Changing Propulsion System and Refuelling Behaviour: Dutch Drivers' Preferences for Electric Cars and Plug-in Hybrids

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Abstract

The large-scale adoption of electric vehicles has been lately considered a potentially promising means of confronting mounting concerns over environmental degradation, oil dependence and increasing petroleum prices. Based on the analysis of drivers' stated preferences, we aim to improve current understanding of the factors determining the demand for EVs. We employ a choice experiment approach to elicit Dutch drivers' preferences for plug-in hybrids and two types of battery EVs, one allowing for fast-charging and one for battery-swapping at specialised stations. We find that battery electric vehicles are still far from attractive for the majority of consumers, who seek for EV alternatives whose attributes resemble the ones of ICE-propelled cars. To this end, the recently introduced plug-in hybrid and extended-range EVs have considerable potential to mitigate drivers' concerns over short driving ranges and long charging times. On the contrary, swappable-battery EVs are not on average considered as improvements to their fixed-battery counterparts. Our estimates further reveal strong non-linearities in the effects of changes in driving range, refuel time and coverage of refuelling infrastructure on drivers' utility, as well as considerable heterogeneity in consumer preferences.

Keywords: Discrete choice; Electric vehicle; Plug-in hybrid; Battery swapping; Refuelling behaviour.

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1. Introduction

Electric vehicles (EVs) have been enjoying the vigorous support of policy makers during the last decades, as their large-scale adoption is considered a means of confronting mounting concerns over environmental degradation, climate change, oil dependence and increasing petroleum prices. This is reflected in recent attempts of the US and European governments to set ambitious goals for the penetration of electric vehicles (EVs) in national car fleets. With the possible exception of hybrid electric vehicles (HEVs), however, consumer adoption of EVs has long been hampered by relatively high acquisition costs, considerable uncertainty over developments in battery technologies, and drivers' reluctance to accept changes in their current refuelling behaviour.

Aiming to partially address these concerns, car manufacturers have recently developed intermediate solutions based on the parallel use of internal combustion engines (ICE) and electric propulsion systems, namely plug-in hybrids and extended-range electric cars (PHEVs). At the same time, new refuelling concepts aiming to bring the EV charging time down to the levels of the refuelling time of ICE-propelled cars, such as fast-charging and battery-swapping, have been developed and are currently being tested worldwide.

In light of these developments, we revisit the way in which consumer stated preferences for electric vehicles have been elicited in transportation and economic literature (see e.g. Calfee, 1985; Bunch et al., 1993; Hess et al., 2012). To this end, we employ a choice experiment approach to elicit Dutch drivers' preferences for plug-in hybrids and two types of battery EVs, one allowing for fast-charging and one for battery-swapping at specialised stations. Drivers make hypothetical choices among cars with alternative propulsion systems, further differing in terms of price, fuel costs, performance, refuelling time, coverage of refuelling infrastructure, and accompanying policy incentives. Choice data are analysed by the use of multinomial and mixed logit models. We evaluate the implied trade-offs among attributes and assess the extent to which battery-swapping options and extended-range EVs can address drivers' concerns over short driving ranges and long charging times. We further investigate the role that drivers' demographic background, current car ownership and use, travel behaviour and EV driving experience play in the formulation of their preferences, and how the latter vary with the characteristics of the car they are likely to purchase next.

The remainder of the paper is organised as follows. Section 2 presents the background and motivation for our study. Section 3 describes the design and implementation of the choice experiment. Section 4 discusses the results of the discrete choice models used for the analysis of the stated preference data. Section 5 concludes.

