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Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach

Christian Brand [a,*], Celine Cluzel [b], Jillian Anable [c]

[a] Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
[b] Element Energy Ltd, Terrington House, 13-15 Hills Road, Cambridge CB2 1NL, UK
[c] Institute for Transport Studies, University of Leeds, Lifton Villas, 1-3 Lifton Place, Leeds LS2 9JT, UK

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ABSTRACT

There is broad agreement on the need for substantial use of low carbon vectors in the long term in the transport sector. Electrification, via mass market adoption of plug-in vehicles (i.e. battery electric and plug-in hybrid electric vehicles), has emerged as a front runner for road transport across the globe, but there are concerns that the pace and extent implied by many modeling studies is problematic and that assessment of (a) the heterogeneity in the market, (b) other low carbon vectors (e.g. conventional hybrids, hydrogen fuel cell) and (c) life cycle energy and environmental impacts have been relatively neglected. This paper aims to fill these gaps by examining the timing, scale and impacts of the uptake of plug-in vehicles in the heterogeneous UK car market from a consumer perspective. To achieve this aim it (a) brings together a bespoke disaggregated model of the transport-energy-environment system (the UK Transport Carbon Model) with previous work by the authors on heterogeneity in the demand for and supply of plug-in vehicles and (b) applies the improved model to develop future low carbon scenarios that assess the potential impact of different investment pathways and policy approaches to the electrification of cars with the view to meeting the UK's legally binding carbon budgets to 2050. The results show the importance of accounting for the heterogeneity in and dynamic nature of the car market in terms of new technology adoption by private consumers, so called 'user choosers' and fleet managers, as well as accounting for potential effects on wider life cycle emissions resulting from different uptake pathways. It allows an assessment of the effectiveness of different policy instruments, market conditions (vehicle supply, private vs fleet market, vehicle segments) and social factors (consumer awareness, range "anxiety", perceived charging requirements) on different consumer segments, thus providing more policy-focused conclusions on the likely pathways to high penetration of plug-in vehicles that may be required to meet future carbon and air quality targets.

1. Introduction

1.1. The need to better understand (and model) the electrification of light duty vehicles

There is broad agreement on the need for substantial use of low carbon vectors in the long term in the transport sector. Electrification, via mass market adoption of plug-in vehicles (PIV, i.e. battery electric vehicles, BEV, and plug-in hybrid

* Corresponding author.
E-mail addresses: christian.brand@ouce.ox.ac.uk (C. Brand), celine.cluzel@element-energy.co.uk (C. Cluzel), J.L.Anable@leeds.ac.uk (J. Anable).

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electric vehicles, PHEV), has emerged as a front runner over the past decade (AEA Technology, 2009; CCC, 2015; IEA, 2011, 2015a; OLEV, 2013; Sims et al., 2014), but there are concerns that the pace and extent implied by the underlying modeling studies is problematic and that assessment of consumer and market factors, effects of climate change mitigation policies on air quality emissions and overall life cycle emissions have been relatively neglected (Anable et al., 2012; Graham-Rowe et al., 2012; Leinert et al., 2013). In the UK, for instance, uptake of the recently released new generation of PIV has been slower than originally anticipated, although there are positive signs that this is improving. Whilst only 0.6% of new cars were PIV in 2014, the share of sales has nearly doubled to 1.1% in 2015 (Fig. 1); PHEV account for around two-thirds of PIVs being sold in the UK, and BEV a third (ibid). These figures represented a similar proportion of new car sales in the UK in 2014 as they did in the US, France and Germany, while California (3.2%) and Norway (17.8%) had two of the largest PIV market shares globally (Brook Lyndhurst, 2015). HEV still dominate the electric vehicle market, but they are not dissimilar to conventional gasoline/diesel ICVs and may not meet ultra-low emissions vehicle (ULEV) standards (currently < 75 gCO_2/km) in the future.

UK policy measures to support higher uptake are in place to 2020, although the recent announcement by the UK Government (HM Treasury, 2015) to abandon CO_2 grading of the road tax (or Vehicle Excise Duty) regime and weakening of the company car tax regime[1] has undermined its carbon mitigation commitment. So while the sales figures are encouraging, analysis by the UK Committee on Climate Change suggests that 9% of new car sales should be EVs by 2020 and 60% by 2030 (CCC, 2015) to meet carbon budgets cost-effectively. This implies mass market adoption of PIV at a rate of nearly doubling each year.

The UK policy focus on vehicle technology and supporting fiscal incentives reflects other global transport modeling exercises that project between 40% and 90% market penetrations of PIV between 2030 and 2050 (IEA, 2011, 2015a, 2015b; Kay et al., 2013; Lieven, 2015; McKinsey & Company, 2009; WBCSD, 2004; WEC, 2007). Many of these modeling studies examine car market at the aggregate level, rely on cost-optimization (e.g. Dodds and McDowall, 2014; IEA, 2015b) or simulate market dynamics based on technological and economic barriers and enablers of uptake (e.g. Kay et al., 2013). They largely ignore the heterogeneous and segmented nature of the car market, both in terms of supply (choice of vehicles) and demand (private/fleet, consumer segments), which needs to be integrated for the models to become more useful. Psychology, behavioral economics and sociology have revealed a coherent view of the importance of non-economically rational aspects of human (choice) behavior (see e.g. Anable et al., 2012; Morton et al., 2014; Schuitema et al., 2013; Schwanen et al., 2011), which suggests that there are potentially many more determinants to include in our models. In the context of low carbon vehicle choice behavior, some researchers have recently focused on consumer heterogeneity in terms of their attitudes and demographics (Anable et al., 2014; Axsen et al., 2009; Daziano and Chiew, 2012).

1.2. The need to focus on the consumer

Consumer and market research has suggested that recharging requirements, "range anxiety", higher upfront purchase costs, lack of knowledge/awareness and limited choice of vehicles are the key barriers to adoption of PIV (Anable et al., 2014; Brook Lyndhurst, 2015; DfT, 2014a; Graham-Rowe et al., 2012; Kay et al., 2013). Recent consumer segmentation work has shown that PIV are more attractive to some segments of the population than others. Funded by the Energy Technologies Institute in the UK, the research involved in-depth two-wave surveys including attitudinal items combined with a quantitative (stated preference) choice experiment with 2729 mainstream UK consumers with recent experience of buying a new or nearly new car (Anable et al., 2011b). This showed that the top factors that distinguish consumer groups not unsurprisingly relate to many of the above barriers to/enablers of PIV uptake: lower running costs of PIV (+); high price premium over non-PIV (−); limited supply, both in terms of vehicle segments (e.g. supermini, small family) and brands (−); limited availability of charging infrastructure (at home, public) (−); shorter range and longer charging times (−); and lack of receptiveness to and acceptance of PIV or any incentives (−). As illustrated in Fig. 2, the study suggested that so-called 'Plug-in Pioneers' (about 2% of private car buyers) differ from mainstream consumers in that they are willing to pay more for fuel economy and environmental benefits, while at the other end of the spectrum, 'Image Conscious Rejecters' (18%) would "never be seen in one of those [PIV]". The factor analysis on more than 106 attitudinal statements[2] further revealed that mainstream attitudes to PHEV are very positive, but most have strong reservations about BEV (Anable et al., 2011b; ETI, 2013). Crucially, using multiple segments significantly increased the explanatory power of the statistical model, highlighting that attitudinal/demographic factors can influence PIV purchase decisions and allowing reactions to different attributes (e.g. willingness to pay for EV range) to be captured explicitly (rather than within the error term of the model) (Anable et al., 2011b).

[1] Ultra Low Emission Vehicles (ULEVs) have attracted lower tax (or 'Benefit-in-Kind') rates in the UK, with zero tax on BEVs until 2015 (Lane, 2016). Rates for ULEVs have since increased, however, and from April 2016, PHEVs are rated at 7% or 11% (depending on CO_2 ratings), and BEVs are rated at 7%. In April 2016 and 2017, BIK rates for cars in the 0–50 g/km and 51–75 g/km CO_2 bands are due to increase by 2% per year with a 3–4% rise planned for 2018.

[2] As described in more detail in Anable et al. (2016), these statements covered six main issues reflecting broad conceptual dimensions around attitudes towards owning/driving a car, innovativeness, environmental values, beliefs about plug-in cars in general, beliefs about PHEVs and beliefs about BEVs. Exploratory factor analysis (principal components and Varimax rotation) was used to uncover underlying psychologically meaningful constructs among these statements.

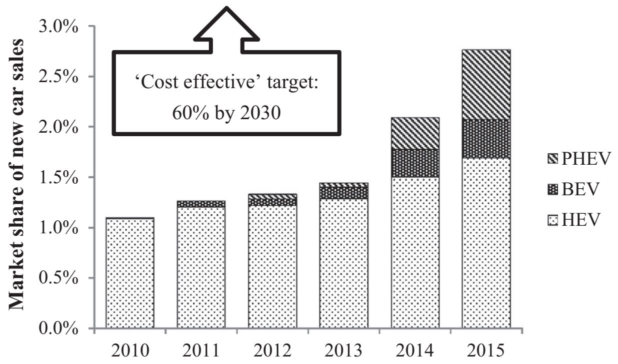

Fig. 1. Recent market shares of ULEV and HEV in the UK. *Source:* UK sales data (SMMT, 2015), 2030 target (CCC, 2015).

