Will current electric vehicle policy lead to cost-effective electrification of passenger car transport?

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ABSTRACT

Encouraged by the falling cost of batteries, electric vehicle (EV) policy today focuses on expediting electrification, paying comparatively little attention to the cost of the particular type of EVs and charging infrastructure deployed. This paper argues that, due to its strong influence on EV innovation paths, EV policy could be better designed if it paid more attention to cost and technology development risk. In particular, using a model that estimates the incremental cost of different EV and infrastructure mixes over the whole passenger car fleet, we find that EV policy with a strong bias towards long-range battery electric vehicles (BEVs) risks leading to higher costs of electrification in the medium term, possibly exceeding the ability of governments to sustain the necessary incentives until battery cost drops sufficiently. We also find that promoting a balanced mix of BEVs and plug-in hybrid electric vehicles (PHEVs) may set the electrification of passenger cars on a lower risk, lower cost path. Examining EV policy in the UK and in California, we find that it is generally not incompatible with achieving balanced mixes of BEVs and PHEVs. However some fine tuning would allow to better balance medium term risks and long term goals.

1. Introduction

1.1. Government support to electric vehicles

Road transport accounted for 21% of global energy consumption and 17% of global CO₂ emissions in 2013 (IEA, 2015c). Carbon emissions from road transport have been growing steadily and will continue to do so if road transport is not progressively decoupled from fossil fuels (IEA, 2014). In particular, stabilizing global temperature increase to below 2 °C relative to pre-industrial levels will require a combination of improved fuel efficiency and deployment of alternative fuels in road transport, particularly advanced biofuels, electricity and, to a lesser extent, hydrogen (IEA, 2015a; Kahn Ribeiro et al., 2012). Scenarios may differ as a multitude of energy technology pathways are possible (IPCC, 2014), however it is generally accepted that electric vehicles (EVs) will have a major role to play, especially in large markets such as the US, Europe, China and India. Electrification of passenger car transport also has the added benefit of reducing emissions of local air pollutants in urban areas, the impacts of which on public health are of growing concern in both developed and developing countries (OECD, 2014).

For the reasons noted, electrification of passenger car transport is receiving strong support from several national governments worldwide which seek not only to meet their environmental protection goals but also to develop national value chains in this emerging industry (Lutsey, 2015). Alongside aspirational targets set by several governments, electrification is increasingly being driven by regulation. Most notably, the California Zero Emission Vehicle mandate sets mandatory targets for EV sales; this type of regulation is increasingly being adopted across the US and Canada. In the European Union the Directive on the deployment of alternative fuel infrastructure (European Union, 2014) mandates that Member States develop national policy frameworks for future EV charging infrastructure rollout.

In order to achieve their targets, both aspirational and legally-binding, national and local governments are deploying sets of incentives to EV adoption, including purchase grants, tax exemptions, non-monetary incentives such as free parking and access to restricted lanes, and financial support for the development of extensive charging infrastructure (IEA, 2013; Lutsey, 2015). Incentives are necessary to overcome the substantial cost gap currently existing between EVs and conventional internal combustion engine vehicles (ICEVs) and the first mover disadvantage that characterises the development of alternative fuel infrastructures (NRC, 2015). For their part, automotive OEMs are producing an increasingly diverse range of EV models in order to comply with mandates and standards while gaining competitiveness. Although fleet penetration on a global level is still low, the market...
share of electric vehicles is growing fast (IEA, 2015b). In some countries, such as Norway and the Netherlands, the market share of EVs has reached substantial levels, while the US, Japan and China lead the way in terms of the absolute size of their EV stocks, and several new markets are starting to develop (IEA, 2015b).

Despite some early success stories and the growing momentum behind the EV transition, rapidly reaching a high level of EV penetration globally will be challenging, because of strong economic, institutional and behavioural barriers, together with the inherently slow turnover rate of passenger car stocks (Element Energy, 2013; NRC, 2015; Struben and Sterman, 2008). For this reason, in today’s policy discourse much emphasis is placed on identifying those mixes of policy instruments that are most effective at accelerating the deployment of EVs and related charging infrastructure (Lutsey, 2015). Comparatively little attention is devoted to clearly articulating a vision of future self-sustained electrification of passenger car transport that does not solely rely on the cost of EV batteries rapidly falling. However, considering that the current high levels of government incentives cannot be sustained indefinitely, we argue that policy should also be designed taking account of the need to guide the EV transition towards low cost and low technology risk pathways.

1.2. Aim and objectives

The aim of our work is to assess whether today’s EV policy is conducive to a future cost-effective use of this technology, considering the policy objectives it aims to achieve, particularly carbon emission reduction. We do so by exploring the incremental costs of future mixes of EVs and charging infrastructures that are broadly compatible with today’s policy and market trends, and that can provide similar carbon emission reductions. We use the results of our cost analysis as a basis for discussion of key features and possible implications of current EV policy, and to identify opportunities for making it more robust under uncertainty.

In Section 2 we discuss the effect that deployment policy has on EV innovation pathways, including the possibility of technological lock-ins. Section 3 presents the methods used in the study and their limitations. Section 4 describes the current policy framework and deployment targets for the UK and California, the case studies chosen. Section 5 presents the results of the two case studies and discusses their policy implications. Section 6 concludes the paper.

2. EV deployment policy and its effect on innovation

Due to the specific characteristics of each market, the widely differing underlying taxation of conventional vehicles and fuels, and the lack of generally accepted best practices, different approaches have so far been used. As a result, different patterns of deployment of EVs and charging infrastructure have begun to emerge in the most active countries and regions, i.e.: China, Europe, Japan and the U.S. (IEA, 2013, 2015b; Lutsey, 2015). In particular, different ratios of pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) and of rapid charging and slow charging infrastructure can be observed across leading countries (IEA, 2013, 2015b). BEVs operate solely on electricity while PHEVs can operate on both battery power and an internal combustion engine, especially once the battery is depleted; the internal combustion engine and electric components of the powertrain can be arranged either in parallel or in series; the latter are also referred to as range extended electric vehicles (RE-EVs). In this paper we will use the term PHEVs for both types, unless otherwise specified. The term slow chargers is here used to indicate charging points of 3–7 kW power; rapid chargers supply power of the order of 40–50 kW. Figs. 1 and 2 provide and illustration of the different patterns of EV and charging infrastructure deployment observed today (IEA, 2016).