2. Background

Stated preference (SP) methods have been identified from the beginning (Beggs et al., 1981) to be prominent candidates for the elicitation of consumer preferences for EVs and other AFVs, as they can closely resemble consumers' actual vehicle purchase behaviour. Researchers' early interest in driver preferences for EVs was triggered by the energy crises of the 1970s and discrete choice and contingent ranking methods were employed to elicit them in the USA and Australia (Beggs et al., 1981; Hensher, 1982; Calfee, 1985). These early studies focussed on consumer trade-offs between EV and petrol-fuelled car attributes, but they did not explore driver preferences for changes in refuelling time and availability of charging infrastructure. The latter issue was addressed in 1990s studies of consumer preferences for alternative fuel vehicles, mainly stimulated by governmental search of means to combat local air pollution problems (e.g. Bunch et al., 1993; Golob et al., 1997; Brownstone et al., 2000). Researchers' renewed interest in driver preferences for EVs and AFVs is well reflected in the recent growth of SP literature in the field (e.g. Hidrue et al. 2011, Mabit and Fosgerau, 2011; Qian and Soopramanien, 2011; Hess et al. 2012).

Despite the fact that more than three decades have passed since the introduction of SP methods to the analysis of consumer preferences for EVs, the same barriers to EV adoption identified in the 1980s studies still play an important role in consumer reluctance to adopt them. The large-scale adoption of electric vehicles is still conditioned on expectations for technological breakthroughs permitting substantial reductions in EV battery costs, increases in driving range, and decreases in the time needed to recharge the vehicle's battery (Dimitropoulos et al., 2011).

In its current state, the use of battery electric vehicles (BEVs) entails a completely different cost structure from the use of ICE-propelled cars. A well-acknowledged difference is associated with the relative importance of the financial costs of car ownership and use. In comparison to their ICE-counterparts, BEVs have a substantially higher purchase price, whereas considerably lower fuel and maintenance costs. BEVs further benefit from lower maintenance costs, due to the presence of fewer mechanical parts in their propulsion system. This relationship between upfront and running costs would imply that BEVs would be beneficial for drivers engaging in relatively intensive car use, such as, for example, individuals who drive many business kilometres. In reality, however, the opposite is observed. Individuals who drive more are the ones who have a stronger aversion towards BEVs. This is due to another important, but less well-pronounced in the literature, difference between the costs of use of BEVs and ICE-propelled cars. The use of BEVs entails considerably higher time and cognitive load costs, due to higher frequencies and longer durations of refuelling actions.

Every time that drivers refuel their car, they have to incur time costs for: (i) the possible detour required to reach the nearest refuelling station, (ii) waiting at the refuelling station until their turn comes, and (iii) the performance of the refuelling action itself. It is worth noting here that the value of refuelling and waiting time might be notably lower than the value of detour time. During waiting or refuelling, drivers are free to engage in other activities, such as working or entertaining themselves by e.g. reading a book or a newspaper or using social media. On the other hand, the primary activity they engage in while detouring is driving. In addition to time costs, each refuelling action imposes cognitive load costs to drivers, as it has to be accommodated in their scheduling of daily or weekly activities.

Time and cognitive load costs are negligible for the users of petrol, diesel and hybrid cars, as: (a) the relatively long driving range of these cars implies that refuelling actions take place rather infrequently, (b) refuelling actions last only a couple of minutes, and (c) the adequate density of refuelling infrastructure limits the need for detours. On the other hand, time and cognitive load costs are an important component of the structure of BEV operating costs. BEVs' short driving range entails a relatively high frequency of refuelling actions. When these actions have to occur away from home or workplace, such as for example in the middle of a long trip, the time and cognitive load costs imposed by them can be considerable, due to charging infrastructure's inadequate density and to relatively long charging durations.

These additional costs of EV use have been acknowledged by car manufacturers and other mobility stakeholders, who have attempted to come up with ways to bring BEVs' time and cognitive load costs to levels comparable to the ones imposed by ICE-propelled cars. On the one hand, car manufacturers have produced electric-motor-propelled alternatives (e.g. extended-range electric cars), which, with the help of a small ICE, bring EVs' driving range to levels comparable with those of their conventional counterparts. In addition, these alternatives provide consumers with the option to choose between refuelling their vehicle at the petrol station and charging it at home or work. On the other hand, new mobility service providers, such as Better Place, aim at developing a network of costly battery-swapping stations to reduce BEVs' refuelling time to the time levels required to refuel a petrol-fuelled car.