1.3. The need to broaden the greenhouse gas emissions metric to life cycle emissions

There is growing consensus that regulation and budgeting based on tailpipe emissions is increasingly no longer fit for purpose and should be changed to be based on well-to-wheel, and ultimately life cycle, emissions (IEA, 2013). Currently the average fuel life cycle greenhouse gas (GHG) saving for a BEV over its full life has been estimated at about 50% under UK conditions – that is, with the current mix of grid electricity generation (Kay et al., 2013). This could increase to 75% in 2020 and to 83% by 2030 with the anticipated decarbonization of grid electricity (this is explored further below). Also, vehicle life cycle emissions (from manufacture, maintenance and scrappage) add significantly to emissions from vehicle use (IEA, 2013; Lane, 2006; MacLean and Lave, 2003) and can be significantly higher for BEV and PHEV than for ICV (Kay et al., 2013). The analytical framework presented in this paper addresses this issue by modeling life cycle emissions including upstream fuel emissions and emissions from vehicle manufacture, use, maintenance and scrappage.

Fig. 2. Illustration of consumer segments of new car buyers in the UK (n = 2729). *Source:* Adapted from Anable et al. (2016, 2011b) and ETI (2013).

1.4. Aims and objectives of this paper

Motivated by the three research needs described above, this paper aims to bring together a bespoke disaggregated model of the transport-energy-environment system with previous work on heterogeneity in the demand for PIV (Element Energy, 2013; ETI, 2013) and apply the model to explore different pathways of the timing and scale of uptake of PIV in the UK context. To achieve this aim it extends previous market and consumer segmentation work for the private car market to the fleet and company car market and integrates this into a whole-systems transport-energy-environment modeling framework previously developed and applied in policy modeling studies (Anable et al., 2011a, 2012; Brand et al., 2013, 2012). This specifically addresses the need to integrate behavioral realism into whole systems transport-energy-environment models and to upscale the insights from place-based research and behavioral sciences (Creutzig, 2015; Sims et al., 2014). The paper then applies the modeling framework in a case study of the UK transport sector by exploring the longer term life cycle[3] GHG effects of electrification pathways with the view to meeting legislated future carbon budgets (CCC, 2013).

By taking this approach, this paper thus fills existing gaps in the work going on relating to the electrification of the vehicle market elsewhere which: (a) usually takes an aggregated approach to vehicle uptake basing demand curves on single price elasticities and discount rates and at best segmenting the market into fleet and private consumers but *ignoring the heterogeneity in the private car market* (Creutzig, 2015); (b) does not account for the *dynamic nature of the market* – i.e. that some market segments are unlikely to adopt new technology until a certain critical mass is achieved in the market at which point their demand characteristics will change; (c) fails to provide policy-focused conclusions which allow an assessment of the *effectiveness of different policy instruments* (including regulation, pricing, availability of charging infrastructure) *on different consumer segments*; (d) usually ignores life cycle emissions resulting from different uptake scenarios; and (e) cannot explore the interaction between (electric) vehicle uptake and the use of other transport modes.

1.5. Paper structure

Chapter 2 outlines the approach, key methods and data sources before describing the pathways used in the modeling. Chapter 3 presents and discusses the main results. Chapter 4 finally discusses the key implications of the findings for research, policy and practice, and concludes the paper by providing an outlook for future research.

2. Modeling approach, methods and data

2.1. Approach

The two-stage approach adopted for this work involved (a) enhancing an existing transport-energy-environment system modeling framework by redesigning the car technology choice module to model multiple user segments and car technologies in a discrete choice model, and then (b) apply the model in a UK case study to quantify the implications of existing scenarios of high electrification of the car fleet to achieve climate and air quality policy goals. Given space limitations, this section focuses on the newly integrated methods relevant to modeling the scale and timing of PIV uptake and its energy and emissions impacts at the system level.

2.2. Advancing the methods

2.2.1. (Re)Introducing the UK Transport Carbon Model (UKTCM)

The UKTCM is a highly disaggregated, bottom-up modeling framework of the transport-energy-environment system. Built around a flexible and modular database structure, it models annual projections of transport supply and demand, for all passenger and freight modes of transport, and calculates the corresponding energy use, life cycle emissions and environmental impacts year-by-year up to 2050. It takes a holistic view of the transport system, built around a set of exogenous scenarios of socio-economic and political developments. The model is technology rich and, in its current version, provides projections of how different vehicle technologies evolve over time for 770 vehicle technology categories[4], including 283 car technologies such as increasingly efficient gasoline internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and hydrogen fuel cell vehicles (HFCV). The UKTCM is specifically designed to develop future scenarios to explore the full range and potential of not only technological, but fiscal, regulatory and behavioral change transport policy interventions. UKTCM played a key role in developing the *Energy2050* 'lifestyle' scenarios (Anable et al., 2011a, 2012) for the UK Energy Research Centre (UKERC) and in exploring the effectiveness of low carbon car purchasing incentives in the UK (Brand et al., 2013). An introduction to the model has been published

[3] In this paper we define life cycle energy use and emissions as the sum of *direct* (tank-to-wheel, tailpipe, at source) and *indirect* (well-to-tank or upstream emissions from fuel supply, plus process emissions from vehicle manufacture, maintenance and scrappage) energy use and emissions.

[4] A UKTCM 'vehicle technology category' is defined as a typical representative of a combination of transport type (passenger or freight), vehicle type (e.g. motorcycle, car, HGV, train), vehicle size (e.g. small car of segment A/B, van, heavy truck, intercity rail), primary fuel type (e.g. gasoline, diesel, electricity), vintage (e.g. ICE Euro 5 2009–15, PHEV 'Euro 7' 2020–25) and hybridisation (ICE, HEV, PHEV). 'Vintaging' is used to simulate changes in performance, efficiencies, consumer preferences, costs and policy levers over time.

in Brand et al. (2012); with further details provided in the Reference Guide (Brand, 2010a) and User Guide (Brand, 2010b). For the analysis presented in this paper, UKTCM was developed, updated and recalibrated from version 2.0 (as reported in Brand et al., 2013) to the current version 3.1, with the development of the technology diffusion model being the main improvement from v2.

Within the UKTCM modeling framework that covers all modes of transport (detailed in Brand et al., 2012), car technology diffusion is modeled at a higher level of detail, particularly in three areas of modeling: (1) the car ownership model, (2) the car choice model and (3) the car use model. We focus on describing the methods of (1) and (2) below.

2.2.2. Car sales and consumer segmentation

The car ownership model projects future car ownership (by private and company/fleet owners), vehicle scrappage and vehicle sales, taking into account established scrappage rates, vehicle buyer behavior, consumer segmentation as well as market response to vehicles attributes, price signals and incentives (financial and otherwise). Total car ownership is modeled based on established methods (DfT, 2013; Whelan, 2007) taking into account household income, average vehicle costs, household location (urban, rural) and car ownership saturation rates for multiple car ownership. New car sales are a function of total car ownership and car scrappage (Brand et al., 2012). The new car market is first segmented into private and company/fleet markets, then into three vehicle segments according to the UK definitions of car segment and size (segments A/B – size 'small', C/D – 'medium', E/F/G/H – 'large') (SMMT, 2014). The same private consumer split applies across each vehicle segment, but the private/fleet sales split and annual mileages vary across vehicle segments. Using UK data to illustrate the segmentation, Fig. 3a shows the sales by vehicle ownership and segment/size in 2013, highlighting the significance of the fleet/company market (52.5% of all new cars).

Consumer acceptance, defined as the readiness to consider purchasing or using an alternative fueled vehicle (AFV), varies across consumers, with the majority of private consumers not accepting as sufficiently advanced the capability of current AFV models. For example, reliability, safety and battery degradation issues, as well as uncertainty regarding residual values, contribute to consumers' reluctance to purchase BEVs. Building on the consumer study of 2729 UK car buyers mentioned above (Anable et al., 2016; ETI, 2013), the private buyer market was simplified from the eight (Fig. 2) into four segments and extended to include company-owned vehicles (Table 1 and Fig. 3b). This takes into account that among company-owned cars, some are chosen by private individuals (termed 'user-choosers') – for whom the same purchase criteria as private cars apply – while the rest are selected by a decision maker within an organisation ('fleet managers').

2.2.3. Car choice model – Overview

The UKTCM's car choice model is a discrete choice model that estimates the purchase choice probability based on an assessment of overall vehicle 'attractiveness' (or 'utility') from amongst a set of vehicle choices (or 'alternatives'), each with their own financial and non-financial 'attributes'. The weighting of attributes varies across consumer segments, because consumers' opinions on the importance of different vehicle attributes (e.g. running costs) vary. The model therefore reproduces the variation in utility of different vehicles across consumer segments, and the variation over time as vehicle attributes improve. Fig. 4 gives an outline of the car choice model including key inputs and outputs.

2.2.4. Car choice model – Private buyers

For private buyers the utility and market share equations are simply:

$$U_i = \sum_j \beta_j * Attribute_{i,j} + ASC_i \tag{1}$$

$$Market\ share_i = \frac{e^{U_i}}{\sum_k e^{U_k}} \tag{2}$$

where U_i is the total utility of alternative i; β_j is the weighting factor for attribute j; and ASC_i is the so-called *Alternative Specific Constant* for alternative *i*. The ASC_i are used to represent the specific technology preference (positive or negative) not captured by the attributes. It depicts the acceptance of the technology that varies across consumer segments; from Enthusiasts, who are willing to pay a premium, to Resistors, who exhibit a strong rejection of the technology. The β_j and ASC_i values used for this study were based on stated preference data obtained from the above mentioned consumer and vehicle choice study (Anable et al., 2016, 2011b; ETI, 2013) and given further below (incl. Table 2, Fig. 5 and Supplementary Material). It should be noted that the consumer segments are only relevant to the UK market. Since attitudes to and technology preferences of EV technology may change significantly over time, the technology preference values revealed in 2011 may well change over the modeling horizon. We have therefore taken into account changes in preference values based on uptake rates and 'consumer learning', as explained further below.

