon)	Assumed 60% tax on top of European oil price projections	Forecasted over vehicle life	3.20, 7.70 for USA, UK ($/gallon)	Own forecast	Forecasted over vehicle lifetime
Incremental cost model	MSRP used	Yes	EPRI, 2001; Kalhammer et al., 2007	Brooker et al. 2010; Clearly et al. 2010	Yes, derived.	MSRP used
Salvage	None	None	Vehicle resale	Vehicle resale	Yes	Vehicle resale
Maintenance	Yes	None	Yes	None	No	Yes
Insurance	Yes	None	Yes	None	Yes	Yes
Tax model	Yes	None	Yes	None	Yes	Yes
Discount rate	None	5%	6%	None	4.1%	3.5% (UK, Japan) 4% (US states)

average mileage. Fuel price, average annual mileage, annual taxes and insurance prices along with driving style and congestion levels are state/country dependent (e.g. Saxena et al. [25]), therefore conclusions of studies from different geographic regions are not necessarily transferable.

As vehicle technology matures manufacturing costs decrease, therefore TCO calculations become outdated. For this reason, it is difficult to directly contrast and compare the findings of multiple publications with different base years. With over 15 years of hybrid cost data this raises questions over how vehicle ownership costs have changed as the market has developed.

TCO methodology has not been standardised in the literature (see Table 1 for details of components included in key published studies). It is apparent that factors such as maintenance, tax costs and vehicle resale are often excluded despite there being variation between vehicle types. Over a long time period such as that of this study, policies and cost incentives that play a crucial role in adoption of new technologies, particularly during the initial stages of deployment can also change. In this paper we deal with this by building a comprehensive model taking all significant vehicle ownership costs including financial incentives into account.

Regression analysis is a common approach to assessing the strength of the relationships between different variables. Relatively few studies have used regression analysis to explore the factors contributing to adoption of new powertrain technologies. Studies such as Diamond [26] use panel regression, examining both fixed and random effects, to assess the impact of incentives on vehicle adoption across different American states concluding that fuel price affects vehicle adoption more than incentives. Gallagher and Muehlegger [27] use a fixed effects model to consider the effect of incentives across different US states concluding that the type of incentive offered is as important as the size of it. Shewmake and Jarvis [28] analysed the link between hybrid vehicle adoption and High Occupancy Vehicle (HOV) lane access using a parametric regression model estimating Willingness-To-Pay figures for HOV lane access. However, studies from the TCO literature (see Table 1) have not used this approach to assess the effect of changing vehicle costs on sales, instead they have generally only focussed on costs at a single point in time.

3. Methods and data

3.1. TCO model overview

A cost comparison of a representative HEV, PHEV, and BEV has been performed across four different geographic regions. The Toyota Prius was first introduced in Japan in 1997. With HEVs now accounting for over 30% of new vehicle purchases [29], Japan is included in this comparison. Like Japan, California has a history of adopting low carbon policies years ahead of other states in the USA [30]. Consequently, hybrid and electric vehicles have been more popular in California than anywhere else in America [31]. The state of Texas has also been included to contrast with the Californian state because HEV/PHEV/BEV sales are lower but average income is similar [32]. In most other markets electric vehicles have been less successful. The UK has been included as a country where electric vehicles still have low market share (below 2%) despite high fuel prices.

This study considers the Toyota Prius (HEV), the Toyota Prius plug-in model (PHEV), and the Nissan Leaf Electric model (BEV), and contrasts these with the Toyota Corolla for Japan, California and Texas, and the Ford Focus for the UK. The conventional comparison vehicles were chosen based on a combination of high market share, size and vehicle power similarity to the Toyota Prius (comparative vehicle specifications can be found in Appendix A).

In Japan non-private car purchases account for less than 5% [33]. In the USA and UK this figure is approximately half of new vehicle registrations [34,35]. The fringe benefits of having access to a company car, such as use for private trips, are taxable by the UK and US government. In the UK the main additional cost for company car owners is the benefit in kind (BIK) tax applied to these vehicles. This is calculated on vehicle carbon dioxide emissions rating. The tax is split between the employee and employer [36]. Because company car costs are based on a number of additional variables, such as annual mileage driven for business and leisure, the TCO discussed in this study is for the private consumer.

The three year vehicle ownership length was chosen in line with average new vehicle ownership length in the UK [37]. A Consumer Price Index based GDP deflator for each country is used to bring all costs in line with 2015 prices [38,39]. A discount rate is applied based on the social discount rates which are available for each case of 3.5%, 4% and 3.5% for Japan, California/Texas and UK respectively [40,41]. The three countries considered all have post-industrial economics with growth rates in the range of 1–3%. In the climate of low interest rates with subdued economic growth, it is reasonable to assume a slightly lower discount rate than the 4–6% range used in previous TCO studies (see Table 1). The effect of the chosen discount rate on the cost is explored further in the sensitivity analysis, but with the short TCO timeframe it was found that changing the discount rate does not have a significant impact on the resultant TCO (see Section 4.3). Note all calculations are kept in original currency to control for changes in exchange rate causing false correlations in results.

The Total Cost of Ownership was calculated using the following formula,

$$TCO_c = \sum_{t=1}^{3} \frac{(I_c - s_c) - (I_c - s_c) * d_c^t + f_{ct} * m_c * e + a_{ct} + n_{ct} + x_{ct}}{(1 + r_c)^t}$$

where I = Initial Price, d = depreciation rate, t = time (yr of ownership), f = annual fuel price, m = annual mileage (miles), e = vehicle fuel efficiency (litre/mile), a = annual maintenance inclusive of vehicle testing, n = annual insurance, x = annual tax, s = annual subsidy, r = discount rate for geographic region c.

Many other rational and irrational factors play a role in vehicle purchase decisions, such as brand loyalty, spatial effects and availability of refuelling infrastructure. Such factors are difficult to accurately quantify and track over time, therefore the modelling in this paper does not include these factors but focuses on vehicle TCO.

3.2. Initial vehicle costs and subsidies

With a larger battery and features such as regenerative braking, engine stop-start and a novel transmission system [4] electric vehicles have historically been associated with a manufacturing price premium over conventional petrol and diesel cars [5]. As HEV powertrain technology has matured, the price premium of development and manufacture has reduced with a proportion of this cost reduction passed on to the consumer. For BEVs and PHEVs the battery is still associated with a significant proportion of this incremental cost, therefore future vehicle prices will be closely linked to falling battery prices.