These initiatives create a need for a fresh look at consumer preferences for alternative fuel vehicles, focussed on EV technologies and the trade-offs between vehicle acquisition and use costs made by consumers. The interplay between driving range, refuel time, and refuelling infrastructure coverage determines the level of time and cognitive load costs for different vehicle technologies. In this framework, the annual costs of ownership and use (AC) of vehicle alternative *i* for individual *n* can be illustrated as follows:

$$\mathrm{AC_{in}} = \mathrm{DEP_{in}} + \mathrm{OC_{in}} + \mathrm{STC_{in}} + \mathrm{DTC_{in}} + \mathrm{HTC_{in}} + \mathrm{CLC_{in}}\,, \tag{1}$$

where *DEP* is annual depreciation, *OC* denotes yearly operation costs, such as fuel, maintenance, and insurance costs and taxes, *STC* the time costs associated with refuelling at the station, *DTC* the detour time costs, *HTC* the time costs of home- or workplace-charging, and *CLC* the cognitive load costs induced by refuelling actions.

In this framework, the annual time costs of refuelling at the station, including possible waiting time, will be:

$$\mathrm{STC_{in}} = \mathrm{VoRT_n^{SC}} * \mathrm{SC_{in}} * \mathrm{ADT_n} \,/\, (\delta_{\mathrm{in}} * \mathrm{DR_{in}})\,, \tag{2}$$

where $VoRT^{SC}$ is the value of station refuelling and waiting time, *SC* is the proportion of refuelling actions taking place at the refuelling station, *ADT* denotes the annual distance travelled by the alternative, δ the average share of driving range depleted before the driver refuels her car, and *DR* the driving range of the alternative. Similarly, the yearly time costs of detouring for the refuelling station could be expressed as follows:

$$\mathrm{DTC_{in}} = \mathrm{VoDT_n} * \mathrm{SC_{in}} * \mathrm{ADT_n} \,/\, (\delta_{in} * \mathrm{DR_{in}})\,, \tag{3}$$

where *VoDT* is the value of detour time. Likewise, the time costs of home-charging per year are illustrated in Equation (4):

$$\mathrm{HTC_{in}} = \mathrm{VoRT_n^{HC}} * (1 - \mathrm{SC_{in}}) * \mathrm{ADT_n} \,/\, (\delta_{in} * \mathrm{DR_{in}})\,, \tag{4}$$

where $VoRT^{HC}$ is the value of home-charging time. Last, the cognitive load costs incurred by the number of refuelling actions carried out annually for alternative *i* will be:

$$\mathrm{CLC_{in}} = \mathrm{ADT_n} \,/\, (\delta_{in} * \mathrm{DR_{in}})\,. \tag{5}$$

In the above, we let $VoRT^{HC}$, $VoRT^{SC}$, and *VoDT* be different from each other, as the alternative activities that consumers can perform while charging at home, refuelling at the station, and detouring are substantially different. Among these three activities, we anticipate that the opportunity costs of detouring per unit of time are the highest, as the main activity that consumers can engage in while detouring is driving. We further expect that the opportunity costs of refuelling at the station are higher than the opportunity costs of home- or workplace-charging as the range of activities that consumers can perform in the latter case is importantly wider. Thus, we expect that $VoRT^{HC} < VoRT^{SC} < VoDT$ per unit of time.

3. Survey design and implementation

Survey design

The data used in this study come from a survey carried out between November 2012 and January 2013. The survey was addressed by a sample drawn from TNS-NIPO's panel of motorists, a panel of Dutch vehicle owners with experience in filling car-related questionnaires in. The sample was stratified by the number of cars owned by the household, their ownership status (private or company car) and their fuel type. TNS-NIPO was requested to draw a sample evenly distributed between single-car and multi-car households, as well as between households having at least one company car and ones owning only private cars. Within these four categories, we asked for an adequate representation of households having at least one hybrid-electric vehicle (HEV), as we were interested in examining possible differences in preferences between HEV drivers and drivers of cars propelled solely by an internal combustion engine (ICE).

The survey was carried out via an online questionnaire developed in Sawtooth SSIWeb. The questionnaire comprised seven sections. The first section collected information about households' vehicle holdings and respondents' use of the car they drive mostly in. Respondents who were driving less often than once a week in household's cars and had a minor role in their household's vehicle choice making were asked whether they intended to purchase a car in the next 5 years. If they did not have that intention, they were excluded from the sample.