Based on previous market research reported in Element Energy (2013) and Greene et al. (2014) the key vehicle attributes concerning private buyers were: vehicle price, running costs, access to charging/refueling infrastructure, charging/refueling time, driving range, model/brand supply and consumer 'receptiveness' (i.e. technology preference). Almost all of these attributes (the exceptions being running costs and access to overnight charging infrastructure) currently present a barrier to PIV adoption. All 'enablers' and 'barriers' were monetized, i.e. put on a 'perceived' basis; this does not mean that they represent

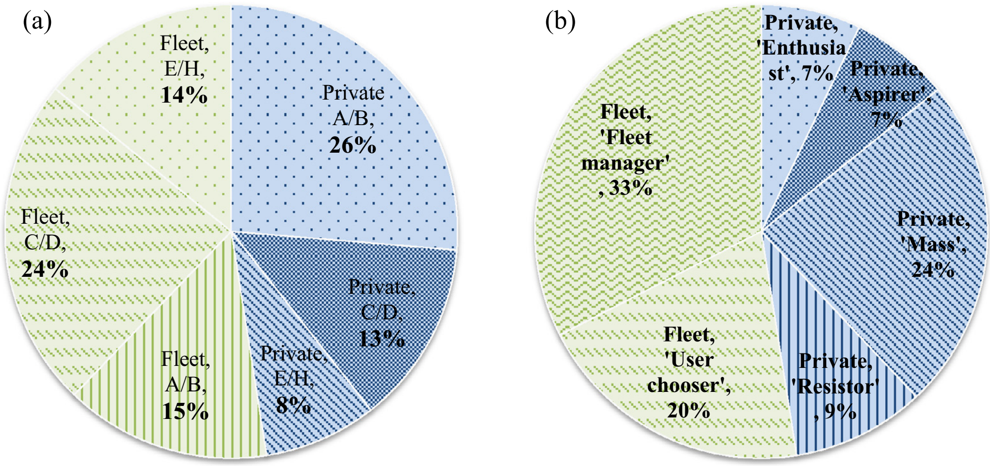

Fig. 3. (a) Car market shares by vehicle ownership (private or fleet/company) and vehicle segment/size; (b) consumer split by vehicle ownership (private or fleet/company) and consumer segment in the UK market (2013 data). Notes: (a) Car segment and size are denoted by A/B – 'small', C/D – 'medium', and E/F/G/H – 'large'. (a/b) Private car market denoted by blue patterned pie segments; fleet/company market denoted by green patterned pie segments. (b) Consumer segments denoted by four private and two fleet/company segments, with further details in Table 1 below. Percentage shares correspond to market shares for each segment. *Source:* Adapted from SMMT (2014) and ETI (ETI, 2013).

Table 1
Consumer segmentation across private and company/fleet markets.

Private (47%)	'Enthusiasts' (15%)	Driven by innovativeness and prepared to pay a premium for AFVs. While they represent most of the early adopters of AFVs, they only account for a small fraction of car buyers
	'Aspirers' (15%)	Interested in AFVs but concerned by theirtechnical limitations. AFV adoption by this group improves with theincreased availability of AFV models from trusted brands and the provision of market incentives that address both cost and technical barriers
	'Mass market' (50%)	While AFV have no particular interest or symbolic meaning to this group, they are followers of social norms and are likely to become more receptive to AFV as their numbers increase
	'Resistors' (20%)	Unlikely to buy AFVs as they strongly reject their symbolism (the perceived status and social acceptability of owning an AFV). This group's receptiveness to AFVs will change only once AFVs have lost their current connotations, i.e. only once already widely adopted
Fleet/ company (53%)	'User-choosers' (38%)	Consider company-car ownership as primarily an individual purchasing behavior, hence utility calculations are similar to those for private buyers
	'Fleet managers' (62%)	More likely to consider the total cost of ownership (TCO) and practical issues (such as technical suitability) and are less concerned with the brand and image

Note: Values in brackets show the UK segment size for the year 2013.

actual costs. The choice model weighting factors β_j were based on stated preferences of the choice experiment conducted for the ETI study (Anable et al., 2016; Element Energy, 2013). Table 2 summarizes the key attribute values and weighting factors for the reference case, with further details provided in Supplementary Material SM1.

In the absence of relevant market data it was assumed that the same private consumer split applies across each vehicle segment, but the private/company sales split and annual vehicle mileages vary across vehicle segments.

Further to attribute values and weighting factors provided in Table 2, the ASC_i (technology preference) values used in this study were based on regression analysis of the empirical data (attitudinal survey and choice experiment) obtained from the ETI segmentation study (Anable et al., 2016) as reported in Element Energy (2013). Fig. 5 shows the monetized and normalized ASC_i for plug-in vehicles for private and 'user-chooser' consumer segments.[5] The data show that all attitudinal segments consider PHEVs more favorably than BEVs due to the performance characteristics of the respective technologies, and there is no clear bias towards owning a PIV as a second car in the household (Anable et al., 2016). Mass market buyers strongly reject BEVs but not PHEVs (as much).

We modeled 'consumer learning' and the neighbor effect by assuming that the technology bias encapsulated in the technology preference parameter (ASC_i) decreased linearly with increasing sales from 100% of the ASC_i value at no sales (essentially the values shown in Fig. 5) to 0% when sales reach 25% and above. (This modeling behavior could be switched on or off for sensitivity analysis, which was explored and reported in the scenarios variants labelled by adding a suffix of "_0" to the core scenario labels.)

[5] ASC values were monetized using the revealed UK price elasticity for private consumers $C_p = -0.0003521$, and normalized against the 'Aspirer' consumer segment. The conversion was done by dividing the utility term by the price coefficient.

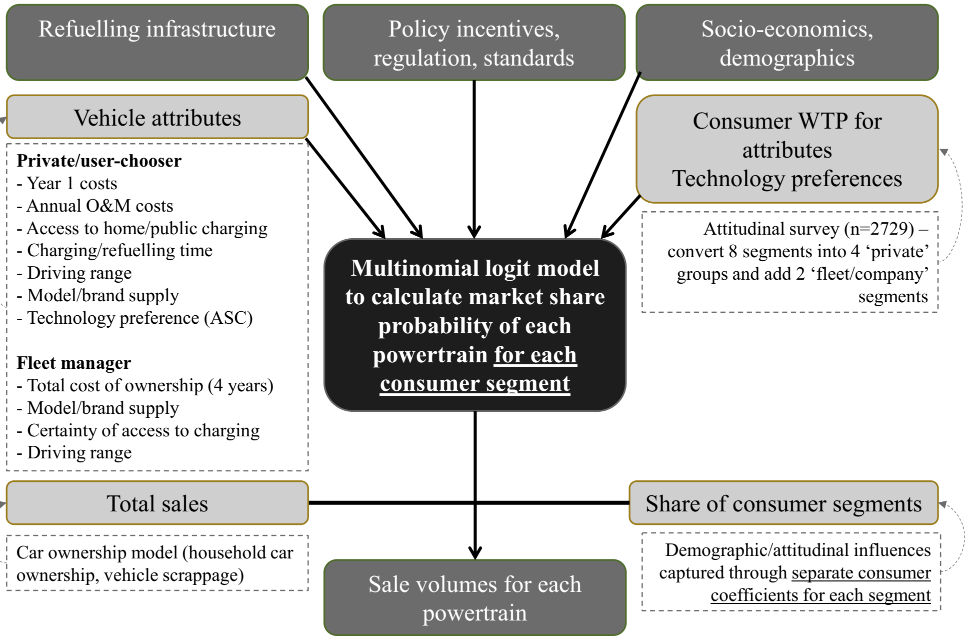

Fig. 4. Outline of the car choice model within the UKTCM modeling framework. Notes: This is a simplified illustration of the model flow. Dark grey shading indicates input and output parameters linked to other UKTCM modules. Light grey shading indicates key parameter sets within model, with key parameters in text boxes shown underneath. – WTP = willingness to pay; O&M = operating and maintenance; AFV = alternative fuel vehicle; ASC = alternative specific constant (latent variable).

2.2.5. Car choice model – Fleet manager segment

In contrast to private buyers, fleet managers are assumed to approach potential AFV purchase based on a rational assessment of TCO (Total Cost of Ownership), model/brand supply and technology suitability (charging access, driving range compatibility). Eq. (1) simplifies to:

$$U_i = \alpha * TCO_i + \beta * SP_i \tag{3}$$

where U_i is the total utility of alternative i; TCO is the total cost of ownership over 4 years; α is the price coefficient for TCO (varies by vehicle segment); and β is the price coefficient for supply penalty SP_i. The TCO includes depreciation costs (capital cost - resale value of 40% $*$ discount factor, at a 10% discount rate) and 4-year running costs (discounted, including existing company/fleet car price signals). The price coefficients for the 'fleet manager' consumer segments were derived from the elasticity in demand as per Greene et al. (2004). They vary by vehicle segment and are provided in Supplementary Material S1.

2.2.6. Car choice model – Decision process

The choice model takes into account two important pre-conditions to be met for AFVs to be part of the choice set. First, all buyers must be aware of AFVs and their incentives. The reference case assumes a sigmoid increase in awareness from low (10%) to moderate (50%) levels by 2030. Second, private buyers must have access to overnight charging (for BEV and HFCV) – this is assumed to stay constant at 70% over the time horizon. Also, fleet buyers must have certainty of access to charging/refueling and the range must meet the duty cycle requirement, in consistence with their technical suitability approach. For BEV, for instance, the reference case assumes low deployment of a rapid charging network so that only 25% of fleet buyers meet the range compatibility condition in 2015, rising to 40% by 2030 and then staying constant.