Evidence shows that incentives strongly influence the overall rate of EV uptake and the relative market shares of BEVs and PHEVs (Mock and Yang, 2014). In Norway for example BEVs receive generous support, whereas PHEVs have only recently become eligible for some, hence the rapid rate of uptake of BEVs. In the Netherlands incentives for BEVs and PHEVs have been similar, hence the dominance of PHEVs that offer better functionality. In California, where BEVs qualify for higher incentives than PHEVs, their market shares are comparable (Brook Lyndhurst, 2015). Hence, government incentives to EV purchase, combined with the underlying taxation of conventional fuels and vehicles, determine the type of EVs that are most competitive and also the market segments in which the value they offer relative to ICEVs is highest. This in turn influences the EV types and models that automotive OEMs will commercialise in order to achieve highest possible sales.

Moreover, public charging infrastructure is a strong enabler of BEV adoption (Sierzchula et al., 2014), so some countries are building extensive networks of public chargers, be they rapid or slow, that anticipates possible user needs (Brook Lyndhurst, 2015; NRC, 2015). The particular type, density and location of charging points aim to reduce range anxiety and increase the perceived utility of BEVs to a level comparable to ICEVs. However, it is difficult to anticipate how well this will work in practice and the extent to which the infrastructure will

![Fig. 1. Market share of EVs in selected countries in 2015, broken down by BEVs and PHEVs. Source: adapted from (IEA, 2016).](image1)

![Fig. 2. Charging point/EV ratio in selected countries in 2015, respectively for fast (top) and slow chargers (bottom). Source: adapted from (IEA, 2016).](image2)
actually be utilised (Brook Lyndhurst, 2015; NRC, 2015).

The trends shown in Figs. 1 and 2 can change in future as policy support measures are periodically adjusted by governments in response to market developments. In particular, at least in part encouraged by recent evidence showing a rapid rate of decrease of EV battery cost (Nykvist and Nilsson, 2015), a growing number of countries are currently increasing their support for BEVs relative to PHEVs, which some consider as a transitional technology. However to the best of our knowledge the relevant policy documents do not explicitly discuss the overall cost of the particular EV and charging infrastructure mixes they seek to promote. Because the emphasis is on rapidly electrifying passenger car transport, it is therefore possible that the EV and charging infrastructure mixes that will be deployed in the short and medium term will not provide the most practical and cost effective way of achieving the intended goals.

This is problematic because the process of development and adoption of new technology such as EVs exhibits path-dependence and is prone to lock-in effects (Ahman and Nilsson, 2008). In other words, the type of EVs and infrastructure initially deployed will influence the behaviour and preferences of adopters and the development of related institutions, and hence will contribute to pushing future EV technology and infrastructure development down a certain path. This will in turn further influence consumer adoption of new EV models and the development of policy and regulation, in a process that in technology studies is generally referred to as co-evolution (Dijk and Yarime, 2010; Geels, 2012). This is schematically illustrated in Fig. 3.

As policy and regulation co-evolve with the new technology and the preferences of its users become entrenched, electrification of passenger cars will become increasingly locked into certain mixes of EV and charging infrastructure types. In the early phases of the EV transition these mixes are made competitive by the policy incentives that support the electrification process. However as higher levels of adoption are reached and policy support measures are withdrawn, costs will increasingly be passed on to EV users. The actual cost of electrification will then become very important in determining whether or not the EV transition will be able to sustain itself. Switching to more cost effective electrification paths later on would still be possible but challenging. Meanwhile the whole EV transition could risk stalling. In light of this, posing the question whether today’s EV and infrastructure policy is conducive to cost-effective electrification of passenger cars becomes more important.

3. Methods

The future cost and emissions of different types of EVs has been studied extensively. Numerous studies can be found in the literature that cover the whole spectrum of economic assessments of EVs, from detailed powertrain cost and performance modelling aimed at guiding the design of systems or components, to studies comparing the lifetime cost and emissions of different EV types in order to inform policy making. Common to most of these studies is the use of the Relative Cost of Ownership (RCO) metrics that enables estimation of the cost of individual EVs over their lifetime and comparison across different powertrain types. As the name suggests, RCO does not consider all costs but only those that are relevant to the comparison being made. A brief critical review of relevant studies in this area is provided in Appendix A. These studies have generated a large amount of knowledge on the economics of EVs, however they tend to focus on single vehicles as opposed to whole fleets and charging infrastructures. Moreover, the results they generate are based on the use of fairly complex models which may lack transparency and flexibility, and may not be easy to communicate or update when new evidence becomes available.

In order to address the gaps we identified, we developed a model that calculates the incremental cost and emission savings of future EV and charging infrastructure mixes. The model performs RCO calculations for single vehicles and integrates them over the whole fleet by including all the key factors with the minimum possible level of detailed complexity. An overview of the model structure is provided in Fig. 4. The model relies on inputs from a number of specific studies and technical modelling activities, which can be updated as appropriate. By following this approach we aim to create a tool that is flexible, transparent, and that can facilitate discussion around policy support to electrification. It is worth mentioning that all those cost elements that are common to both EVs and ICEVs are not considered in the model. Nor are vehicle and fuel taxation accounted for in our study. This corresponds to assuming that non-CO$_2$ related taxation of EVs will be the same as that of ICEVs. CO$_2$ taxation is not included either. However, to ensure our analysis is meaningful, we compare only EV mixes that are characterised by similar average tailpipe CO$_2$ emissions across the whole fleet. In this way our results are not influenced by assumptions on the price of CO$_2$ emissions. Furthermore, to ensure that the utility of the BEVs and PHEVs is broadly comparable, we set the range of BEVs and the availability of charging infrastructure so as to satisfy the stated requirements of passenger car users or their observed driving needs. A full description of the model can be found in Appendix B.