A country specific Manufacturer Suggested Retail Price (MSRP) is taken as the initial vehicle cost [42–45] with depreciation rates from Storchmann [46]. The same depreciation rate is assumed across all vehicle types as evidenced by Gilmore and Lave [47]. The number of consumers purchasing vehicles with finance in the UK over the past decade has grown from 45% of new registrations in 2006 to 86% in 2016 [10], however, the amount paid by the consumer over the three years is comparable to the vehicle depreciation assumed in this study. For example for the Toyota Prius over the three year period £13,980 would be paid on finance whereas the vehicle depreciates by approximately £13,196.

Initial vehicle subsidies were applied before depreciation was calculated as it is reasonable to assume that a proportion of the cost savings will be passed on when the vehicle is sold. Several countries have

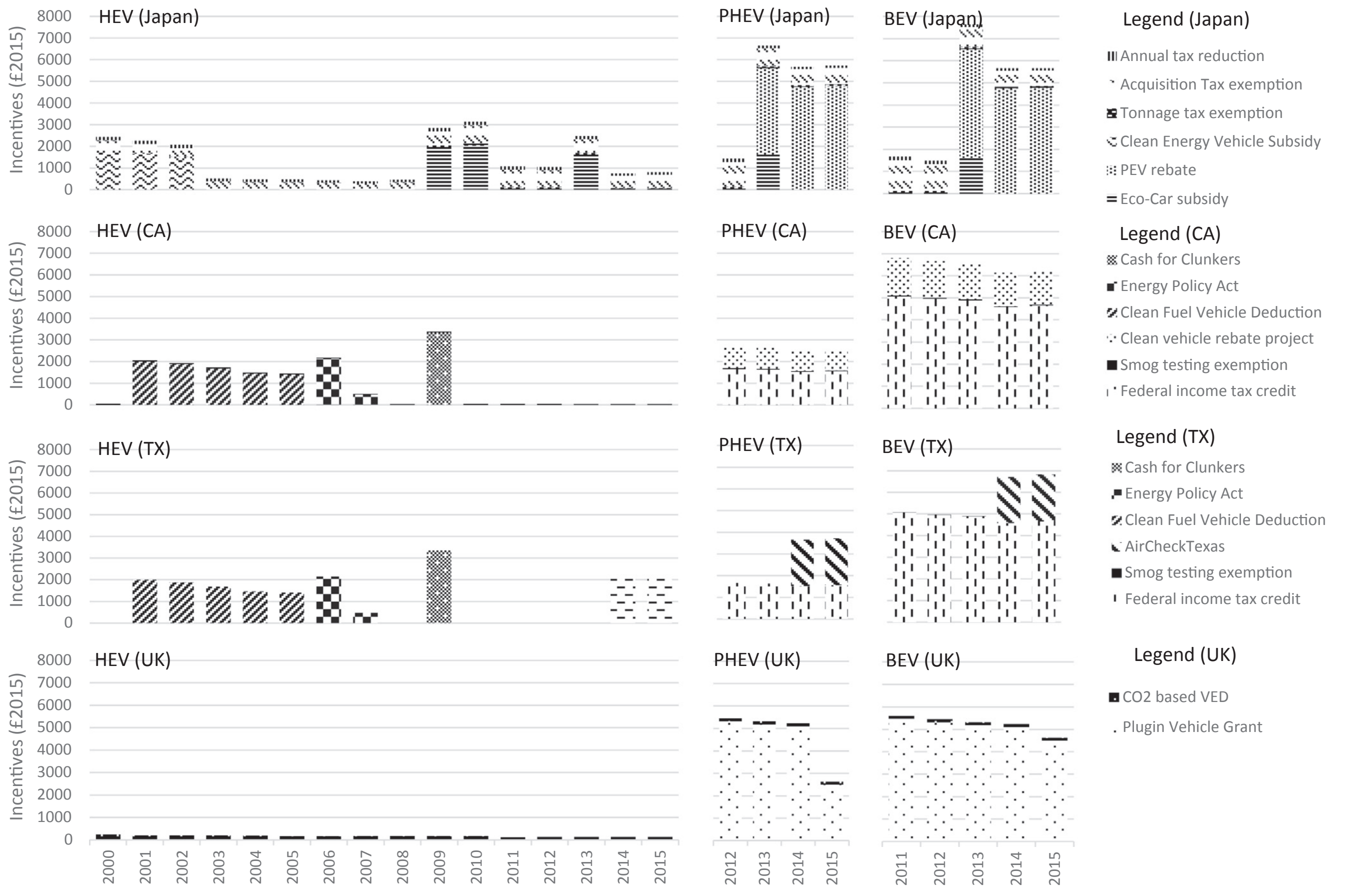

Fig. 1. Timeline of financial incentives available for Hybrid Electric Vehicles (HEVs) and Plug-in Electric Vehicles (PEVs e.g. Battery Electric Vehicles and Plug-in Hybrid Electric Vehicles). (Compiled from [6,8,50–54]).

levied subsidies to increase market share of low-emission vehicles (see Fig. 1 for timeline and size of incentives over the regions considered). Japan brought in the Clean Energy Vehicle Subsidy in 1998 which consisted of a subsidy along with tax cuts for low-emission vehicles. This was superseded by the Eco-Car subsidy available between April 2009 to September 2010 and December 2012 to September 2013, varying between ¥100,000 to ¥250,000 depending on whether the new vehicle replaces an existing vehicle or not [48]. For this analysis it was assumed the new vehicle was a replacement. In 2013 a plug-in vehicle subsidy was introduced where two thirds of the incremental cost of the plug-in vehicle compared to a similar conventional petrol vehicle was funded [49]. In the USA, the Clean Fuel Vehicle deduction was introduced in 2001 providing a $2000 initial cost reduction for the first 60,000 vehicles sold by each manufacturer. This was replaced with a hybrid tax credit (part of the Energy Policy Act) in 2006, which was phased out by the end of 2007 [50]. The Car Allowance Rebate System (often referred to as Cash for Clunkers) ran in 2009 and provided a subsidy of between $3500 and $4500 towards fuel efficient vehicles such as HEVs [55]. In Texas the AirCheckTexas Drive a Clean Machine Program introduced in 2013 provides up to $3500 subsidy towards hybrid or electric vehicles providing certain replacement and income criteria are met [51]. For plug-in vehicles, a federal income tax credit was introduced based on battery capacity in 2010, but an additional smaller state incentive (Clean Vehicle Rebate Project) is available in California [7]. In addition to financial incentives, in California HOV lane access stickers were sold to HEV owners from 2005 to 2011, and PHEV and BEV owners from 2005 to present [28]. With consumers able to apply for stickers for retrospective HEV purchases e.g. pre 2005, the ability of this incentive to stimulate new HEV purchases was limited. However, Shewmake and Jarvis [28] found by utilising historic vehicle resale value and market share data that this incentive corresponded with a Willingness-To-Pay for HOV lane access at nearly $1000. In the UK, the plug-in vehicle grant applies to BEVs and PHEVs with different subsidy amounts available depending on CO_2 tailpipe emissions, this does not extend to HEVs [6]. For more information on subsidies in different countries see studies by Jenn et al. [56], Alhulil and Takehuchi [48] and Zhang et al. [57]. In developed countries such as these considered in this study the new vehicle market is primarily a replacement market therefore electric vehicle adoption will predominantly displace purchase of petrol or diesel vehicles [58]. From Fig. 1 it is clear that PHEV and BEV incentives have a higher financial value than HEV incentives in all countries. Japan, California and Texas all offer significant HEV subsidies and tax breaks of a similar magnitude, however, in the UK the financial incentives are much smaller.