Respondents were also asked a few questions about the car preceding the vehicle they currently drive mostly in. At the end of the first section, they were requested to state whether their next car choice would be made in the context of purchasing or leasing a vehicle. The present study draws only on the responses of individuals reporting that they would purchase a vehicle. The second section gathered details about the car that the respondent would buy next, such as whether it would be a new or second-hand car, its body and fuel type, its purchase price and the annual distance expected to be travelled in it.

In the third section, respondents were introduced to the choice experiment. The context provided was that of their next car purchase, either being a replacement of the current vehicle or the adoption of an extra car. Following an elaborate presentation of the alternative types of propulsion systems and the vehicle attributes used in the study, respondents were given the opportunity to familiarise themselves with the choice experiment by means of an example choice scenario. Thereafter, they were invited to address 8 hypothetical choice scenarios. The design of the choice experiment is described in the next subsection. At the end of the section, respondents were asked to report how they made their choices, i.e. whether they considered all attributes or just a subset of them or whether they chose an option at random.

In continuation, the questionnaire collected details about respondent's perceptions towards EVs and PHEVs and about their hypothetical refuelling behaviour in case they adopted one of these technologies. The fifth section examined respondent's experience with boarding and driving EVs, PHEVs and HEVs, while respondent's environmental concerns and attitudes towards innovative products were investigated in the sixth section. The last section asked about respondent's gross household income and for comments on the questionnaire layout and length. The time that respondents spent to handle different parts of the questionnaire was closely monitored, in order to provide us with a measure of how seriously respondents addressed the questionnaire. Demographic characteristics of respondents were provided by TNS-NIPO.

The questionnaire launch was preceded by focus group discussions, a small-scale pretesting of the questionnaire with colleagues and a pretesting of the survey with 206 respondents. Following some minor adjustments to the questionnaire, 3900 invitations were sent to TNS-NIPO panel members. 2921 complete responses were collected, leading to a response rate of 75%. Another 134 respondents (3.5%) were disqualified from the rest of the questionnaire after reporting that they made random choices in the choice scenarios. Slightly more than 15% of the complete responses were excluded from the rest of our analysis, due to respondents' extremely fast handling of choice scenarios. All questionnaires with a median duration of response to the choice scenarios of less than 10 seconds were not further processed, as it would be hard to argue that these respondents actually attempted to make trade-offs between the vehicle attributes. Of the remaining 2473 valid responses, 1514 concern a car purchase (as opposed to a car lease) and are used in the rest of the analysis.

Choice experiment

In the beginning of Section 3, respondents were instructed to think about their next car purchase and treat each choice scenario presented to them as a real choice task. Each respondent addressed 8 choice scenarios. In each scenario, respondents were invited to choose their preferred option, assuming that the car model they were intending to purchase next was available in 4 versions: a plug-in hybrid (PHEV), an electric with fixed battery (FBEV), an electric with swappable battery (SBEV) and a version driving on respondents' preferred propulsion system and fuel (e.g. petrol, diesel, LPG, HEV, biofuels, etc.). When respondents reported that they would opt for a BEV or a PHEV at their next car purchase, the fourth alternative was automatically set to a petrol-fuelled car. Respondents were instructed to assume that the four options were different only in the 9 attributes presented to them. Table 1 presents an overview of the attributes and attribute levels employed in the choice experiment. Details about the descriptions of the PHEV and BEV technologies provided to the respondents are offered in Appendix I.