Moreover, considering that the cost of electrification depends in part on the technology inputs and in part on the specific vehicle market examined, in our analysis we take a case study approach. We selected the UK and California because both are aggressively pursuing electrification of passenger cars and their markets are illustrative of large European countries such as France and Germany and of North America respectively. Another reason is the availability of information in English. Finally, by comparing and contrasting the two cases, we test the extent to which general lessons can be learned about the cost-effectiveness of policy-driven electrification. We base our analysis around year 2030, because: a) current policy targets tend to refer to the 2025–2030 timeframe; b) the level of adoption foreseen is such that lock-in effects may begin to occur; and c) technology projections become very uncertain beyond 2030.

As part of our analysis, we develop a set of electrification scenarios for the UK and California in 2030 based on narratives that are broadly consistent with current policy and market trends. It is worth stressing though that they are not intended as predictions of the composition of EV and infrastructure mixes in 2030 as they follow from particular choices made by policymakers. In fact policy-making in the UK, California and elsewhere, is flexible enough to allow shifting direction should it be required, and anticipating future decisions of policymakers and their effects is beyond the scope of our research. However, due to lock-in effects, major changes in direction will no doubt involve time lags and additional costs.

The main limitations of the analysis presented in this paper are that: a) it is of a snapshot type, i.e.: it assesses the incremental cost of electrification for year 2030 only instead of the cumulative cost until that year, and b) it does not apportion the incremental cost of electrification.

Fig. 3. Schematic representation of the complex interlinkages among the multiple dimensions of the EV socio-technical system. Source: Adapted from (Geels, 2012).
among government, car manufacturers and passenger car buyers. The implications of these limitations on our policy insights are discussed in Section 5.4.

4. EVs in the UK and California: current policy and future deployment

4.1. The UK

The UK is subject to EU transport and environmental policy (although this will change as a result of the UK's referendum vote to leave the EU). In particular the post-2020 EU fleet average CO₂ emission standards for passenger cars, currently under negotiation, and the alternative fuels infrastructure Directive will provide the strongest drivers for electrification at European level. In addition to that, the UK has set itself the legally binding target of reducing total GHG emissions, to which transport is a major contributor, by 80% relative to 1990 levels in 2050. In order to fulfil its domestic and European obligations, the UK is committed to supporting the development and deployment of ultra-low emission vehicles (ULEVs), particularly EVs, which the government also sees as an opportunity to revive the country’s automotive industry (Chase et al., 2014). The UK government aspires to achieve near complete decarbonisation of passenger car transport by 2050 and supports electrification through financial and non-financial incentives, which are periodically revised based on observed market and technology development. The UK government’s approach to ULEVs is in general technology neutral, though the recently revised EV grant now has different levels for long and short All-Electric Range (AER) EVs, which is intended to increase BEV over PHEV sales. Moreover, at present the maximum number of grants available is capped at the same level for BEVs and PHEVs, which also suggests a desire to balance the sales of either EV type. See Table 1 below for an overview of current EV and infrastructure deployment, government incentives supporting it and future estimated EV and infrastructure levels required in order to support the UK achieve its climate change policy goals (Brook Lyndhurst, 2015; DfT, 2015; Element Energy, 2015; Element Energy, 2013; OLEV, 2016).

Evidence gathered from EV users in the UK suggests that adoption of EVs is mainly by affluent, multi-vehicle households in urban areas. EVs are typically used as the main car, relied upon for the majority of daily trips and driven on annual mileages comparable to those of ICEVs, while the latter are used more for infrequent, longer journeys (Hutchins et al., 2013). EV consumer research suggests that key barriers to EV adoption remain price and for BEVs also range, with users expressing desire for longer range vehicles for infrequent, longer trips (Brook Lyndhurst, 2015). EV owners strongly prefer charging overnight at home. This is due to convenience and not much influenced by availability of public infrastructure (Hutchins et al., 2013). However a fully developed charging infrastructure, particularly rapid, is also perceived as required for further BEV market expansion (Brook Lyndhurst, 2015). Analysis conducted suggests that, to complement private residential charging, the most valuable option is rapid charging infrastructure. However the business case for it is still challenging, due to the expected low utilisation rate. Continued government support will therefore be required in order for the rapid charging infrastructure to develop in the UK (Element Energy, 2015).

4.2. California

Like the UK, California has set itself the target of achieving an 80% reduction of GHG emissions by 2050 relative to 1990 levels (Governor’s Office, 2015b), with an interim target of 40% reduction by 2030. This complements strong air quality policy, including the Low Emission Vehicle standards of the California Air Resources Board. In order to facilitate the achievement of the intended reduction in emissions of GHGs and air pollutants from road transport while supporting the development of a clean car industry in California, in 2012 Governor Brown issued an executive order aimed at facilitating the rapid commercialisation of Zero Emission Vehicles (ZEVs) (Governor’s Office, 2012). The executive order sets specific EV deployment targets, the strategy for achieving which is set out in the 2013 ZEV Action Plan of February 2013 (Governor’s Office, 2013), updated in 2015 based on a review of the progress achieved until then (Governor’s Office, 2015a). The strategy includes providing incentives to EV adoption and infrastructure deployment as well as studying future infrastructure needs. An infrastructure study was conducted by the National Renewable Energy Laboratory (NREL) in 2014. The targets and key elements of the strategy are summarised in Table 2 (AFCD, 2016; California Auto Outlook, 2016; California Secretary of State, 2013b; Governor’s Office, 2013, 2015a; NREL, 2014). It is also worth mentioning that the 2015 ZEV Action Plan explicitly states that incentives should be cost-effective and withdrawn as early as possible: “Financial incentives continue to play a critical role in making ZEVs cost competitive with conventional vehicles during the early phases of their deployment, until economies of
scale lead to cost reductions and a fully self-sustaining market” (Governor’s Office, 2015a).