3.3. Fuel costs

Annual fuel cost is usually the largest operating cost, therefore it is important to use representative real driving fuel consumption figures [59]. Fuel consumption figures have been sourced from Spritmoniter [60] with electric-only range efficiency figures from The Idaho National Laboratory [61]. Vehicle fuel efficiency is assumed to be the same across all regions.

Electricity is taxed at a lower rate than motor fuel, and combined with the increased efficiency of the electric drive powertrain during urban driving, annual fuel costs are usually cheaper for BEVs and PHEVs (depending on the percentage of driving in fully electric mode) than a conventional Internal Combustion Engine (ICE) vehicle. The all-electric range of the Toyota Prius PHEV is 12.3 miles [62]. Despite 70% of trips in the USA being under 10 miles [63], Tal et al. [64] found that the average percentage of battery-only driving for PHEV vehicles was 26% of vehicle miles travelled. The average PHEV driver clearly does not fully utilise the electric-only drive capability for every trip. In the UK the number of trips under 10 miles is considerably lower than the USA at approximately 30% [65], but without evidence of the average percentage of electric mode driving for these other regions the same ratio of battery to internal combustion engine driving has been assumed for all the regions in this study.

A region specific average annual mileage is assumed in the TCO calculations. This varies from a minimum of 6213 miles/yr in Japan, 10,400 in the UK, 11,071 in California, to a maximum of 15,641 miles/yr for Texas [58,66,67] (see Table 1 for all regional mileage). With BEV range exceeding 100 miles, the restricted vehicle range does not necessarily pose an issue for the average daily commuter, therefore it is appropriate to assume the same annual mileage for all vehicle types.

Historic fuel prices were sourced from the International Energy Association [68] for Japan, the U.S. Energy Institute Administration for California and Texas [69], and the Department of Energy and Climate Change for the UK [70]. Future fuel prices for all regions were derived from UK price projections [70] and the average price difference from historical data.

3.4. Maintenance and insurance costs

An average annual maintenance cost for each vehicle type is included. Costs were found to be cheaper for electric vehicles due to less wear on the brakes and fewer moving parts. Vehicle model specific costs were sourced from CAPP automotive consulting [71].

The Prius is classed as an average vehicle for insurance purposes [72]. Therefore, the average comprehensive cover is considered to adequately represent insurance costs for all vehicle types. Estimates are used for Japan [73] assuming that real costs have remained constant over the study timeframe. For the Californian model, the comprehensive average premium for California is used for years 2003–2012 [74–78]. Insurance costs for the Texas model are estimated as a proportion of Californian prices [79]. For the UK model, the British Insurance Premium Index is used [80].

3.5. Vehicle tax

Vehicle tax systems have changed over the time period of the TCO model in this study. In Japan, three different taxes are payable: an acquisition fee is dependent on the Manufacturer Suggested Retail Price of the vehicle, every two years weight tax is owed, and an annual tax must be paid [48]. In the USA, a state dependent registration and title fee is payable [6]. In the UK the only vehicle tax is the annual Vehicle Excise Duty (VED) payment. A new CO_2 emissions-based VED system was introduced in 2001 [81], but vehicle taxes will change again in 2017 [53].

3.6. Regression methods

To analytically assess the link between historic TCO and market share across the different geographical regions a fixed effects panel regression model was developed. The fixed effects specification was chosen instead of random effects to control for cross-sectional model variance and unobserved effects between the different geographic regions. The panel regression took a multivariate linear form which fitted the parameters using the Ordinary Least Squares method. The regression was run primarily for HEVs because market share and TCO input data was available for 16–19 years whereas for BEVs and PHEVs there is insufficient data (< 6 years of annual data) for reliable regression analysis.

Three forms of the general regression model were chosen for comparison to determine the relationship of best fit between the independent cost variables and the dependent market share variable. The initial model (Model 1) takes a linear specification between the TCO ratio defined as the total three year TCO of the HEV to the total three year TCO of the conventional vehicle, such that

$$S_{ct} = \propto_c + \beta_1 T_{ct} + \varepsilon_{ct}, \qquad \text{(Model 1)}$$

where S is vehicle market share, T is defined as the ratio of the TCO of the HEV to the TCO of the conventional vehicle, β is the variable dependent coefficient, α is given as the geographic region specific intercept, ε represents the residuals, c is a proxy for the geographic region and t represents the year.

The second model form (Model 2) compared the same variables but took a log-log specification in line with other studies (see Diamond [26], Bajic [82], and Gallagher and Muehlegger [27]), such that

$$\log S_{ct} = \propto_c + \beta_1 \log T_{ct} + \varepsilon_{ct}. \qquad \text{(Model 2)}$$

The final model specification (Model 3) split the TCO cost into initial cost and running cost components. This took the form,

$$\log S_{ct} = \propto_c + \beta_1 \log I_{ct} + \beta_2 \log R_{ct} + \varepsilon_{ct}, \qquad \text{(Model 3)}$$

where I is defined as the ratio of the initial cost of the HEV taking subsidies into account to the initial cost of the conventional vehicle and R is defined as the ratio of the running cost of the HEV vehicle over the three year ownership period to the conventional vehicle. This model specification will be tested with and without inclusion of the Willingness-to-Pay for HOV lane access for California (in line with results from Shewmake and Jarvis [28]) and for different TCO ownership periods.