Table 1: Attributes and attribute levels used in the choice experiment

Attributes	**Attribute levels**			
Propulsion system and fuel type	**ICE or Hybrid**	**Plug-in hybrid**	**Electric with fixed battery**	**Electric with swappable battery**
Purchase Price (€)	Customised on respondent's reported price range for next car purchase	0.8 * ICE 1.4 * ICE 2.0 * ICE	0.8 * ICE 1.4 * ICE 2.0 * ICE	0.8 * ICE 1.1 * ICE 1.4 * ICE
Fuel costs (€/100km)	Base value - 2.5 Base value Base value + 2.5	3.5 5.5 7.5	3 4.5 6	9 11 13
Residual value after 5 years (% of purchase price)	40% 50% 60%	30% 45% 60%	30% 45% 60%	30% 45% 60%
Range (kilometres)	600 750 900	500 700 900	100 300 500	100 300 500
Refuel time at the station (minutes)	5	5	15 30 45	5
Charging time at home or work (hours)	N.A.	1.5 3 5	4 8 10	4 8 10
Extra detour time (minutes)	N.A.	N.A.	0 10 20	0 15 30
Exemption from annual road tax (years)	No exemption	No exemption Exemption for 2 years Exemption for 4 years	No exemption Exemption for 2 years Exemption for 4 years	No exemption Exemption for 2 years Exemption for 4 years

Apart from the propulsion system, the options differed with respect to the 8 attributes described below:

- *Purchase price*: The final price that the respondent would have to pay in order to acquire the vehicle. For BEVs and the PHEV, the price was inclusive of the costs of the charging cable and the standard home-charging unit. In Section 2, respondents were asked to select the price range that their next car purchase would most likely fall into from a list of possible ranges. The presented price intervals for respondents reporting that their next purchase would be a second-hand car were narrower and lower than the ones for the respondents reporting that they would opt for a new one. The purchase price of the ICE car was customised on respondent's selected price range. For each choice scenario, a random integer value was drawn from a uniform distribution defined in the interval between 1/100th of the lowest value of the price range selected by the respondent and 80% of 1/100th of the highest one. The resulting integer was multiplied by 100 in order to present the respondent with a price rounded to hundreds of Euros.[1] The purchase price of the three other options varied around the price of the ICE car in accordance with the coefficients shown in Table 1. As the table shows, we also considered cases where BEVs and PHEVs were priced lower than the ICE, in order to have the flexibility to examine a wider range of attribute trade-offs.

- *Fuel costs*: Respondents were presented with three figures for each alternative; a fuel costs per 100km one and two annual fuel costs figures, based on the yearly distance they expected to travel in their next car. The calculation of the base value of the fuel costs/100km of the ICE car was based on the average fuel efficiency of the fuel type and propulsion system selected by the respondent and on current retail fuel prices.[2] Fuel costs/100km for BEVs and the PHEV vary according to the values presented in Table 1. The SBEV fuel costs are higher than the FBEV and PHEV ones as the first ones also include the rental price of the battery-pack and the costs of using the battery-swapping stations.

We assumed that oil-derived fuel and biofuel prices would be more volatile than electricity prices and thus we considered larger deviations for the fuel costs of the ICE technologies than for the ones of the PHEV and BEV ones. The smallest deviations were considered for the FBEV, as fuel costs would be least affected by changes in oil prices (as is the case with the PHEV) or by changes in the terms of battery-rental contracts or in the costs of usage of battery-swapping stations (influencing the fuel costs of SBEVs).

In order to facilitate respondents' calculations, we also provided them with figures for the annual costs into which the *fuel costs/100km* figures would translate. These were based on their response in a preceding question where they had to select the range containing the annual distance they were expecting to travel in their next car from a list of available ranges. Annual fuel costs were then presented for the minimum and maximum distance in the selected range.

- *Residual value of the car after 5 years*: In the Netherlands, most cars remain under the ownership of the same individual for about 5 years. Under the precondition that the car would be

[1] For example, if the respondent reported that their next car purchase would fall in the price range €15,000-€20,000, a random integer was drawn from the uniform distribution in the interval [150,190]. The integer was then multiplied by 100 to provide a price in the range €15,000-€19,000.

[2] With the exception of petrol-fuelled ICE cars, where we considered different base values for compact and large cars, we employed a single base value per fuel type.

in good condition at that time, we assumed that the individual would then have the opportunity to sell their car at a satisfactory price. Since there is much uncertainty about the trajectories that the technology and the prices of battery packs and other EV components will follow in the next years, we considered a wider range of depreciation rates for PHEVs and BEVs than for ICE cars.