The executive order targets are broadly in line with the EV penetration levels required by the ZEV mandate, although the exact EV numbers required by the latter will depend on the compliance strategy chosen by the OEMs. In particular, the ZEV mandate sets a minimum number of credits that large and intermediate volume manufacturers have to earn or purchase to comply and avoid fines. The credits are earned through manufacturing pure ZEVs (i.e.: BEVs, a newly introduced category of range extended BEVs called BEVx, and fuel cell electric vehicles (FCEVs); the latter are not discussed in this paper) and other ULEVs (such as PHEVs, also referred to in the regulation as transitionals ZEVs or TZEVs)). BEVx are full BEVs also equipped with a small ICE auxiliary power unit enabling them to operate at reduced power when the AER is exhausted, and their non-electric range cannot exceed their AER; hence the structure of the powertrain is similar to that of a RE-EV but the components are sized differently and the utility of the vehicle is substantially lower. The number of credits for each EV is awarded proportional to its AER, based on different formulas for ZEVs and ULEVs. Although the regulation allows OEMs a certain degree of flexibility in the way they meet their credit obligations, minimum ZEV credit floors apply. A synthesis of the ZEV mandate credit mechanism is provided in Table 2; we refer the reader to the relevant regulation for full details (California Secretary of State, 2013a, b). However it is important to note that the ZEV mandate will play a strong role in defining the future split between BEVs and PHEVs in California, ensuring that BEVs (either pure BEV or BEVx) retain a substantial share. Moreover, the credit mechanism for ZEVs is a contributing factor to the

### Table 1
Current deployment, policy support measures, and future estimated EV and charging infrastructure deployment needed in order to meet the UK’s GHG emission reduction targets.

**Source:** (OLEV, 2016; Element Energy, 2015, Brook Lyndhurst, 2015; Element Energy, 2013, DfT, 2015.

| Current deployment level | Current government incentives | Future government targets / deployment requirements |
|--------------------------|-----------------------------|-----------------------------------------------|
| EVs                      | “Plug-in Car Grant” amounts to up to 35% of the vehicle’s retail price, for a maximum of £4500 for EVs with AER of at least 110 km (currently BEVs) and £2500 below 110 km (currently PHEVs). The grant originally offered a maximum of £5000 per EV, irrespective of AER, and was amended in Mar 2016. Exemption from road user charges, notably London’s Congestion Charge. | Aspirational target of 100% ULEV new car registrations in 2040. No mandated EV targets. |
| Charging infrastructure  | Circa 30,000 home charging points, 7000 workplace (open access) and 8000 public charging points (7100 slow and 900 fast) as of Feb 2015 | The Committee on Climate Change estimates that meeting UK’s GHG emission targets requires between 4 and 8 m EVs on the road in 2030. EU regulation requires the UK to develop a rollout plan for charging infrastructure. The Directive indicates a target density of 0.1 chargers/vehicle, depending on the type of EVs and chargers deployed. It is estimated that a network of 2100 rapid charging sites (10 charging points per site) could provide UK-wide coverage. Around 70% of UK households have access to private parking; however this is as low as 10% in certain urban areas. |

### Table 2
Current deployment, policy support measures, future EV mandates, and charging infrastructure needs in California.

**Source:** (California Auto Outlook, 2016, Governor’s Office, 2015a; AFCD, 2016; NREL, 2014; Governor’s Office, 2013; California Secretary of State, 2013b.

| Current deployment | Current government mandates / incentives | Future government targets / deployment requirements |
|-------------------|----------------------------------------|-----------------------------------------------|
| EVs               | 3.2% market share in 2015 (1/2 BEVs, 1/2 PHEVs). ZEV mandate currently forces the commercialisation of BEVs and PHEVs in sufficient numbers for individual car manufacturers to generate the necessary number of credits. Federal tax rebate of up to $7500 (proportional to EV battery size). California Clean Vehicle Rebate, a state rebate of $2500 for BEVs and $1500 for PHEVs. Non-financial incentives such as access to high occupancy vehicle (HOV) lanes and parking benefits. | Executive order sets a target of 1 m ZEVs on the road by 2020 and 1.5 m ZEVs by 2025, and for new vehicle purchases in light-duty fleets of government agencies to reach 10% ZEVs by 2015 and 25% by 2020. Post – 2018, ZEV credits are earned by BEVs and BEV x with AER > 80 km proportional to their AER (e.g., 160 km AER = 1.5 credits; 480 km AER = 3.5 credits). PHEVs with AER comprised between 16 and 120 km also earn credits proportional to the AER 0.4–1.10 credits respectively). Large volume car manufacturers have to earn the majority of their credits from pure ZEVs (i.e.: BEVs, BEV x and FCEVs). Executive order mandates the roll-out of the necessary charging infrastructure to support the ZEV targets. |
| Charging infrastructure | 120,000 EVs on the road in Jan 2015. The California Energy Commission administers a number of programs providing funding for new charging infrastructure. It also conducts and commissions studies on the future need for charging infrastructure across the State. The California Building Code requires all recently constructed parking lots or housing to put electrical capacity in place to easily install EV chargers. | NREL study estimates that, to support the 1 m EVs by 2020 target, between 20k–50k public chargers will be needed. It suggests two alternative options: “Home dominant”: 100k workplace and 22,250 public chargers (of which 550 rapid) “Public access”: 167k workplace and 48,600 public chargers (of which 1550 rapid). |
emergence of long-AER BEVs manufactured by Tesla Motors Inc., and will most likely continue to influence future OEM decisions about the AER of their EVs. 

As in the UK, EV owners in California are predominantly affluent, highly educated, multi-vehicle households, and use their EVs as the main car for frequent, shorter journeys, with similar annual mileages to ICEVs (Center for Sustainable Energy, 2013). BEV users in California report that for full satisfaction their vehicles would need to have a range of more than 250 km (Center for Sustainable Energy, 2013). In California charging of EVs happens mainly at home, as also in the UK. PHEV users' charging behaviour is currently being investigated, but early results suggest that long-AER PHEVs are used on electricity as much as possible. EV users generally were not entirely satisfied with public charging infrastructure, although this is improving as infrastructure coverage increases (Brook Lyndhurst, 2015; Center for Sustainable Energy, 2013).

5. Analysis and discussion

5.1. Driving patterns and fleet structure: comparing the UK and California

Among the key differences between UK and California are the structure of the fleet and the vehicle usage patterns.