The Engle ARCH and Durbin Watson tests were conducted on each model to check for heteroscedascity and autocorrelation respectively. Although evidence has shown that household income is a factor in low-emission vehicle purchase decisions [9], it was not included in the model because it was found to be difference stationary and therefore caused spurious regression. The market share data was sourced from Japan Automobile Manufacturers Association for Japan [83], IHS Markit for the two US states [84], and the Society of Motor Manufacturers (SMMT) for the UK [34]. This data was split annually for each region broken down by powertrain type.

4. Results

4.1. TCO cost components

Cost components were found to vary over country, vehicle type and purchase year; however, the greatest cost to the consumer has always been vehicle depreciation (see Fig. 2 for TCO breakdown, costs table can be found in Appendix B). This is most pronounced for BEVs and PHEVs due to the greater initial purchase cost coupled with low running costs. In Japan, insurance featured as the second greatest percentage cost, but for the UK, California and Texas annual fuel cost contributed a greater percentage of the vehicle TCO for petrol, diesel and hybrids.

4.2. Geographic TCO comparison

The HEV cost ratio (defined as HEV TCO divided by Petrol TCO) has reduced in all regions from introduction to 2015. This is most pronounced in Texas where the cost ratio has dropped by 0.23 in 15 years. Even in the UK where subsidies were absent, the cost ratio has fallen by 0.09. Between the years 2000 and 2015, the lowest average cost ratio for HEVs is in the UK at 1.03.

The cost ratio for PHEVs is greater than for HEVs in all regions considered except Japan. Conversely, in California, Texas and the UK subsidies have enabled BEVs to reach cost parity. The lowest average cost ratio for BEVs across the regions is the UK (0.89). For PHEVs, the lowest average cost ratio is in Japan (0.97).

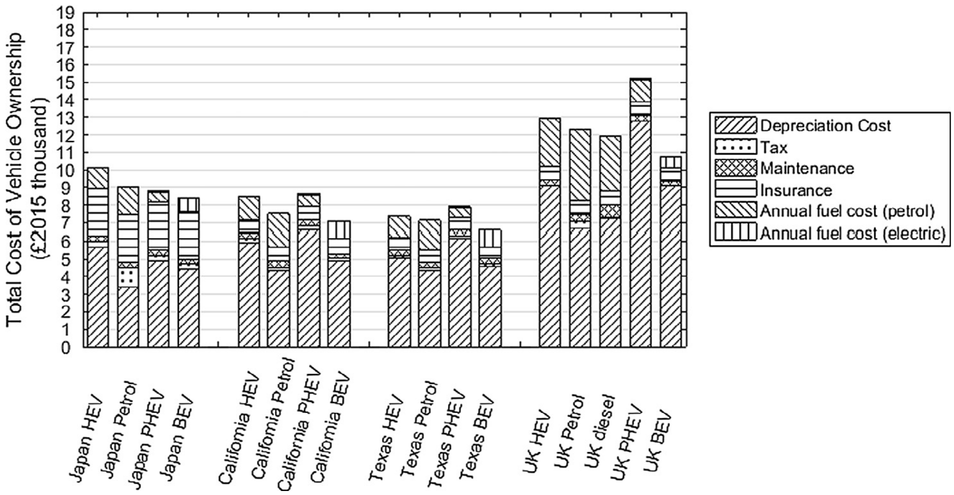

Fig. 2. TCO component breakdown for 2015 across all regions.

4.3. Region specific TCO trends over time

For Japan, the HEV cost ratio varied between 0.85 and 1.17 (see Fig. 3 for Cost ratio and market share over time). Vehicle cost initially decreased from 1997 to 1999 leading to a lower cost ratio and increased market share. In 2009 greater tax cuts and an initial vehicle subsidy was introduced such that HEVs were cheaper than conventional vehicles for the first time, this was met with a peak in HEV market share. With the Japanese tsunami in 2011, Toyota experienced manufacturing disruptions which propagated down the supply chain and caused shortages [85]. Despite this, market share in Japan still rose. In 2013 the cost ratio dropped due to a second wave of subsidies, again this corresponded to a peak in market share. With fuel price falling in 2014 and 2015, the cost ratio increased and HEV market share levelled out. The PHEV cost ratio varies between 0.82 and 1.28 whereas the BEV cost ratio varies between 0.84 and 1.32. This indicates that the large subsidies have brought PHEV and BEV TCO in line with conventional vehicles.

For California, the HEV cost ratio varied between 0.9 and 1.25. The cost ratio decreased from 2001 to 2005 as a result of rising petrol price despite the value of incentives falling. The Car Allowance Rebate System subsidy in 2009 (see Fig. 1) results in a clear dip in HEV cost ratio and spike in market share. The supply disruption from the Japanese tsunami led to a dip in market share in 2011 and a return to 2009 market share levels by 2013. Larger subsidies for BEVs than PHEVs (e.g. approx. $10,000 for BEV versus $2500 for PHEV) led to a lower TCO cost ratio for BEVs of 0.94 compared to 1.14 for PHEVs. As a consequence BEV market share is almost double that of PHEV market share.

For Texas, the HEV cost ratio varied between 1.02 and 1.14. The market share time series is similar in shape but roughly half the size of California. The cost ratio curve is also very similar to that of California, exhibiting the same dips and peaks for the same reasons (primarily fuel price and subsidy changes). Higher mileage (15,641 versus 11,071 miles per year) offsets the lower price of petrol in Texas compared to California leading to a similar annual fuel cost ($1353 and $1191 respectively). The drop in cost ratio in 2014, attributed to the introduction of an initial vehicle subsidy incentive, has not stimulated HEV sales in 2014/15. In Texas a subsidy is available in equal value for all low-emission vehicles (AirCheckTexas Drive a Clean Machine) therefore HEVs are cheaper than PHEVs and BEVs. The state financial subsidies available for BEVs in Texas are smaller than California ($3500 versus $10,000) for this reason the cost ratio is lower in California than Texas.