The decision process and choice model are run for each vehicle segment and consumer segment, with the share of vehicle and consumer segments being kept constant in the Reference case.

2.3. The UK case study – Modeling pathways to high uptake of PIV to 2050

2.3.1. Reference pathway – Key data and assumptions

UKTCM v3.1 was calibrated to UK national statistics for the year 2013 (DfT, 2014b). The base case or 'Reference scenario' (REF) broadly depicts a projection of transport demand, supply, energy use and emissions as if there were no changes to transport and energy policy beyond March 2015. It was modeled using UKTCM based on exogenous assumptions and projections of socio-demographic, economic, technological and (firm and committed) policy developments, including the relatively complex CO_2-graded road tax (i.e. vehicle excise duty, or VED) and company car tax regimes. Economic growth data up to 2014 were based on UK government figures. Future GDP/capita growth were assumed to average 1.7% p.a. up to 2050 – in

Table 2
Vehicle attributes taken into consideration in the choice model for private buyers.

Attribute	Value (reference case) – varies with time	Weighting factors β_j OR value of penalty – constant with time
Vehicle price	Price of vehicle + existing policy price signals (e.g. first year VED, plug-in vehicle grant, scrappage rebate), incl. VAT	Price coefficient ($\beta_j = Cp$) based on revealed UK price elasticity: −0.0003521 for private consumers.[a,b]
Running cost	Fuel costs (varies by fuel) + existing policy price signals (e.g. VED, BIK, ECA) + insurance and maintenance costs	The β_j vary across consumer segments (Supplementary Material), from high weighting for 'Enthusiasts' ($\beta_j = 7 * Cp$) to low weighting for 'Resistors' ($\beta_j = 2 * Cp$).[a,b]
Access to overnight charging	70% of private buyers have access to overnight off-street charging up to 2050. 25% of fleet buyers have certainty of access in 2015, rising to 40% by 2030	Overnight charging: pre-requisite for BEVs; Day charging: value of access for BEVs (£2000) and 4 year fuel savings (variable) for PHEVs.[c]
Charging/refueling time	Average energy used for recharging (varies by fuel type, vehicle segment and hybridization) divided by power rate (e.g. BEV/PHEV: 3 kW in 2015)	Based on stated preference, value of £250/h is assumed to decrease over time by taking the highest charging rate available to calculate the charging time. Charging time coefficient: −0.088025.[d]
Driving range	Real world range, varies by vehicle segment and powertrain, from 110 km (BEV, 2015) increasing to 400 km for large cars by 2030	Decreasing slope function of approx. £30/km, from approx. £3000 at 150 km to zero at 'ideal range' (from which there is no perceived penalty) at 370 km.[3]
Model/brand supply	Low supply, varies by vehicle segment and powertrain: $Penalty = 2/3 * \frac{\ln(shareofAFV)}{C_p}$	Supply penalty is quantified as per the technique first developed by Greene in the U.S., i.e. based on the share of AFV models for sale. Values range between £0 (equal availability) to £10,484 (only 1 model available in medium size segment).[e]

[a] In line with the price elasticity reported in the Eftec (2008) and Tanaka et al. (2014) studies. Running cost coefficients are set to reproduce the willingness to pay (WTP) for running cost savings which differs for each consumer segment, see Supplementary Material S1. BIK = Benefit-In-Kind, graded by CO_2, with tax payable by individuals with a fleet car ('user-choosers'); VED = CO_2-graded Vehicle Excise Duty (road tax); PC = price coefficient; ECA = Enhanced Capital Allowance, benefit to company in 'fleet manager' case.
[b] Eftec (2008).
[c] Lin and Greene (2010) and Element Energy (2013).
[d] Dimitropoulos et al. (2011), Hidrue et al. (2011) and Stephens (2013).
[e] Greene (1998, 2001).

Fig. 5. Variation of 'technology preferences' for/against plug-in vehicles for private and 'user-chooser' consumer segments, 2011 data. Notes: Perceived prices were derived by monetizing (dividing the utility term by the price coefficient) and normalizing against the 'Aspirer' consumer segment. *Sources:* Hidrue et al. (2011), Hoen and Koetse (2012), Batterbee and Lidstone (2013), Element Energy (2013).

line with the historic 50-year average for the UK. Transport demand projections were modeled based on average demand elasticities (of GDP/capita, population and generalized cost) for the 1995–2013 period. Fuel price and retail electricity price projections were based on 2014 UK Government 'Central' forecasts (DECC, 2014). Vehicle Excise Duty (VED, i.e. annual road tax) and other fuel duties were assumed to remain constant at 2015 levels. Following an approach commonly used in technology futures and modeling studies (European Commission, 2005; Fulton et al., 2009; Strachan and Kannan, 2008; Strachan et al., 2008; UK Energy Research Centre, 2009; WEC, 2007), pre-tax vehicle purchase prices (applied in nominal terms) were kept constant over time for established technologies and gradually decreased for advanced and future technologies, thus exogenously simulating expected global improvements in vehicle production costs, the faster-than-expected reduction in battery costs (Nykvist and Nilsson, 2015), economies of scale and market push by manufacturers operating within a globalised market.[6] For example, average purchase prices for BEV cars were assumed to decrease by 2.8% pa from 2015 to 2020, by 1.6% pa until 2030 and 0.6% pa until 2050. The Reference scenario further assumed gradual improvements in specific

[6] The assumption that alternative technologies improve (cost, energy and environmental performance, consumer preferences) at a faster rate over time applies equally to all scenarios modeled here, not just the reference scenario.

fuel consumption and tailpipe CO_2 emissions per distance travelled (see Supplementary Material SM2 for further details). The rates of improvement were based on technological innovation driven entirely by market competition, not on policy or regulatory push.[7] Fuel consumption and CO_2 improvement rates for future car vintages were assumed 1.5% pa (a somewhat lower and more conservative rate than the average rate of 4% pa observed for all new cars between 2008 and 2013). Indirect emissions from fuel supply and vehicle manufacture, maintenance and scrappage have been updated with data from a recent UK based review (Kay et al., 2013).The default electricity generation mix follows central government projections (mainly natural gas, wind & nuclear – with some CCS coal and gas by 2030), implying the carbon content of retail electricity is gradually decreasing from about 390 gCO_2/kW h in 2015 to about 160 gCO_2/kW h in 2030. Finally, the Reference scenario assumed that the segment sizes revealed in 2011 did not change over time.

2.3.2. High electrification pathways exploring UK carbon budgets

Two 'core' high electrification pathways (EV1 and EV2) were developed to assess the potential impact of different investment pathways and policy approaches to the electrification of cars with the view to meeting the UK's legally binding carbon budgets to 2050[8] and compare these with the above REF case. This involved an iterative process starting with defining 'pathway targets', i.e. specific PIV market share targets for key years (2020, 2030, 2050). The UKTCM was then used to model how PIV market shares, total PIV car fleet, and resulting direct and life cycle energy and emissions would change under a set of policy and investment interventions (or measures) designed to promote uptake. The measures included in this set addressed the barriers discussed above and included supply-side measures (model/brand supply, charging infrastructure) and demand-side measures (consumer awareness and acceptance, pricing). Most external influences (such as fuel price and retail electricity price projections) were left as in the REF case.

Based on analysis by the Committee on Climate Change (CCC) to cost-effectively meet the economy wide targets (CCC, 2013, 2015), the central pathway targets for 2020 and 2030 were assumed to be 9% and 60%, respectively. We also explored an indicative target of 100% by 2040[9]. The CCC recommended to *"maintain support for the up-front costs of [plug-in] electric vehicles, while they remain more expensive than conventional alternatives and push for stretching 2030 EU CO_2 targets for new cars and vans*" (CCC, 2015: p.11); therefore we have focused our analysis on transformation of vehicle supply and infrastructure markets (core scenario 'EV1' focusing on supply measures) and additional support to reduce up-front costs (core scenario 'EV2' focusing on supply *and* demand measures). A large number of scenarios were run in an iterative process that led to the 'final' two core scenarios: EV1 and EV2. The key results of this exercise are presented next, with any sensitivity runs reported where relevant.

3. UK case study: Results and discussion

3.1. Future car market evolution

We found that in order to achieve the ambitious target of 60% PIVs by 2030 a transformative change in supply, demand, infrastructure and policy may be required. No scenario achieved the 60% PIV target for 2030. Out of all the scenarios modeled in the iterative process, the most balanced pathway that came closest in meeting the 2030 target was scenario EV2 (Fig. 6), with 37% (1.2 m) of new cars being PHEVs and 8% (0.3 m) BEVs. The 2020 target was not met by any of the scenarios; however, a 4% share (3% PHEV, 1% BEV, or 108 thousand in total) may be achievable over the 5-year timeframe. The lack of equivalent value support in EV1 (and EV1_0) resulted in a collapse of the new PIV market from 2018 to the early 2020s. No scenario achieved the aspirational 100% PIV target for the 2040s.