We modelled the structure of the 2025–2030 fleet in a simplified way. We have assumed that the overall size of the fleet will stay the same as today. We divided the fleet into four main market segments, with their size based on new passenger car sales for a reference year and modelled based on the characteristics of the best-selling cars for that same year (California Auto Outlook, 2016; SMMT, 2013). A stock model would provide more accurate projections of future fleet composition. However we consider our simplified approach adequate given the purpose of the analysis. See Table 3 and Table 4 for the details of how the future fleets in the UK and California are modelled in our study (California Auto Outlook, 2016; Cars.com, 2016; DfT, 2008; DoT, 2009; SMMT, 2013; U.S. News Best Cars, no date; Whatcar.com). In the tables the vehicle segments are named as is most common. Note that in our incremental cost model the reference vehicle weight is reduced relative to today's based on future scenarios on the use of lightweight materials (Lotus Engineering Inc, 2010), and the powertrain size is downscaled accordingly (Brooker et al., 2013; Pagerit et al., 2006).

As for the vehicle usage patterns, we analysed data from the UK National Travel Survey (DfT, 2008) and the US National Household Travel Survey (DoT, 2009) respectively and have derived the frequency distributions of daily distances driven shown in Figs. 5 and 6. These distributions are used when calculating utility factors of PHEVs and relative shares of home vs public charging for BEVs.

As can be observed from the tables and figures, the UK and California markets today are different in terms of segments attributes, relative shares and associated driving patterns. In particular, the structure of the fleet in California is slanted towards larger and heavier vehicles. This is generally the case comparing North America with Europe. Moreover, in the UK larger vehicles are on average driven more frequently on longer distances and have higher annual mileages than smaller vehicles, whereas in California all segments are on average driven similarly and have comparable annual mileages. In our study we make the simplifying assumption that this will not change until 2030.

Finally, it is worth noting that modelling the fleet as we did has its limitations. However, as previous studies have shown (Offer et al., 2011), even a relatively simple segmentation approach like ours can provide substantial additional insight compared with treating the whole passenger car market as homogenous.

5.2. UK scenario analysis

Based on the current status and future targets for electrification discussed in Section 4.1, we built a set of key scenarios for year 2030 and we have estimated their incremental cost relative to a base case where the whole passenger car fleet is composed only of ICEVs.

All scenarios are consistent with the UK aspiration of 60% EV market share, or 8 m EV fleet, by 2030 but differ in terms of the EV types and related infrastructure deployed. It is also worth noting that, despite the difference in EV types across scenarios, average fleet tailpipe CO2 emissions are comparable, of the order of 55gCO2/km NEDC. This is well below the 75-65gCO2/km range currently being discussed at EU level for the 2030 CO2 fleet average for passenger cars. The key elements of each of the 4 scenarios modelled are listed below and further illustrated in Table 5.

- Scenarios 1 and 2 are based on the current trend of seeking to balance the relative shares of BEVs and PHEVs through incentives. Hence we assume a 40/60 split between BEVs and PHEVs and the country-wide charging infrastructure needed for rapid adoption of BEVs.
- In Scenario 1, rapid charging infrastructure is modelled based on the analysis by (Element Energy, 2015); slow charging infrastructure is based on the indicative target of the European Commission directive (European Union, 2014), i.e.: the equivalent of at least 0.1 public charging points per EV.
- In Scenario 2 only rapid charging infrastructure is present, because this is seen by users as most valuable, and hence the public charging point per EV ratio becomes 0.01.
- Taken together, Scenarios 1 and 2 represent possible upper and lower bounds for a country-wide charging infrastructure in the UK that is capable of supporting a fleet consisting of a mix of 250 km-range BEVs and 50 km-AER PHEVs. A 250 km range may be the least required for BEVs to offer similar functionality to ICEVs. Finally, we assume that BEVs will penetrate the market across all

| Segment                | Reference model | Weight (kg) | Power (kW) | Annual mileage (km) | Fleet share (%) |
|------------------------|-----------------|-------------|------------|---------------------|-----------------|
| Small                  | Toyota Corolla  | 1270        | 98         | 19,850              | 26.8            |
| Medium                 | Honda Accord    | 1475        | 140        | 18,900              | 31.1            |
| Luxury                 | Mercedes E-class| 1735        | 224        | 20,600              | 10.7            |
| SUV                    | Ford Explorer   | 2010        | 216        | 21,000              | 20.1            |

Table 3
Structure of the UK market in 2030 — Main segments and their key attributes.
Source: Authors’ scenario, based on (DfT, 2008; SMMT, 2013; Whatcar.com).

| Segment                | Reference model | Weight (kg) | Power (kW) | Annual mileage (km) | Fleet share (%) |
|------------------------|-----------------|-------------|------------|---------------------|-----------------|
| Mini/Supermini (A/B)   | Ford Fiesta     | 1050        | 64         | 12,950              | 40.6            |
| Medium (C/D)           | Volkswagen Golf | 1300        | 92         | 14,950              | 40.8            |
| Executive/Luxury (E/F) | Mercedes C-class| 1550        | 135        | 17,450              | 4.8             |
| Dual purpose/MPV (H/I) | Vauxhall Zafira | 1550        | 105        | 22,200              | 11.3            |

Table 4
Structure of the California market in 2025 – Main segments and their key attributes.
Source: Authors’ scenario, based on (California Auto Outlook, 2016; U.S. News Best Cars, no date; Cars.com, 2016; DoT 2009).

Source: Authors’ scenario, based on (California Auto Outlook, 2016; U.S. News Best Cars, no date; Cars.com, 2016; DoT 2009).
segments, with the exception of the small car segment (A/B) where fuel efficient ICEVs currently benefit from a relatively low level of taxation and where a long-range BEV will be both expensive and not required. PHEVs are also present in all segments except A/B, due to the same reasons of cost-competitiveness with ICEVs.

– Scenario 3 meets 60% EV penetration by 2030 with the least amount of battery capacity and infrastructure installed. This means only using 100 km-AER PHEVs that do not require public charging infrastructure at all and use the same type of batteries as BEVs, sharing with them all other components of the electric powertrain. Thus they could generate the necessary scale economies that would also be needed for BEVs to become competitive. However by not developing the charging infrastructure and user preferences for BEVs the latter could become locked out, potentially delaying the achievement of full electrification of passenger cars post-2030. A PHEV-only scenario is also clearly not consistent with current policy.