The HEV cost ratio varied between 0.91 and 1.14 in the UK. The initial fall in the cost ratio, comes as a result of the change in the vehicle excise duty tax in 2001. This new vehicle excise duty system differentiated annual charges based on NEDC CO_2 emissions figures in contrast to the flat rate system it replaced. The cost ratio remained fairly constant from 2002 to 2007 in line with stable fuel prices. With the fuel price increase in 2010, the cost ratio dropped, with a corresponding increase in market share. Conversely, the fuel price slump in 2015 led to an increased cost ratio coupled with a surprising increase in market share. This surge in sales is most likely a result of the pending vehicle excise duty change in 2016. The new vehicle excise duty system will involve a CO_2 emissions based initial charge of up to £2000 followed by a flat annual cost of £140 per year for all vehicles except those with zero emissions [53]. Diesel vehicles were found to have a lower TCO than petrol vehicles, to the point that the TCO model calculated that HEVs have never been cheaper than diesel vehicles over the time period considered. In the UK the TCO ratio is lower for BEVs at 0.88 than PHEVs at 1.24. This is mainly a result of the plug-in vehicle grant which allocates a larger subsidy to BEVs (£4500) than PHEVs (£2500).

4.4. Panel regression analysis

The regression analysis evidences a historical link between HEV TCO and market share for the four geographic regions (see Table 2 for regression results for the three models specified in Section 3.6). The linear form model, which treats the independent variable as TCO and the dependent variable as market share, has a poor value of R^2 (0.319) with large standard errors. This indicates that the model is mis-specified because it does not sufficiently explain the variation of market share over the given time period.

Comparing the first model to the second, where the linear form has been replaced with a log–log specification (see Section 3.6), the R^2 value increases in value from 0.319 to 0.481 indicating that this model is a better fit than the last. The standard error for the TCO variable drops to approximately a quarter of that of the first model. Overall this model specification is significantly better ($p < .01$) than the initial model evidencing the link between vehicle cost and market share.

By splitting the TCO into its constituent components: initial cost (including subsidy) and running cost, the R^2 value increases again from 0.481 to 0.549. By accounting for the different cost components separately, the model is anticipated to improve. Toyota initially subsidised the Prius model to ensure it was cost-competitive on the market, and as initial prices increased government subsidies were introduced to encourage uptake. In this model the initial cost coefficient is more significant ($p < .01$) than running cost ($p < .05$). The initial cost coefficient indicates that a one percent reduction in the cost ratio leads to a 10% increase in market share, whereas a one percent reduction in running cost ratio leads to a 5.5% increase in market share. This directs us to the conclusion that at an aggregate level HEV purchases are more

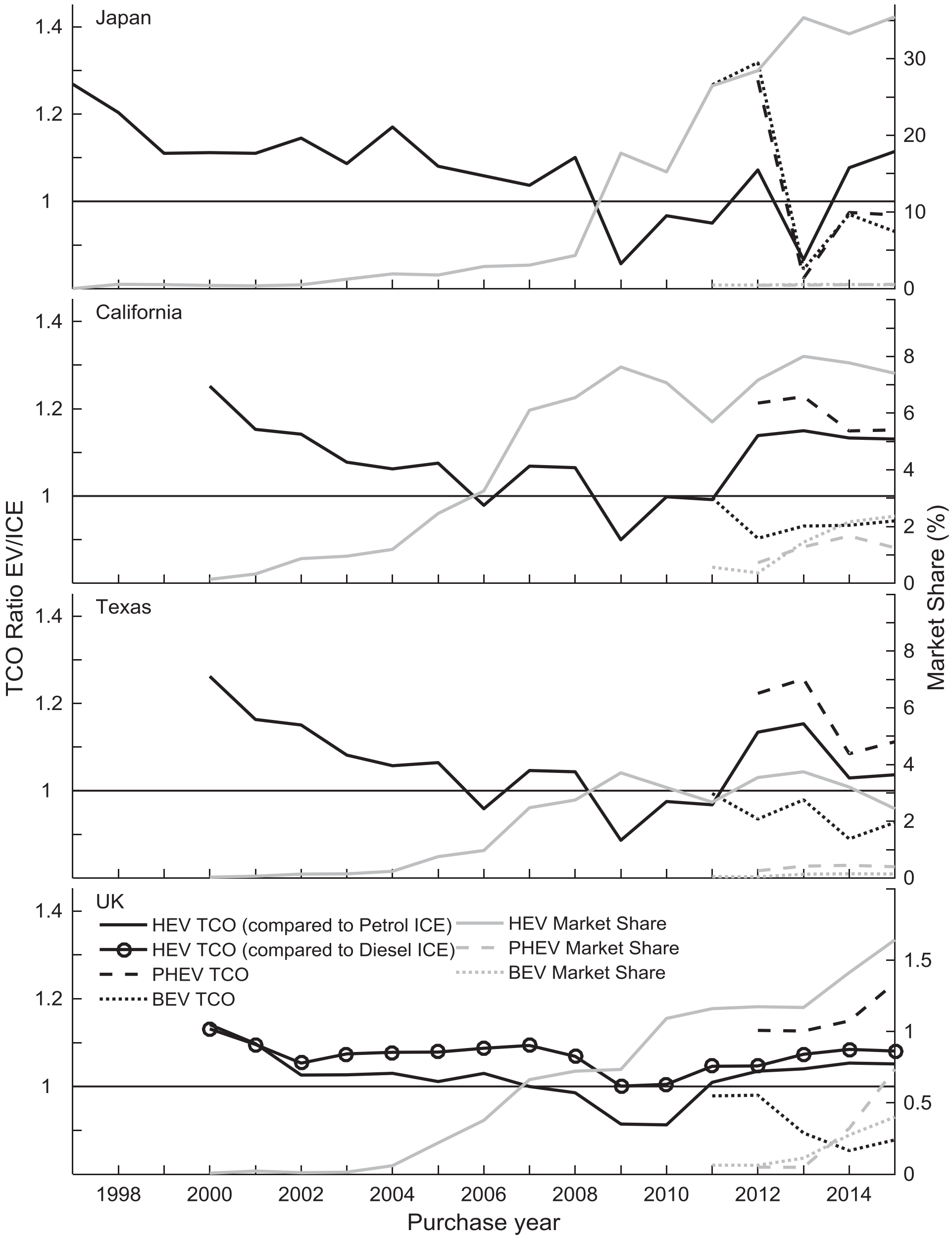

Fig. 3. TCO ratio and market share for the UK, California, Texas and Japan 1997–2015.

sensitive to changes in subsidies and vehicle price (e.g. the initial cost components) than fuel price change (e.g. the running cost component with most variation over time).

Changing the ownership period from three years to one year improves the fit of the model slightly (increasing R^2 from 0.549 to 0.567). The most marked effect of this model comparison is the increasing

Table 2
Regression results.