The EV2 pathway implied change in a number of areas. First, in terms of vehicle supply, scenario EV2 assumed that PIV availability increases following existing trends, meaning they will be widely available in all vehicle segments and by all major brands by 2030 (in REF vehicle supply stays constant at 2015 levels, implying perceived supply penalties). Significant investment and repositioning by the major manufactures would be required, potentially driven by increasingly stringent new car CO_2 regulation after 2020 that could only be met by PIVs in high renewable scenarios. Second, consumer awareness and acceptance would have to increase significantly, with a steep increase in the 2020s (simulated by an S-curve) leading to 95% of potential buyers being aware of PIVs and their incentives by 2030, and 100% by 2040. This may require a raft of measures, including large scale promotional campaigns, large PIV field trials, and dedicated car clubs. Third, the scenario further assumed investment in the next 15 years in high levels of overnight (mainly off-street) charging complemented by a national network of about 2000 rapid charging points for day charging to increase the market base for PIVs (in particular for the fleet segment) and provide national coverage by 2030. This effectively meant that by 2030 74% of private buyers (compared to 70% in the REF case) and 80% of fleet buyers (compared to 40% in REF) would have certainty of access to charging. The invest-

[7] This implies that the EU mandatory agreement on new car CO_2 emissions would not be met. However, separating innovation by competition and innovation by regulation/policy push is slightly arbitrary here as the effects are never easy to untangle. We merely assume that the recent improvement came partly from market competition and partly from policy (mainly fiscal) and regulation.

[8] The first four carbon budgets, leading to 2027, have been set in law. The UK is currently in the second carbon budget period (2013–17). Meeting the fourth carbon budget (2023–27) will require that emissions be reduced by 50% on 1990 levels in 2025. The Committee on Climate Change will publish its advice to government on the fifth carbon budget in December 2015, covering the period 2028–2032, as required under Section 4 of the Climate Change Act. The government will propose draft legislation for the fifth budget in 2016.

[9] The CCC has an indicative target of 100% market share for PIVs by 2040, so that, taking the stock turnover into account, the vehicle stock is 'virtually decarbonised' by 2050.

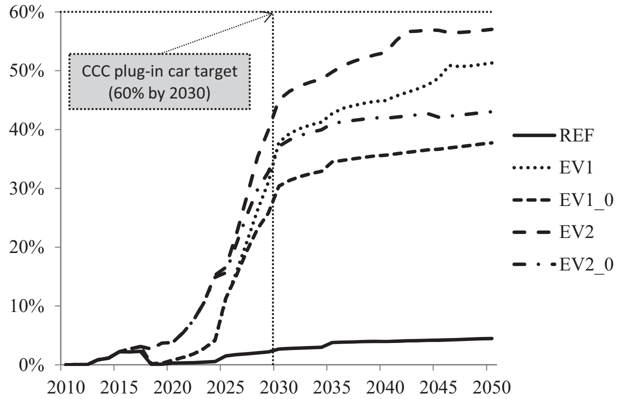

Fig. 6. Plug-in car sales (as share of total) for four selected scenarios compared to the reference case (REF). Notes: REF = reference scenario; EV1 = scenario with increased vehicle and infrastructure supply; EV2 = scenario with increased vehicle and infrastructure supply plus policy incentives; a scenario label ending in "_0" denotes a sensitivity run where technology preferences do *not* change with increasing sales. PIV = plug-in vehicle (PHEV and BEV). CCC = Committee on Climate Change PIV target for 2030 (CCC, 2013, 2015).

ment needed would be in the tens of millions of GBP. Fourth, with a growing fast charging network happening over time the *perceived* PIV charging times were decreasing with increasing BEV power rates (assumed to increase rapidly from 3 kW in 2015 to 7 kW in 2020 and then to 50 kW; for PHEV, this maxed out in 2020 at 7 kW). Last, in order to mitigate the purchase price premium of PIVs the scenario assumed continued and improved equivalent value support for PIVs for both private and company/fleet buyers, through capital incentives and continuation of the graded VED. The plug-in car-grant was extended to 2019 (instead of stopped after 2017) at the current rate of £5000, then reduced by half to 2024 (no grant from 2025). In addition, the company car tax regime was revised so that cars emitting 50 gCO_2/km or less (effectively BEV and PHEV) see the 9% BIK rate (as opposed to 13–16% as currently planned) (HM Treasury, 2015; Lane, 2016).

The trajectories further show that in the REF scenario PIV take up was generally low and slow (Fig. 6). Indeed, once the current fiscal support for PIVs (plug in car grant, favorable company car tax regime) diminishes or even ceases to exist from 2018 onwards, the demand for PIV virtually disappears and only reemerges in the late 2020s (although at low levels, <5%) once capital costs decrease sufficiently to compete with established vehicle technologies, especially on a TCO basis in the fleet market. The low deployment is largely due to lack of vehicle supply, charging infrastructure, consumer awareness and receptiveness. Furthermore, the lower and 'delayed' trajectories of scenario EV1 (essentially the EV2 scenario without the short to medium term policy measures) suggest that equivalent value support, whether as upfront cost subsidies or future cost savings, can make a significant contribution to PIV diffusion. This is particularly apparent in the short term when policy support for private and company car buyers will be taken away (HM Treasury, 2015). Sensitivity of results to the choice model coefficients (which stay constant over the years) and assumptions related to the purchase decision process showed the financial attributes have the greatest impact on market share, under the baseline inputs. An exception is the assumption that fleet managers do not display technology preferences. In the extreme case where their bias against EVs is set identical to the Mass Market buyers, sales estimates are reduced by up to 50% by 2030.

Further sensitivity analyses of comparative pathways where technology preferences change at a lower rate or do not change at all with increasing sales show significant differences in outcomes. Switching off the technology preference learning (i.e. no decrease in technology preference cost/benefit with increasing sales, as explored in the sensitivity scenario runs) in EV1_0 and EV2_0 slowed down and decreased BEV and PHEV uptake considerably, with PIV shares about a quarter lower than the scenarios where technology preference learning was enabled. In the extreme case where PIV acceptance does not improve with increasing sales, the equivalent value support (e.g. continuation of the plug in car grant) required to reach the PIV uptake targets would need to increase to about £6000 post 2025.

In terms of the evolution of the total car fleet the analysis shown in Fig. 7 provides evidence to support three key findings. First, in all scenarios the 2020 stock will look pretty much the same as it is today. Second, by 2030 PIVs (PHEVs in particular) will have taken significant shares away from ICVs and HEVs in the alternative cases. Third, by 2050 the majority of the fleet will be plugged-in *if* we adopted appropriate PIV support measures. Conversely, the modeling suggests that the aspirational 100% PIV penetration of the fleet by 2050 is unlikely to materialize without further policy incentives (e.g. free parking, free electricity, new business models of PIV ownership and use), supply shift to PIV (e.g. decreasing model/brand supply of gasoline ICV cars) and regulation (e.g. eventually banning gasoline and diesel cars in urban areas thus making PIV the preferred or even only choice).

3.2. Who buys plug-in vehicles?

Our results suggest that the majority of new PHEV and BEV cars will be purchased by company car owners, in particular fleet managers, as shown for scenario EV2 in Fig. 8. While the analysis suggests that Enthusiasts (~8% of new PIVs by 2025)

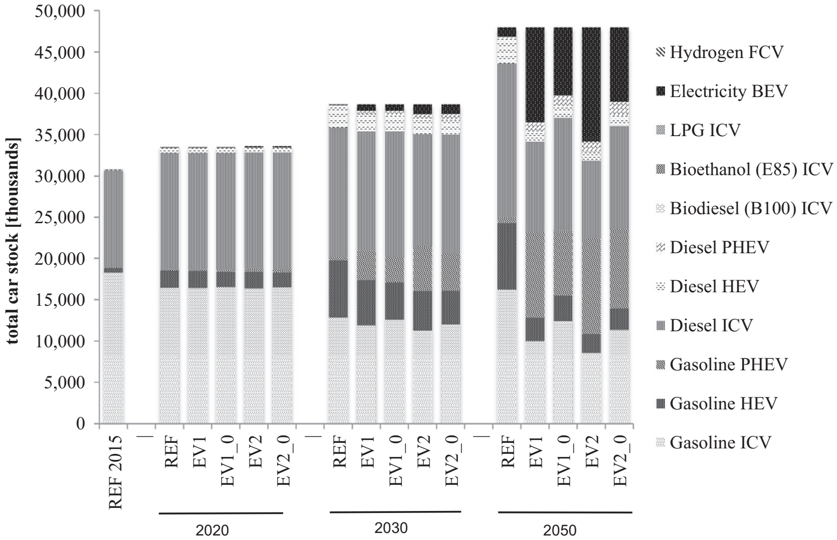

Fig. 7. Projections of technology make-up of total UK car fleet. Notes: While shown in the legend, the analysis suggested no significant take up of hydrogen FCV, dedicated biofuel ICV and gas powered ICV. This was largely due to the assumed lack of any model/brand supply over the modeling period.

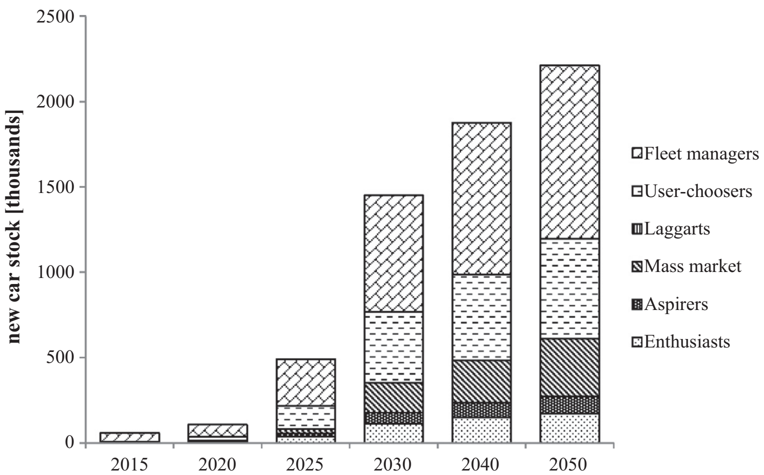

Fig. 8. New car sales by consumer segment, scenario EV2.

and Aspirers (~4% of new PIVs by 2030) are important in the short-to-medium term, the Mass market only picks up in the 2030s, and Laggards are resisting to switch to PIVs all the way through (less than 1% of new PIVs). The marked difference between private and company buyers is largely due to the more favorable policy support, higher receptiveness and increased certainty of access to charging in the company/fleet segment.