– Finally, Scenario 4 offers a compromise where 100 km-AER PHEVs dominate the market, with the exception of the A/B segment where only 150 km-range BEVs are present. This is in principle compatible with the current structure of the Plug-In Vehicle grant that does not favour longer-AER BEVs and potentially rewards long-AER PHEVs in the same way as BEVs. In this way the BEV option remains open but, by targeting the smaller vehicles typically used for shorter distances in urban areas, expensive long-AER BEVs and a country-wide infrastructure is no longer needed. Adoption of BEVs as urban vehicles can be further encouraged by developing charging infrastructures accordingly.

Fig. 7 shows the incremental cost of the scenarios as calculated using our model. The error bar indicates the full range of uncertainty associated with future battery technology development. In particular, the highest cost corresponds to today’s battery technology cost ($300/kWh) and energy density (100 Wh/kg) as reported by the leading industry players, while the lowest cost corresponds to battery technology meeting its long-term cost reduction target ($100/kWh) and doubling its energy density. The midpoint case falls exactly in between with respect to both battery cost and energy density; as far as cost is concerned, $200/kWh is considered as a plausible scenario for 2025–2030 based on recent projections (Nykvist and Nilsson, 2015). The same logic applies to PHEV batteries. The battery cost and energy density scenarios we built are based on (Element Energy, 2012; IEA, 2016; Moawad et al., 2016; Nykvist and Nilsson, 2015) and are illustrated in Tables 6, 7. While it is unlikely that battery technology will not improve at all by 2025–2030, using today’s state of the art as worst case scenario also gives a sense of the extent to which different EV mixes will require policy support while battery technology develops, and hence of the cumulative transition cost and technology risk associated with each particular scenario.

It is worth noting that the absolute value of the incremental cost of EV scenarios as shown in Fig. 7 is influenced by the relative cost of gasoline and electricity as well as other variables, and hence should be regarded as only indicative. Based on the type of analysis conducted, the most important insight that can be gleaned is the relative cost of the different EV scenarios. This is particularly sensitive to battery technology development, less so to other parameters. Accordingly, only the effect of the former is discussed. However, when examining the results obtained, it is also important to note that they are based on assumptions that particularly favour BEVs over PHEVs. Specifically, we assume EV batteries to last the whole lifetime of the vehicle; due to the larger size of the BEV battery pack, having to replace it would incur a much higher cost penalty than in the case of PHEVs. Moreover, possible grid reinforcement costs associated with public charging infrastructure are excluded, which also favours BEVs over PHEVs. So in effect the risk associated with large numbers of long-range BEVs could be much higher.

As can be seen from Fig. 7, Scenarios 1 and 2 show the greatest cost sensitivity to future battery development, around 40% higher than Scenario 3 and 4. This means that initially a similar EV mix would have to be subsidised substantially more than one dominated by long-AER PHEVs. Even at a BEV battery cost of $200/kWh, Scenarios 1 and 2 would cost around £400–600 M a year more than Scenario 4. Only with batteries that cost of the order of $100/kWh and have double the energy density of today’s best in class would the cost of all scenarios
battery technology development than Scenario 3. Moreover by strategically siting the rapid charging infrastructure in and around urban areas, better utilisation levels could be achieved at around four charges a day on average. It therefore follows from our analysis that pursuing an EV and charging infrastructure mix of the kind of Scenario 4 would provide a relatively low cost, low risk electrification path for the UK.

5.3. California scenario analysis

Based on the discussion of current state and future EV targets in California provided in Section 4.2, we built a set of key scenarios for year 2025 and estimated their incremental cost, applying the same logic as for the case of the UK.

All scenarios are consistent with the target of 1.5 m EVs on the roads in 2025 set by the executive order of the Governor of the State of California. Although they differ widely in terms of the types of EV and infrastructure deployed, all scenarios are characterised by comparable average fleet tailpipe CO₂ emissions. The key elements of each of the 5 scenarios modelled are listed below and further illustrated in Table 8; their respective incremental cost are shown in Fig. 8. It is worth noting that, with the exception of Scenario 1, all other scenarios mirror those chosen for the UK, which makes comparing between the two case studies easier.

– Scenarios 1, 2 and 3, in addition to meeting the Governor’s target, also broadly fulfill the requirements of the ZEV mandate in terms of number of credits and ZEV floor.

– We assume that the ZEV floor is met using BEVs only. We do not model BEVs due to their reduced utility, however we will later discuss their possible role from a qualitative standpoint, and we do not consider the effect of possible deployment of FCEVs.

– We assume the BEV/PHEV ratio to be 40/60, although in reality this will vary somewhat depending on the compliance strategy chosen by the OEMs. In particular, longer-AER EVs qualify for more credits hence fewer of them would be required. For simplicity though we ignore the few percentage point difference between compliance scenarios.

– BEVs and PHEVs feature in all segments of the passenger car market, which is not incompatible with today’s rapidly growing offer of new EV models.

– The only difference between Scenarios 1 and 2 is the range of the BEVs, which is 300 km and 250 km respectively. A longer range BEV earns more credits, so it could provide OEMs with a cheaper way of complying with the ZEV mandate, while at the same time better meeting the stated preferences of Californian BEV users. A shorter range BEV that does not fully satisfy the desire of the users in terms

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### Table 5

| Scenario | BEV share (%) | BEV segments | PHEV share (%) | PHEV segments | BEV AER (km) | PHEV AER (km) | # slow chargers | # fast chargers |
|----------|---------------|--------------|----------------|---------------|--------------|--------------|----------------|----------------|
| 1        | 40            | C/D, E/F, H/I| 60             | C/D, E/F, H/I| 250          | 50           | 300,000        | 20,000         |
| 2        | 40            | C/D, E/F, H/I| 60             | C/D, E/F, H/I| 250          | 50           | 0              | 20,000         |
| 3        | 0             | –            | 100            | C/D, E/F, H/I| –            | –            | 100            | –              |
| 4        | 20            | A/B          | 80             | C/D, E/F, H/I| 150          | 100          | –              | 5000           |

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### Table 6

| BEV battery pack | Cost ($/kWh) | Energy density (Wh/kg) |
|------------------|--------------|------------------------|
| high             | 300          | 100                    |
| medium           | 200          | 150                    |
| low              | 100          | 200                    |

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### Table 7

| PHEV battery pack | Cost ($/kWh) | Energy density (Wh/kg) |
|-------------------|--------------|------------------------|
| high              | 350          | 70                     |
| medium            | 275          | 130                    |
| low               | 135          | 150                    |

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**Fig. 7.** Incremental annual user cost of the UK EV and infrastructure scenarios modelled (in British pounds). The error bars indicate uncertainty associated with future battery technology development.
of range however allows higher utilisation of the battery installed and hence is more economical. We also assume that the remaining ZEV credits are earned with 50 km AER PHEVs, which qualify for circa 0.8 ZEV credits each and enable meeting the overall 1.5 m EV target.