	Model 1	Model 2	Model 3	Model 3 + HOV lane WTP	Model 3
Ownership Period	3 yr	3 yr	3 yr	3 yr	1 yr
Indep. variable	Coeff. (Std. error)	Coeff. (Std. error)	Coeff. (Std. error)	Coeff. (Std. error)	Coeff. (Std. error)
(HEV TCO/ICE TCO)	−33.9 (10.0)***	–	–	–	–
Log (HEV TCO/ICE TCO)	–	−13.0 (2.22)***	–	–	–
Log (HEV IC Cost/ICE IC)	–	–	−10.0 (1.93)***	−3.56 (1.42)***	−8.01 (2.15)**
Log(HEV RC/IC RC)	–	–	−5.52 (2.13)**	−7.73 (2.37)***	−5.90 (1.90)***
N	67	67	67	67	67
Adjusted R^2	0.360	0.512	0.583	0.455	0.600
R^2 (overall)	0.319	0.481	0.549	0.411	0.567

RC = Running Cost, IC = Initial Cost, HOV = High Occupancy Vehicle, WTP = Willingness-to-Pay.
** denote significance at 5%.
*** denote significance at 1%.

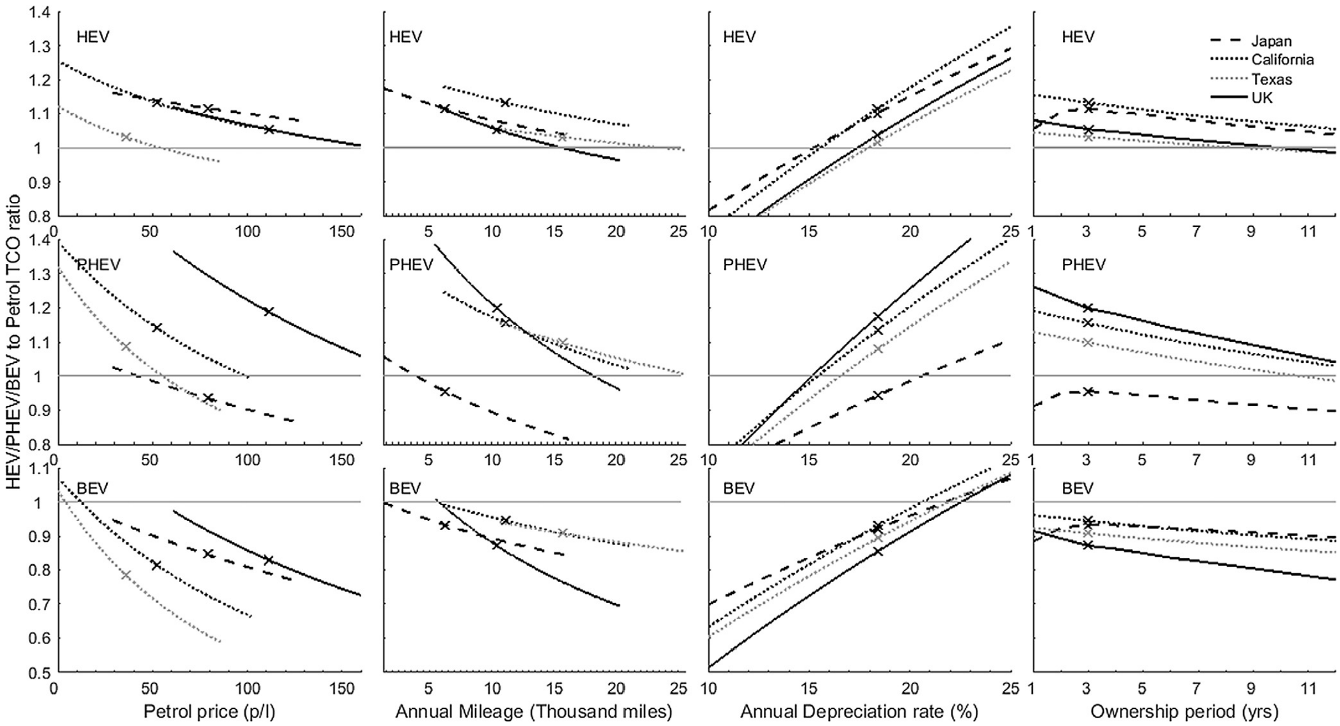

Fig. 4. TCO sensitivity analysis for base year 2015, cross (X) indicates baseline value.

significance of the running cost component (from $p < .5$ to $p < .01$) with lower standard error. Whereas the initial cost coefficient decreases in significance with larger standard error. The inclusion of Willingness-To-Pay for HOV lane access for California did not improve the model fit, but increased the standard error for the running cost coefficient. With this model considering cost on an annual basis, the annual time resolution used is not adequate to account for purchasers who adopt HEVs for HOV lane access.

4.5. Sensitivity analysis of cost parameters

Several inputs variables were investigated to assess the model sensitivity to their variation. These variables include; fuel price, discount rate, annual mileage, vehicle depreciation rate, and TCO ownership length (see Fig. 4 for Sensitivity Analysis Results).

The discount rate assesses a person's revealed time preferences, with a higher rate indicating that a person's opportunity costs are greater. Studies in the literature (see Table 1) use significantly different rates and because of this inconsistency, this variable has been investigated using a sensitivity analysis. Generally, the greater the discount rate the greater the variation in cost ratio over the time period considered. The effect of varying the discount rate was negligible over the three year ownership period. For example, increasing the discount rate from 2 to 11% caused the cost ratio to increase by approximately 0.2%. For a longer ownership period it is anticipated that varying the discount would have a greater effect on the TCO ratio.

Fuel price is arguably the most variable input to the model. Clearly historical changes in fuel price have had a significant impact on HEV cost ratio and vehicle market share (as discussed in Section 4.3). A higher fuel price creates more favourable conditions for HEV/PHEV/BEV adoption. The fuel price sensitivity in this study examines the 2015 fuel price for each region ± £0.50, whilst maintaining a fixed electricity price. From Fig. 4 it is clear that the regions with higher average mileage such as Texas are more sensitive to changes in fuel price. BEVs and PHEVs are more sensitive to changing prices than HEVs. For example a 10p increase in fuel leads to a 0.2 drop in cost ratio for HEVs, but 0.4 for BEVs.