3.3. Size and rate of emissions savings of key GHG and AQ pollutants

The above pathways translate into emissions savings of key GHG and AQ pollutants as follows.

3.3.1. Direct or tailpipe CO_2 emissions

We found that already in the reference case (REF) *direct* emissions of CO_2 from cars fell from the peak in 2005 of 75 $MtCO_2$ to 65 $MtCO_2$ in 2015, and further to 61 $MtCO_2$ (2020), 53 $MtCO_2$ (2030) and 45 $MtCO_2$ (2050).[10] While the post-2008 economic downturn and rising fuel costs are major factors underlying the short term fall, the longer-term decrease of about

[10] Changes in carbon emissions are the result of a number of interrelated factors, including the penetration of lower emission cars into the vehicle fleet, changes in demand for cars and other modes, changes in car total ownership (e.g. a decrease in total ownership means lower indirect carbon emissions from manufacture, maintenance and scrappage) and changes in upstream fuel emissions. For further details on how this is done in UKTCM see Brand (2010a/b) and Brand et al. (2012).

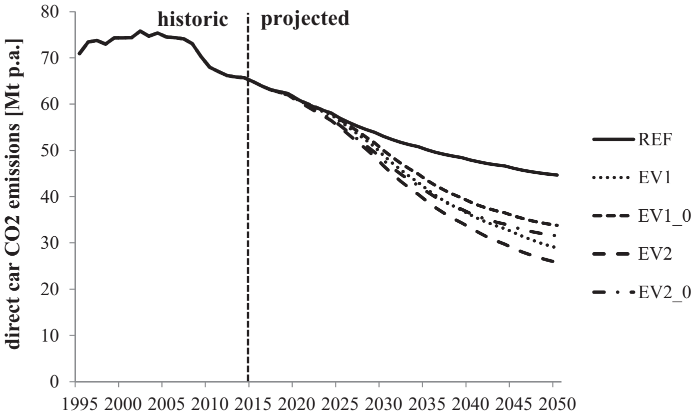

Fig. 9. Pathway comparison of direct CO_2 emissions from cars in the UK.

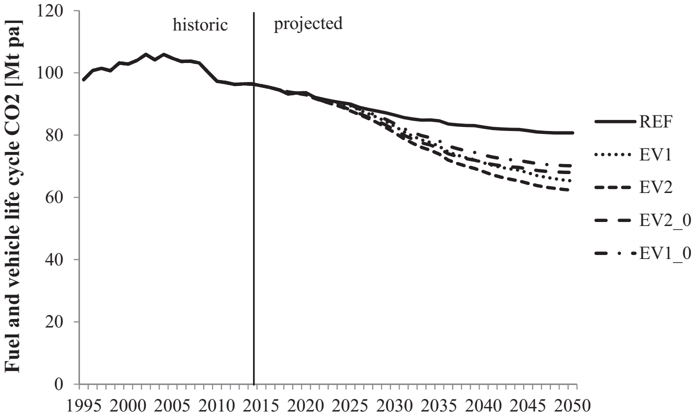

Fig. 10. Pathways comparison of life cycle greenhouse gas emissions (as CO_2e) from cars.

18% between 2015 and 2030 is largely the result of improvements in fuel efficiency and emissions performance of new cars penetrating the fleet and some fuel switching to HEV and PIV cars, thus offsetting the overall growth in the demand for car travel.

When compared to the reference case, the high PIV scenarios showed various levels of success in reducing *direct* car CO_2 emissions. As shown in Fig. 9, the highest PIV diffusion pathway (EV2) reduced *direct* emissions fastest and by the highest amounts, saving 12% (2030) and 42% (2050) of direct car CO_2 emissions when compared to baseline (REF). The rate and size of the savings was somewhat lower for the 'supply only' PIV pathway (EV1), starting later and saving about 8% and 35% of CO_2 over baseline by 2030 and 2050 respectively.

3.3.2. Life cycle greenhouse gas emissions impacts

In contrast to the general trend of a significant decline in *direct* emissions, *total life cycle* GHG emissions[11] in the reference case decreased by only 10% between 2015 and 2030 (16% by 2050), saving about 15 $MtCO_2e$ p.a. by 2050 (Fig. 10). This lower rate can be explained by a gradual increase in *indirect* GHG emissions from growing car ownership (with higher emissions from manufacture and scrappage) and some increase of emissions from upstream electricity generation, even though the carbon content of electricity is expected to decrease from about 390 gCO_2/kW h in 2015 to about 160 gCO_2/kW h in 2030.

Again, when compared to the reference case, the high PIV pathways showed significant reductions over the outlook period. By 2030, life cycle GHG emissions were 16% (EV2) and 14% (EV1) below baseline (REF). 20 years on, and life cycle GHG emissions were 35% (EV2) and 32% (EV1) lower than baseline, saving about 15 $MtCO_2e$ p.a. (EV1) and 18 $MtCO_2e$ p.a. (EV2) in 2050.

In terms of reducing climate forcing, cumulative GHG emissions savings are an arguably better metric than annual emissions. In view of the findings presented so far it comes as no surprise that the EV2 pathway *cumulatively* saved the most life

[11] Includes fuel and vehicle (production, maintenance, disposal) life cycle emissions. Based on the 100-year global warming potentials of CO_2, CH_4 and N_2O.

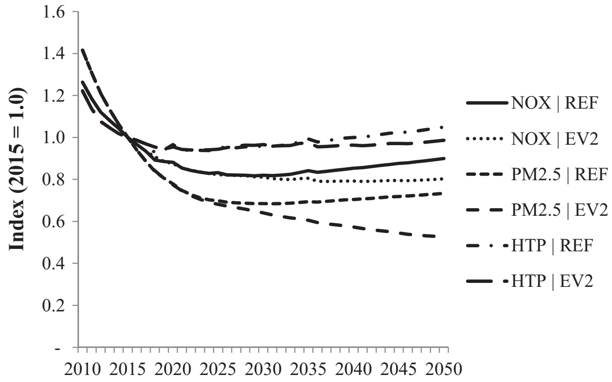

Fig. 11. Pathway comparison of selected air quality indicators, index of total life cycle NO_X, $PM_{2.5}$ and HTP (REF vs. EV2, 2015 = 1.0).

cycle GHG emissions over the outlook period. We found that the EV2 pathway saved 26 $MtCO_2e$ (i.e. 1.1% of the cumulative total) more between 2015 and 2030 than baseline (REF). The real impact would be felt after 2030, however, with cumulative savings of around 300 $MtCO_2e$ (5.3%) more between 2015 and 2050 than baseline. This supports the finding that in EV2 the 2030 to 2050 period would be the 'age of plug-in cars'.

3.3.3. 'Co-benefits'? – A note on air pollution impacts

This section looks briefly at potential changes to human health that is mainly affected by particulates (PM), including primary (from combustion) and secondary PM (sulphur dioxide, SO_2 and nitrogen oxides, NOx contribute to particulate levels through the formation of sulphate and nitrate aerosols). The Human Toxicity Potential (HTP) of air pollution is an impact indicator that provides a means to describe environmental damage and to compare different pollutants with respect to human health impacts using weighting factors (or human toxicological classification factors: e.g. 1.2 for SO_2, 0.78 for NO_X, 1.7 for non-methane hydrocarbons) and being measured in kgHTP (Azapagic et al., 2011).

Fig. 11 compares the reference and high PIV pathway EV2 in terms of their total life cycle NO_X, $PM_{2.5}$ and HTP indicators in an index graph (2015 = 1.0). This suggests that on a life cycle basis (that includes tailpipe, upstream and downstream emissions) high electrification of the car market from the late 2020s onwards can reduce noxious NO_X and $PM_{2.5}$ pollution by 11% and 28% by 2050 respectively. Total Human Toxicity Potential was also reduced by up to 6% from the late 2030s onwards.

4. Conclusions

4.1. Key results: Approach

The paper has shown how the integration of a disaggregated model of the transport-energy-environment system with previous work by the authors on heterogeneity in the demand for and supply of plug-in vehicles can be used to explore the timing, scale and energy and environmental impacts of uptake of plug-in vehicles from a consumer perspective. With regards to the five gaps identified in Section 1.4, the results show the importance of accounting for the heterogeneity in and dynamic nature of the car market in terms of new technology adoption by private consumers, so called 'user choosers' and fleet managers, as well as accounting for potential effects on wider life cycle emissions resulting from different PIV uptake pathways. The results allow a perhaps more realistic assessment of the effectiveness of different policy instruments, market conditions (vehicle supply, private vs fleet market, vehicle segments) and social factors (consumer awareness, range "anxiety", perceived charging requirements) on different consumer segments, thus providing more policy-focused conclusions on the likely pathways to high penetration of low carbon vectors in the transport system that may be required to meet future carbon budgets and air quality targets. Finally, the whole-systems approach used allows an assessment of interactions between PIV vehicle uptake, competing vehicle technology uptake (e.g. HEV) and their use by different actors within the wider transport system. We were therefore able to place the electrification of the car market in the context of other (low carbon) transport behaviors on the basis of their whole life cycle emissions, including potential changes in the way in which cars are used, together with the impacts on government tax revenue.