- In both cases we assume that public infrastructure is provided based on the 2020 “public access” scenario of the NREL study (NREL, 2014), scaled up to 2025 as appropriate.
- Comparing Scenarios 1 and 2 allows us to test the effect of BEV range on the incremental cost of electrification.
- Scenario 3 is the same as Scenario 2, except that the public infrastructure provision is reduced based on the “home dominant” scenario of the NREL study. Comparing Scenarios 2 and 3 allows assessing the impact of different types of public charging infrastructure in California on incremental costs.
- Scenarios 4 and 5 meet the Governor’s target but do not comply with the ZEV mandate.
- Scenario 4 is based on the same logic as the corresponding one for the UK, i.e.: to achieve electrification with the least deployment of battery capacity and charging infrastructure. This means using 100 km-AER PHEVs and no public charging infrastructure at all.
- Scenario 4 also mirrors the corresponding one for the UK, with 150 km-range BEVs adopted in the small vehicle segment, complemented by 100 km-AER PHEVs in all other segments.

Comparing Fig. 8 (California) with Fig. 7 (UK) we observe a similar trend across scenarios. In the case of California however we have added a scenario (Scenario 1) with longer range BEVs that better meet user requirements while qualifying for more ZEV credits; comparing Scenarios 1 and 2 shows that increasing BEV range even by a small amount has a strong impact on battery technology risk. We also notice that the economics of long-AER PHEVs in California are overall worse than in the UK, mainly due to the effect of the extra weight of the series PHEV powertrain in large, powerful cars. This explains why, as battery technology improves, the incremental cost of Scenarios 2 and 3 converge with those of Scenarios 4 and 5 already at a battery cost of $200/kWh, assuming that battery lifetime was not an issue. Whether rapid uptake of BEVs with 250 km range can be achieved without extensive public charging infrastructure provision is small, albeit not negligible. The cost of Scenario 3 in particular could start to converge to those of Scenarios 4 and 5 already at a battery cost of $200/kWh, assuming that battery lifetime was not an issue. Scenario 4 shows that, if not complying with the ZEV mandate was an option, the same level of tailpipe emissions could be achieved at lower risk using only PHEVs with 100 km AER; these have a utility factor of around 85% if fully charged at home every day and without using public infrastructure, and require, at least initially, substantially less support than the other scenarios discussed so far. Finally, Scenario 5 which combines 100 km-AER PHEVs with 150 km-range BEVs may be preferable as it is only marginally riskier than Scenario 4 while probably sufficient to continue promoting BEV innovation.

5.4. Policy implications

Despite the substantial differences in terms of passenger car market structure and usage patterns in the UK and California, we find that the incremental cost of the different EV and charging infrastructure mixes we explored follows qualitatively a similar pattern. In particular, our analysis suggests that lower cost, lower risk electrification of passenger cars in the 2030 timeframe can be achieved through a balanced mix of relatively short-range BEVs and long-AER PHEVs. This can be broadly extrapolated to the North American and European markets in general. While it is apparent that once BEV batteries achieve their cost reduction target and increase their energy density substantially, long-range BEVs have the potential to outstrip PHEVs on a cost basis, to rely on this happening rapidly is potentially risky. Hence the main implication of our findings is that, by designing policies primarily aimed at accelerating complete electrification of passenger car transport through supporting the rapid roll-out of long-AER BEVs and extensive charging infrastructures, the EV transition may be set on a higher cost, higher risk path which could eventually result in its losing momentum and possibly stalling.

When discussing the policy implications of our analysis, however, the limitations of the methods used should not be overlooked. As already mentioned in Section 3, the analysis we performed is of the snapshot type, i.e.: it assesses the incremental cost of electrification for year 2030 only. For a full picture of the technology risk associated with the different electrification pathways, their cumulative cost until year 2030 should be estimated instead. Moreover, our analysis does not apportion the incremental cost of electrification among government, car manufacturers and passenger car buyers. If this was done, further policy insight could be gained. In fact it is possible that the car manufacturers will prefer, for technical or strategic reasons, to pursue a technology pathway that we identify as higher risk, and that they will be prepared to internally subsidise to a large extent. However we do not want to speculate on this in the absence of sufficient evidence. Similarly, we do not want to speculate on the preferences of mainstream EV buyers in year 2030. Should they be prepared to pay a significant premium for long-range battery electric vehicles over plug-in hybrids though this would somewhat alter the findings of our research. This is however at least in part offset by the favourable assumptions we have made for BEVs over PHEVs, as discussed in Section 5.2.

We now proceed to further examine the UK and California EV policy in relation to our findings. In general, EV policy in both the UK and California today shows, to different degrees, signs of favouring the rapid development of the BEV market alongside that of PHEVs. The UK approach is generally cautious and no commitment has so far been made for the long term, particularly on EV incentives which are reviewed periodically. On the infrastructure side, however, the development of a country-wide network of chargers may soon be underway. Hence we argue that, due to the path-dependent nature of EV innovation processes, even a relatively cautious approach based on monitoring market and technology development and periodically revising support measures may unintentionally lead to higher-cost, higher-risk pathways. The probability of this happening is higher though in the case of California, where the unique technology-forcing approach of the ZEV mandate has already had a strong effect on EV innovation and will continue to do so in the foreseeable future. Based on our analysis, we also infer that the specific design of both EV and infrastructure incentives and mandates can potentially have a strong impact on the cost of future EV pathways and is therefore worth considering carefully and investigating further. Specific aspects of the UK and California policy are here briefly discussed in turn.