In the standard TCO calculation, annual mileage has been assumed to be constant for the geographic region. However, this is highly variable among different drivers and therefore this sensitivity analysis demonstrates different use cases. For example higher mileage cars such as taxis or business travellers may find hybrid and electric vehicles (although there could be potential BEV range limitations) more cost effective as a result of fuel cost savings. For HEVs, the UK has the lowest break even mileage at approximately 15,000 miles, this figure exceeds 20,000 miles in the other regions considered. The break-even mileage of PHEVs is greater than HEVs in all regions except Japan where annual mileage of around 4000 miles equates to cost parity. BEV subsidies mean that BEVs break-even at a lower average mileage of around 7000 miles for the UK, California and Texas, but are always the lower cost option in Japan.

Depreciation is the greatest component of TCO across all geographic regions. Varying the annual depreciation rate from 15% to 20% leads to an increase of cost ratio of approximately 0.17 across all regions (see Fig. 4). This figure is greater for PHEVs at 0.2 because the initial purchase cost constitutes a greater percentage of TCO than HEVs. However, this figure is slightly lower for BEVs at 0.15 due to subsidies bringing the initial cost in line with HEVs (see Fig. 3).

As previously discussed, low-emission vehicles are associated with a price premium which can be offset by lower running costs over a certain time period. In this study the baseline TCO was taken as three years; in line with average length of UK and Japan new vehicle ownership. Generally this ownership period longer in the USA therefore the impact of a longer ownership period has been investigated. The longer the ownership period the lower the TCO ratio (see Fig. 4). Because this study took vehicle salvage value into account when calculating TCO for different ownership lengths, the TCO ratio was not found to be particularly sensitive to changing ownership period with a drop in TCO ratio of approximately 0.01–0.02 with each additional year of ownership.

5. Discussion

5.1. Factors affecting adoption rates

This paper aims to compare historical total cost of ownership of BEVs, PHEVs and HEVs across countries with different levels of hybrid and electric vehicle uptake. As previously discussed in Section 4.4, regression analysis reveals that there is a clear link between changing HEV TCO and market share. First these results are significant because they can inform the setting of policies to stimulate HEV adoption in regions where market share is lacking. Second, the approach and results may be applicable to future BEV and PHEV vehicle adoption. These vehicle types have been available on the market for a shorter amount of time and currently represent very low fleet share in most vehicle markets.

This analysis has focused on assessing the link between HEV TCO and market share. This enquiry has isolated ownership costs as the most pertinent time-dependent variable affecting adoption rates for HEVs. There is considered to be no underlying drivers which have caused a false correlation. However, several variables which could affect HEV adoption, such as HEV depreciation rates, income and HOV lane access, have changed in the time period considered and will be discussed in more detail in this section.

With depreciation as the largest cost to the consumer, sensitivity analysis found that vehicle TCO was highly sensitive to changing depreciation rates (see Section 4.5). Uncertainty surrounds low-emission vehicle depreciation rates even among HEVs which have been available on the second hand vehicle market for over a decade. HEVs in California historically have had an inflated vehicle retention value due to supply issues and HOV lane access [28,47]. However, results from Lebeau et al. [86] found that BEVs, PHEVs and HEVs depreciated quicker than conventional vehicles in the Belgian vehicle market.

A key factor in the high adoption rates of low-emission vehicles in California compared to other states is the comparative wealth. The median income in California is $64,500 (the 10th richest state) whereas in Texas this figure is $55,653 (23rd richest state) compared to the US average of $55,775 [32]. As a result of this wealth, many more residents can afford the additional incremental cost of a low-emission vehicle. Average income has increased over time, but this variables has not been included in the regression analysis as it is a non-stationary variable which results to spurious regression.

In California, low-emission vehicles have access to HOV Lanes [28]. Such incentives are difficult to financially quantify (although Willingness-to-Pay figures were estimated by Shewmake et al. [28]). Vehicle owners who had already purchased HEVs could apply for HOV lane access stickers, although these were only available for a limited number of vehicles.

With the highest count of Green Party registered voters (both as total number and as a percent of total registered voters) [87], Californians are evidently more environmentally aware than voters from other states. Kahn et al. [88] found a link in California between green party voting and HEV adoption, therefore it is reasonable to assume that high HEV market share in California can partly be attributed to environmentally-friendly attitudes.

Other factors have also contributed to high HEV market share in Japan. Japan has a history of innovation in this field, and represents the domestic Prius market where the vehicle model was first developed and tested [89]. The majority of vehicles purchased in Japan are domestic brands, with only a small percentage imported from the USA and Europe [90]. With small roads and low annual mileage the Japanese tend to favour smaller cars. Evidence for this can be found in the high market share of the Prius compact which is now one of the best selling cars in Japan [90].

Charging infrastructure is a major barrier to BEV adoption. Although most BEV and PHEV owners have access to a home charging point, public charging points are important for visibility as well as practical use [91]. In California the number of charging stations has increased to 3820 whereas in Texas this number is lagging behind at 885 [92]. Japan has chosen to invest heavily in charging infrastructure, aiming to stimulate uptake [93]. In the UK, PEV charging infrastructure has been installed strategically in dozens of cities [94].

Since Toyota introduced the Prius to the global market in 2000, many vehicle manufacturers have developed hybrid models. Toyota still maintains market dominance with over 50% of HEV market share having diversified their hybrid range to include vehicles across most segments. As the number of hybrid models across different segments and brands diversifies and capacity to supply vehicles grows it is anticipated that HEV market share will continue to expand. The PHEV market is dominated by vehicles from larger segments (such as SUVs) [34], such that the Toyota Prius is one of the smallest PHEVs available. It is anticipated that as the number of PHEV models expands its market share will also grow. It is also worth noting that in the UK additional competition exists from diesel vehicles which are more cost efficient than petrol vehicles at high mileages.

Many of these additional factors are difficult to quantify for all geographic regions and across the time period considered. The variables discussed are not deemed to be variable or significant enough to have caused a false correlation in the HEV TCO/market share regression analysis.

5.2. Payback periods compared to other TCO studies

The studies in the literature largely reached the same conclusions as this paper; that the TCO of HEVs, PHEVs and BEVs without subsidies is still greater than that of conventional vehicles. The historical analysis in this paper shows that incremental vehicle cost varies depending on the vehicle purchase year (see Fig. 3), this is echoed by the conclusions of other papers in the TCO literature. The payback period of a new technology compared to its conventional counterpart is a common metric in the cost analysis literature. When comparing electric vehicle payback periods, unless a vehicle depreciation or a loan model is used to represent initial vehicle costs, the calculated payback periods will be unrepresentative of the true payback period.