4.2. Key results: UK case study of high PIV pathways

The UK case study modeled different pathways to high uptake of PIV to 2050, with the aim to meet existing GHG emissions targets for the 5th carbon budget period (2027–2032) and beyond to 2050. The results contribute to the growing consensus that to achieve such deep cuts in carbon emissions via mass market electrification in the car market, we may need a wider set of 'push' and 'pull' measures than the current focus on vehicle technology and supporting fiscal incentives. The results also contribute to the debate on which model to use for which purpose. The car market is highly heterogeneous and segmented, both in terms of supply (choice of vehicles) and demand (private/fleet, consumer segments); therefore, a model that attempts to integrate market heterogeneity and consumer segmentation is arguably more useful than a model that focuses purely on technological change.

We showed the importance of the fleet/company market, in particular in meeting short and medium term targets and as an entry point for 'new technology', as well as the crucial roles of increasing model/brand supply, reducing or spreading upfront costs and concerted promotion of PIVs by governments and industry. The results suggest that the measures needed to transform UK car market may have to go well beyond what recent modeling studies have suggested – none of the relatively ambitious scenario pathways achieved the 2030 target proposed by the CCC. While this is directly the result of relatively slow and conservative market dynamics, it may also be due to the different modeling approaches used; for instance, this study had a larger vehicle choice set (including gasoline ICV, diesel HEV, HFCV, CNG ICV, etc.) that may limit the uptake of PIV within the choice model – in particular efficient HEV 'compete' well with future PHEV (and BEV). We believe that it is more realistic to model a wider range of existing and future alternatives rather than to focus on ICV, BEV and PHEV only (Element Energy, 2013). The findings further suggest that moving towards a 100% PIV uptake by the 2040s may require further (day charging) infrastructure investment and choices, as well as regulations that phase out non-PIVs (Lieven, 2015). Such action could be direct (procurement rules, emission zones) or indirect (for example a penalty on OEMs to encourage them to cross subsidize PIVs by making ICVs more expensive, in the UK, or potentially in other markets once the PIV market share is close to 100%). Cities are likely to be an instrumental stakeholder, as suggested by the EU Transport Strategy, as well as the recent UK move to Local Authorities being in charge of air quality and public health issues to maximize 'co-benefits' of climate mitigation efforts.

4.3. Limitations of the study

The data underlying the consumer segmentation model were based on stated preference and collected in 2011. While the survey participants were considered mainstream with experience of owning and driving a PIV (as opposed to early adopters), more up-to-date evidence is needed on the characteristics, behaviors and attitudes of a larger, more 'experienced' population of PIV owners in the UK. For instance, while the literature suggests that technology preferences diminish with increasing market presence and the neighbor effect (Arthur, 1989; Axsen et al., 2009; Mau et al., 2008), only revealed preference data can confirm the rate of the relationship between sales and receptiveness. In order to keep pace with the rapid development of the market and inform future policy making aimed at supporting the growth of the PIV market in the UK, evidence on PIV owners should ideally be collected on a continuous or semi-regular basis (Brook Lyndhurst, 2015). This study has undertaken only a limited sensitivity analysis around the key factors determining PIV uptake. Further work is required in exploring sensitivities around vehicle costs (and new business models of ownership and use of different PIV components), the dynamic nature of attitudes and EV technology, the relative importance between upfront and future costs and benefits (Brand et al., 2013), vehicle supply (not just PIV, also HEV, ICV and HFCV) and acceptance by a wider set of the heterogeneous fleet/company market.

4.4. Implications for policy and industry

Consideration of the wider impacts has important implications for the rate with which cumulative carbon reduction budgets are managed and each instrument's likely political feasibility. The predicted low uptake of PIV by the end of the decade (up to 2020) suggest targets may have to be revised and other policy measures implemented, including demand measures that do not rely on the relatively slow car stock turnover, as shown in this paper. In order to deliver the high EV uptake pathway, the major OEMs must continue to release new PIV models at, or faster than, the current launch rate of over 10 new PIV models per year. The UK and other countries must ensure that the post-2020 new car CO_2 legislation is beneficial for PIV (and low-CO_2) market development and to support the emerging PIV manufacturing base. To address the capital cost premium of PIVs innovative leasing and new ownership models should be supported by the public (lower risk) and private (higher innovation) sectors. Both sectors also have crucial roles to play in promoting PIVs to raise awareness and acceptance through large scale, coordinated and sustained marketing campaigns, in providing more opportunities for PIV test drives, demonstrations and local licensing (e.g. taxis, car clubs). Furthermore, given the key role identified for the rapid charging network in PIV market development for the fleet/company segment, we argue that Government should actively support the development and financing of new rapid charging services to ensure adequate roll-out of rapid charging facilities across the UK and beyond (Lieven, 2015). Finally, a range of financial and/or non-financial measures may be needed to provide equivalent value support for some time yet (Tanaka et al., 2014). The scale of support potentially required to achieve the high PIV pathway to 2030 and beyond would present a challenge to a future UK administration, suggesting alternative policy options will be needed. Continuation of the lower tax rate for Benefit-in-Kind for company cars, or an equivalent capital support, for leased and rental fleets, would be highly advantageous to supporting the future PIV market in the UK. One alternative to (just) providing capital grants is the use of technology-neutral 'feebates', which combine a CO_2-graded system of 'fees' for the most polluting vehicles, with CO_2-graded purchase 'rebates' for PIVs. Revenue-neutral feebate schemes (as in France) offer the possibility of supporting market transformation over the longer-term (Brand et al., 2013). Also, local and city authorities (and national government) should provide further non-financial benefits (e.g. preferential parking and road access as in Norway) to provide high value benefits to end users at relatively low cost.

4.5. Future work

The model uses an aggregate representation of fleet owners and users. Future research should disaggregate or segment the fleet managers in order to address the many existing gaps in the evidence on their characteristics, attitudes and usage of PIV. This would help to assess the effectiveness of incentives and other policy measures targeted at fleet managers and inform their future design. There is more work to be done to assess the effects of different combinations of a wider set of measures. For instance, the work could be extended to include travel behavior measures that target the use of vehicles (not just ownership). The UKTCM could easily be used for such an analysis; hence we consider this as a first step for future work. GHG emissions will be dependent on the carbon intensity of the grid which was not altered between scenario pathways. This is one of the sensitivities to be explored in future work. There is also more to be done to understand the spatial distribution of car ownership as well as the distributional impacts with respect to congestion and air pollution impacts using more spatially disaggregated analysis within a life cycle assessment framework. We are currently working on developing the modeling framework to take this forward. The focus of this work was on cars; yet the analysis could easily be applied to vans, trucks and buses where, arguably, attitudinal, preference and socio demographic factors play lesser roles – suggesting we tackled the more difficult market first. Finally, more work needs to be done to understand system-wide energy implications of low carbon transitions in transport as well as other sectors, in particular when looking at the likely electrification of all road and rail transport and its linkages with systemic changes in the energy system (Anable et al., 2012; Baruah et al., 2014).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tra.2017.01.017.

References

AEA Technology, 2009 Market Outlook to 2022 for Battery Electric Vehicles and Plug-in Hybrid Electric Vehicles, Final Report to the Committee on Climate Change, ED46299. Didcot.

Anable, J., Brand, C., Eyre, N., Layberry, R., Bergman, N., Strachan, N., Fawcett, T., Tran, M., 2011a. Energy 2050 - WG1 Energy Demand: Lifestyle and Energy Consumption, Working Paper REF: UKERC/WP/ED/2011/001. UK Energy Research Centre (UKERC), Energy Demand Theme, Oxford.

Anable, J., Brand, C., Tran, M., Eyre, N., 2012. Modelling transport energy demand: a socio-technical approach. Energy Policy 41, 125–138.

Anable, J., Kinnear, N., Hutchins, R., Delmonte, E., Skippon, S., 2016. Consumer Segmentation and Demographic Patterns. Report for Energy Technologies Institute Plug-in Vehicles Infrastructure Project (April 2011). Transport Research Laboratory Published Project Report PPR769. Energy Technologies Institute, Crowthorne..

Anable, J., Schuitema, G., Stannard, J., 2014. Consumer Responses to Electric Vehicles: Literature Review, TRL report PPR728. TRL, Crowthorne..

Anable, J., Skippon, S., Schuitema, G., Kinnear, N., 2011b. Who will adopt electric vehicles? A segmentation approach of UK consumers. In: Proceedings of European Council for an Energy Efficient Economy Summer Study, Giens/Hyeres, France. Paper 4–560.

Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Econ. J. 99, 116–131.

Axsen, J., Mountain, D.C., Jaccard, M., 2009. Combining stated and revealed choice research to simulate the neighbor effect: the case of hybrid-electric vehicles. Resource Energy Econ. 31, 221–238.

Azapagic, A., Perdan, S., Clift, R., 2011. Sustainable Development in Practice - Case Studies for Engineers and Scientists. John Wiley & Sons.

Baruah, P.J., Eyre, N., Qadrdan, M., Chaudry, M., Blainey, S., Hall, J.W., Jenkins, N., Tran, M., 2014. Energy system impacts from heat and transport electrification. Proc. Inst. Civil Eng. - Energy 167, 139–151.

Batterbee, J., Lidstone, L., 2013. An Affordable Transition to Sustainable and Secure Energy for Light Vehicles in the UK. Energy Technologies Institute LLP, Loughborough.