In the case of the UK, comparing the fleet average CO₂ emission associated with the scenarios we have modelled with the post-2020 EU fleet average standards for passenger cars currently under discussion,
we notice that there is insufficient regulatory pressure to force the deployment of EVs on this scale by 2030. Therefore, in the absence of a UK equivalent to the California ZEV mandate that influences the direction of EV innovation, the type of EV and infrastructure deployed in the UK under the current policy framework will largely depend on the combined effect of the incentives provided, EV models offered and users’ needs and preferences. In this context, the recently introduced two-tier incentive system for EVs, with a step in the value at the 110 km AER mark, arguably favours shorter-AER over longer-AER PHEVs. This could be rebalanced by either moving the Plug-in Vehicle Grant step to an AER of 80–100 km so that long-AER PHEVs could also benefit from the higher grant available to BEVs, or by making the value of the grant for PHEVs proportional to their AER. As for BEVs, the flat rate of the grant currently provided is in principle favourable to short-range BEVs in the city car segment, although these face tough competition from small, fuel-efficient ICEVs that benefit from low CO₂-based taxation. In all other segments, based on current driving patterns, it is plausible that BEV users will require their vehicles to have relatively long ranges if they are to penetrate the market rapidly, for which a higher grant may be initially required. The other important influence on BEV adoption in the UK is the EV charging infrastructure strategy, which is currently under development. Focusing on providing extensive urban and suburban charging infrastructure, particularly of the rapid type, could further support the uptake of short-AER BEVs in the small car segment. On the contrary, a country-wide infrastructure may indirectly encourage adoption of long-AER BEVs in larger car segments and probably also result in low infrastructure utilisation levels.

In California the ZEV mandate shapes EV innovation and forces the deployment of substantial numbers of these vehicles. In particular, the current structure of the ZEV credits strongly supports longer-range BEVs and is likely to have played an important role in the development of such vehicles, initially by Tesla Motors Inc. and increasingly also by other OEMs. Post-2018 the ZEV credit structure will change and the support for longer-range BEVs will weaken but continue to exist. The effect that this will have on the compliance strategies of the OEMs remains to be seen, though it is plausible that they will introduce more BEVs with sufficiently long AER that appeal to customers while earning the manufacturer more ZEV certificates per vehicle. On the other hand, short-range BEVs are not a natural fit in California, not even in the small vehicle segment as these vehicle tend to be driven for similar distances to larger vehicles. As for PHEVs, the current structure of ZEV credits and EV incentives favours longer-AER PHEVs. However, the ZEV floor present in the mandate limits the contribution these will likely make to the EV fleet. Despite the increased flexibility granted by the recently introduced category of BEVs, which is allowed to generate up to half of the credits needed to meet the ZEV floor, the tension between supporting strong BEV innovation and achieving the necessary level of CO₂ emission reduction at a low cost remains. In conclusion, the evolution of the California ZEV mandate suggests that costs are increasingly being taken into consideration. However, given the strong influence that this has on EV innovation in the US and beyond, we argue that more could be done to guide the EV transition towards a path that is robust under uncertainty. An option could be to calculate credits based on actual electric miles driven as opposed to range. Our analysis suggests that a balanced mix of EVs in California in 2025–2030 should include long-AER PHEVs and possibly also relatively short-range BEVs in specific segments where they can be competitive such as shared urban car fleets. BEVs, if adequately supported, could facilitate the subsequent transition from long-AER PHEVs to BEVs.

Finally, it is worth mentioning that in our analysis we have not taken into account new technology paradigms such as autonomous vehicles, shared ownership, and mobility services. In the long term these could have a profound effect on the passenger car market structure and use patterns. However our modelling approach lends itself to this type of analysis and we recommend that these effects are accounted for especially if extending the timeframe of the analysis beyond 2030.

6. Conclusions

In this study we have considered whether current EV and infrastructure policy is conducive to cost-effective electrification of passenger car transport. To investigate this, we developed a model that estimates the incremental cost of different EV and infrastructure mixes over the whole passenger car fleet, compared with a base case where only ICEVs are present. We have applied our model to the two case studies, the UK and California, because both are aggressively pursuing electrification and are illustrative of Europe and North America. We base our analysis around year 2025–2030. For both we have developed a set of key scenarios that are broadly consistent with current policy approaches. All scenarios are characterised by the same overall number of EVs and similar fleet average CO₂ tailpipe emissions, however they differ in the type of EVs and infrastructure deployed.

Despite the substantial differences in the passenger car market structure and use between the UK and California, the results we have obtained are qualitatively similar. Notwithstanding the limitations of the methods used, our results suggest that policy strongly backing BEV innovation by promoting rapid uptake of a near equal split between BEVs and PHEVs exposes the passenger car transport system to a higher risk in relation to future battery technology development. This is because rapidly achieving high levels of BEV penetration will involve making their functionality close to that of ICEVs, which means equipping them with large batteries providing extensive charging infrastructure networks so they can travel anywhere with minimum inconvenience. While the incremental cost of extensive charging infrastructure may be relatively small compared to that of large batteries, its level of utilisation will probably be low, making its economics problematic.

We also find that an approach where BEVs are limited to the relatively short-range, small vehicle segment, supported by mainly urban charging infrastructure networks, and where relatively long-all electric range (AER) PHEVs are prevalent in all other segments is one that could substantially reduce the risk of the cost of the EV transition becoming unsustainable by 2030 or earlier. Long-AER PHEVs have most powertrain components in common with BEVs, so technology development and scale economies could still be realised that would pave the way for possible future substitution by long-range BEVs should battery technology improve sufficiently. At the same time, by continuing to support BEVs where they are less costly, this option would not become locked out and would allow more time for user practices and institutions to adapt, thus better preparing for rapid BEV uptake later on.

It is clear from UK and California policy that neither government is prepared to sustain EV incentives indefinitely and both will seek ways of achieving their policy goals at the least cost. As the case studies of the UK and California show, by assessing the future incremental cost of EV mixes that follow from current policy we have identified possible criticalities that, if further researched and adequately addressed, could contribute to making EV policy more robust under uncertainty.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.07.062.

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