Al-Alawi and Bradley [19] estimated a HEV payback period of approximately 8 years when considering the vehicle salvage value in the TCO model. For base year 2010, the payback time in this study is shorter at approx. 3 years for Texas and 4 years for California. Al-Alawi and Bradley [19] find a PHEV with a 10 mile electric range (similar to the Toyota Prius which has an all-electric range of 12.3 miles) has a smaller payback period of approx. 7 years. The discrepancy in these results stems from differences in sourcing of initial vehicle cost data: Al-Alawi and Bradley have used an incremental cost model rather than the Manufacturer Suggested Retail Price.

Thiel et al. [21] estimated that in 2010 the payback period for HEVs, PHEVs and BEVs was 20, 22 and 23 years respectively, much greater than that calculated in this study. Thiel et al. [21] used an initial cost model that did not consider important subsidies or vehicle salvage it is perhaps unsurprising that the conclusions do not align with the findings for the UK in this paper.

Hutchinson et al. [4] found that the incremental cost of a HEV or PHEV depends largely on the style of driving. Hutchinson et al. [4] conclude that in 2013 HEVs and PHEVs have a payback period of 6.7 and 10.1 years respectively for city driving, but do not reach cost parity for highway driving. The greater fuel efficiency of HEVs and PHEVs in urban driving explains the shorter payback time calculated in Hutchinson et al. [4] compared to this paper which estimates this to be greater than the vehicle lifetime in California. The conclusions from Hutchinson et al. [4] are echoed in this paper such that in the UK HEV and PHEV TCO is closer to cost parity with conventional vehicles than in the USA.

Wu et al. [22] find that in 2015 TCO depends on annual mileage driven which is mirrored in our sensitivity analysis. Wu et al. [22] use

Germany as their geographical focus, different fuel prices compared to the UK again limit the comparisons between the conclusions from Wu et al. [22] and this study.

6. Conclusion

Hybrid and electric vehicles offer a low-carbon, low-pollution alternative to conventional cars but at present the fleet share in most vehicle markets is too small to make a significant difference. This paper establishes a clear connection between historic HEV TCO and market share; with evidence from regions such as Japan and California that long term government support enables higher adoption rates. These findings are significant for policymakers in regions around the world who are under increasing pressure to decarbonise roads and improve urban air quality. Government support for low-emission vehicles clearly needs to address financial barriers if hybrid and electric vehicle market share is to break out of the niche market. Most importantly, government support needs to be tailored to include an element to account for the greater upfront initial vehicle cost and a subsidy to account for fuel price variation. It is paramount that there is a gradual phase out of incentives once technology has reached cost parity especially when oil prices are low. In many countries lack of reliable vehicle TCO information is an additional purchase barrier, this could be addressed by creating an impartial resource such that potential purchasers can at least assess their fuel saving against depreciation costs given their annual mileage and share of urban/motorway driving. With a high upfront cost and low test cycle emissions, PHEV market share is dominated by business purchase. To stimulate second hand sales as these vehicles move from the company to private car market, Mitsubishi have introduced a PCP finance scheme for second hand Outlander PHEVs [95]. In light of recent evidence illustrating the effects of urban air pollution on public health; introducing incentives for replacing diesel vehicles with hybrid/electric vehicles should be prioritised, especially in the business market which accounts for disproportionate diesel market share in the UK. An indication of lower TCO for high mileage vehicles in London (UK) is that the Toyota Prius is now the most popular private hire vehicle in London [96]. Replacing high urban-mileage diesel vehicles with petrol-HEVs such as these should be one of the first steps taken to cut urban air pollution.

Although the link between TCO and market share has been the focus of this study, TCO is not the only factor in vehicle purchase decisions. Many other factors such as brand loyalty, distrust in new technology and even model colour come into play at the point of purchase. This is where non-financial incentives such as HOV lane access, allocated parking and bus lane access have a part to play in persuading consumers to choose a low-emission vehicle. Social costs of emissions and noise have not been included in this analysis. Incorporating these factors would further improve the preference for hybrid and electric vehicles.

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Appendix A. Vehicle specification for comparison vehicles (2015 model year)

	Powertrain type	Battery capacity (kWh)	Power (bhp)	Engine size (l)	Fuel Economy (MPG)	Vehicle length (mm)	Weight (kg)
Toyota Corolla (Petrol)	Conventional petrol ICE	–	130	1.8	42.2 (A)	4638	1295
Ford Focus (Petrol)	Conventional petrol ICE	–	103	1.6	38 (M)	4358	1270
Ford Focus (Diesel)	Conventional diesel ICE	–	93	1.6	51 (M)	4358	1338
Toyota Prius	Full parallel Hybrid HSD	1.3	120	1.8	56.7	4540	1395
Toyota Prius plug-in	Plug-in Hybrid HSD	6.4	122	1.8	90.8*	4481	1449
Nissan Leaf electric	Full Electric	24.0	107	–	141.7*	4445	1471

Sources: [42,61,97].
A indicates Automatic transmission, M Manual transmission system. HSD stands for Hybrid Synergy Drive.
* MPG equivalent.

Appendix B. TCO cost component breakdown for the year 2015 (accompany output to Fig. 2 all costs converted to £2015 for easy comparison)

Geographic region	Cost component	Petrol	Diesel	HEV	PHEV	BEV
Japan	Depreciation	3410	–	5648	6848	6368
	Tax	1078	–	315	315	315
	Maintenance	358	–	323	323	276
	Insurance	2652	–	2652	2652	2652
	Petrol cost	1556	–	1158	535	–
	Electric cost	–	–	–	79	796
California	Depreciation	4323	–	5921	6629	4849
	Tax	196	–	196	196	196
	Maintenance	384	–	314	314	268

	Insurance	792	–	713	792	792
	Petrol cost	1821	–	1353	625	–
	Electric cost	–	–	–	98	982
Texas	Depreciation	4323	–	5029	6119	7119
	Tax	147	–	147	147	147
	Maintenance	352	–	318	318	268
	Insurance	691	–	691	691	691
	Petrol cost	1602	–	1191	550	–
	Electric cost	–	–	–	90	897
UK	Depreciation	6717	7223	9080	12755	9078
	Tax	369	57	0	0	0
	Maintenance	354	742	319	319	273
	Insurance	783	783	783	783	783
	Petrol cost	4062	3146	2733	1263	–
	Electric cost	–	–	–	65	653

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.10.089.

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