Brand, C., 2010a. UK Transport Carbon Model: Reference Guide v1.0, Available for Download. UK Energy Research Centre, Energy Demand Theme, Oxford <http://www.ukerc.ac.uk/programmes/energy-demand/uk-transport-carbon-model.html>.

Brand, C., 2010b. UK Transport Carbon Model: User Guide v1.0. UK Energy Research Centre, Energy Demand Theme, Oxford.

Brand, C., Anable, J., Tran, M., 2013. Accelerating the transformation to a low carbon passenger transport system: the role of car purchase taxes, feebates, road taxes and scrappage incentives in the UK. Transp. Res.: Part A: Pol Pract. 49, 132–148.

Brand, C., Tran, M., Anable, J., 2012. The UK transport carbon model: an integrated life cycle approach to explore low carbon futures. Energy Policy 41, 107–124.

Brook Lyndhurst Ltd for the Department for Transport, 2015. Uptake of Ultra Low Emission Vehicles in the UK, A Rapid Evidence Assessment for the Department for Transport. London.

Committee on Climate Change (CCC), 2013. Fourth Carbon Budget Review – Technical Report, Sectoral Analysis of the Cost-Effective Path to the 2050 Target. London.

Committee on Climate Change (CCC), 2015. Meeting Carbon Budgets - Progress in Reducing the UK's Emissions, 2015 Report to Parliament. London.

Creutzig, F., 2015. Evolving narratives of low-carbon futures in transportation. Transport Rev., 1–20

Daziano, R.A., Chiew, E., 2012. Electric vehicles rising from the dead: data needs for forecasting consumer response toward sustainable energy sources in personal transportation. Energy Policy 51, 876–894.

Department of Energy and Climate Change, 2014. Updated Energy & Emissions Projections - September 2014, Annex M: Growth assumptions and prices. London.

Department for Transport (DfT), The Stationary Office, 2013. Road Transport Forecasts 2013, Results from the Department for Transport's National Transport Model. London.

Department for Transport, 2014a. Public Attitudes to Electric Vehicles: 2014. London.

Department for Transport, 2014b. Transport Statistics Great Britain 2014. London.

Dimitropoulos, A., Rietveld, P., Ommeren, J.N.V., 2011. Consumer Valuation of Driving Range: A Meta-Analysis, Tinbergen Institute Discussion Paper. Tinbergen Institute, VU Amsterdam, Amsterdam.

Dodds, P.E., McDowall, W., 2014. Methodologies for representing the road transport sector in energy system models. Int. J. Hydrogen Energy 39, 2345–2358.

Eftec, 2008. Demand for Car and Their Attributes. Eftec for the Department for Transport, London, p. 46.

Element Energy, 2013. Pathways to High Penetration of Electric Vehicles - Final Report. Element Energy Ltd, Ecolane and University of Aberdeen for the Committee on Climate Change, Cambridge.

ETI, 2013. Transport: An Affordable Transition to Sustainable and Secure Energy for Light Vehicles in the UK. Energy Technologies Institute, Loughborough.

European Commission, 2005. World Energy Technology Outlook - 2050 (WETO-H2). Luxembourg.

Fulton, L., Cazzola, P., Cuenot, F., 2009. IEA Mobility Model (MoMo) and its use in the ETP 2008. Energy Policy 37, 3758–3768.

Graham-Rowe, E., Gardner, B., Abraham, C., Skippon, S., Dittmar, H., Hutchins, R., Stannard, J., 2012. Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations. Transp. Res.: Part A: Pol. Pract. 46, 140–153.

Greene, D.L., 1998. Survey evidence on the importance of fuel availability to choice of alternative fuels and vehicles. Energy Stud. Rev. 8, 215–231.

Greene, D.L., 2001. TAFV Alternative Fuels and Vehicles Choice Model Documentation, ORNL/TM-2001/134. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Greene, D.L., Duleep, K.G., McManus, W., 2004. Future Potential of Hybrid and Diesel Powertrains in the U.S. Light-Duty Vehicle Market, ORNL/TM-2004/181. ORNL, Oak Ridge, TN.

Greene, D.L., Park, S., Liu, C., 2014. Analyzing the transition to electric drive vehicles in the U.S. Futures 58, 34–52.

Hidrue, M.K., Parsons, G.R., Kempton, W., Gardner, M.P., 2011. Willingness to pay for electric vehicles and their attributes. Resour. Energy Econ. 33, 686–705.

HM Treasury, 2015. Budget March 2015. London.

Hoen, A., Koetse, M.J., 2012. A Choice Experiment on AFV Preferences of Private Car Owners in the Netherlands, PBL Working Paper 3. PBL Netherlands Environmental Assessment Agency, Den Haag, Netherlands.

IEA, 2011. Energy Technology Perspectives 2010, World Energy Outlook 2011. International Energy Agency (IEA), Paris, France.

IEA, 2013. Life Cycle Assessment of EVs, Task 19. International Energy Agency, Paris. <www.ieahev.org/tasks/task-19-life-cycle-assessment-of-evs> (Retrieved 26 March 2015).

IEA, 2015a. Energy and Climate Change: World Energy Outlook Special Report. International Energy Agency, Paris.

IEA, 2015b. Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action. OECD/IEA, Paris.

Kay, D., Hill, N., Newman, D., 2013. Powering Ahead: The Future of Low-Carbon Cars and Fuels. Ricardo-AEA for the RAC Foundation and UKPIA, London.

Lane, B., 2006. Life Cycle Assessment of Vehicle Fuels and Technologies. Final Report including Appendices, Ecolane Transport Consultancy, Bristol.

Lane, B., 2016. BIK Rates and Company Car Tax. Next Green Car Ltd., Bristol, UK. <http://www.nextgreencar.com/company-car-tax/bik-rates/> (Last accessed 23/03/2016).

Leinert, S., Daly, H., Hyde, B., Gallachóir, B.Ó., 2013. Co-benefits? Not always: quantifying the negative effect of a CO_2-reducing car taxation policy on NOx emissions. Energy Policy 63, 1151–1159.

Lieven, T., 2015. Policy measures to promote electric mobility – a global perspective. Transp. Res.: Part A: Pol. Pract. 82, 78–93.

Lin, Z., Greene, D.L., 2010. Rethinking FCV/BEV Vehicle Range: A Consumer Value Trade-off Perspective. EVS-25, The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, China.

MacLean, H.L., Lave, L.B., 2003. Life cycle assessment of automobile/fuel options. Environ. Sci. Technol. 37, 5445–5452.

Mau, P., Eyzaguirre, J., Jaccard, M., Collins-Dodd, C., Tiedemann, K., 2008. The 'neighbor effect': simulating dynamics in consumer preferences for new vehicle technologies. Ecol. Econ. 68, 504–516.

Mckinsey Global Institute, 2009. Averting the Next Energy Crisis: The Demand Challenge. San Francisco, USA.

Morton, C., Anable, J., Brand, C., 2014. Uncertainty in the demand for electric vehicles: an analysis of its location and governmental response. In: Proceedings of the 2014 UTSG Annual Conference, Newcastle.

Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nat. Clim. Change 5, 329–332.

OLEV, 2013. Driving the Future Today - A Strategy for Ultra Low Emission Vehicles in the UK. Office for Low Emission Vehicles, London.

Schuitema, G., Anable, J., Skippon, S., Kinnear, N., 2013. The role of instrumental, hedonic and symbolic attributes in the intention to adopt electric vehicles. Transp. Res.: Part A: Pol. Pract. 48, 39–49.

Schwanen, T., Banister, D., Anable, J., 2011. Scientific research about climate change mitigation in transport: a critical review. Transp. Res.: Part A: Pol. Pract. 45, 993–1006.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Meza, M.J.F., Fulton, L., Kobayashi, S.O.L., McKinnon, A., Newman, P., Ouyang, M., Schauer, J.J., Sperling, D., Tiwari, G., 2014. Transport. Climate Change 2014: Mitigation of Climate Change. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Stechow, C.V., Zwickel, T., Minx, J.C. (Eds.), Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

SMMT, 2014. New Car CO_2 Report 2014: The 13th Report. The Society of Motor Manufacturers and Traders (SMMT), London.

SMMT, 2015. Electric and Alternatively-Fuelled Vehicle Registration Figures for the Month and the Year-to-Date, 2010–2015. Society of Motor Manufacturers and Traders, London. <http://www.smmt.co.uk/category/news-registration-evs-afvs/> (Last accessed on 11/09/2015).

Stephens, T., 2013. Non-Cost Barriers to Consumer Adoption of New Light-Duty Vehicle Technologies, Transportation Energy Futures Series, DOE/GO-102013-3709. Argonne National Laboratory for the U.S. Department of Energy, Argonne, IL.

Strachan, N., Kannan, R., 2008. Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Econ. 30, 2947–2963.

Strachan, N., Kannan, R., Pye, S., 2008. Scenarios and Sensitivities on Long-Term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models. UK Energy Research Centre (UKERC), London.

Tanaka, M., Ida, T., Murakami, K., Friedman, L., 2014. Consumers' willingness to pay for alternative fuel vehicles: a comparative discrete choice analysis between the US and Japan. Transp. Res.: Part A: Pol. Pract. 70, 194–209.

UK Energy Research Centre, 2009. Making the Transition to a Secure and Low-Carbon Energy System: Synthesis Report. UK Energy Research Centre, London.

World Business Council for Sustainable Development (WBCSD), 2004. Mobility 2030: Meeting the Challenges to Sustainability. Geneva.

World Energy Council (WEC), 2007. Transport Technologies and Policy Scenarios to 2050. London, UK.

Whelan, G., 2007. Modelling car ownership in Great Britain. Transp. Res.: Part A: Pol. Pract. 41, 205–219.