- *Driving range*: The maximum distance that the car could travel on a fully-charged battery or a full tank under normal driving style and without any compromise at the level of comfort (e.g. heating, air-conditioning, etc.). For the PHEV, we considered values spanning from the current situation for extended-range cars (e.g. Opel Ampera – ca. 500 km range) to the current situation for plug-in hybrids (e.g. Toyota Prius Plug-in – ca. 900 km range).[3] For BEVs, we employ driving range levels from as low as 100 km, slightly lower than the one advertised for most commercially available BEVs, to 500 km, somewhat higher than the one estimated for the 85-kWh battery-pack of Tesla Model S[4].
- *Refuel time at the station*: The time required to refuel the tank of the ICE car or the plug-in hybrid, to fast-charge the battery of the FBEV and to swap the batteries of the SBEV at specialised stations. Refuel time at the station varied only for the FBEV, from 15 to 45 minutes for a full charge.
- *Charging time at home or work*: The time needed to recharge the battery of the PHEV or the BEVs at a standard charging point, available at home or work. Standard charging time was substantially shorter for PHEVs, as they usually have much smaller battery-packs than BEVs. Charging duration varies from 1.5 (advertised duration for Toyota Prius Plug-in) [5] to 5 hours for the PHEV, and from 4 to 10 hours for the BEVs.
- *Extra detour time*: The time required to reach the nearest fast-charging or battery-swapping station on top of the detour time spent now by the respondent to reach its nearest petrol station. This is essentially a measure of the availability of refuelling infrastructure. In contrast to most previous studies (e.g. Achtnicht et al., 2012; Brownstone et al., 2000), we think that an attribute presenting the availability of BEV refuelling infrastructure as a percentage of the current availability of petrol stations is not always relevant, as it does not inform respondents about the locations where these refuelling stations will be available. Instead, *extra detour time* informed respondents about the extra time they would have to spend in searching for a quick alternative to standard home-charging, if they were to adopt a BEV.[6] As the investment required for the building of a battery-swapping station is about 20 times higher than the installation of an AC fast-charging unit, we considered higher levels of this attribute for SBEVs than for FBEVs.

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[3] Opel Ampera: http://www.vauxhall.co.uk/vehicles/vauxhall-range/cars/ampera/driving/battery-range.html, Toyota Prius Plug-in: http://en.wikipedia.org/wiki/Toyota_Prius_Plug-in_Hybrid#Battery_and_range.
[4] http://www.teslamotors.com/models/options.
[5] http://www.toyota.com/prius-plug-in/features.html#!/mpg/1235/1239
[6] A similar attribute is also used by Train (2008). The main difference with Train's approach is that the extra detour time considered here does not refer to a one-way trip. Instead, it refers to a trip with return.

- *Reductions in the applicable road tax*: The annual road tax constitutes a substantial share of the operating costs of a car in the Netherlands. Its value primarily depends on the fuel type and weight of the car. The road tax ranges from around €160 for a very light, petrol-fuelled, car to more than €2,000 for a diesel-fuelled car weighing more than 2,000 kg. As a rule of thumb, each additional 100 kg of car weight entail a €100 higher annual road tax. The applicable tax for diesel and LPG cars is about twice as high as the tax for petrol-fuelled ones, while the tax for CNG cars is about 50% more than the one for the latter. Road tax exemptions are currently provided for low CO2 emission cars, including PHEVs and BEVs, but they are expected to be suspended at the end of 2015. The tax values presented to the respondents were customised upon the size of the car they were most likely to purchase next and their preferred fuel type. No tax exemptions were considered for ICE cars. For PHEVs and BEVs, we considered 3 cases: no tax exemption, a 2-year tax exemption, and a 4-year one. Respondents were further informed that after the exemption period had passed they would have to pay the tax applicable to the ICE car.

Figure 1: Example of a vehicle choice scenario

Choice Question 1

The four options presented below are different versions of the same model. They differ only in the presented attributes.

	Option 1	Option 2	Option 3	Option 4
Fuel type	Plug-in hybrid	Petrol	Electric with fixed battery	Electric with swappable battery
Purchase price	€ 46,400	€ 23,200	€ 18,600	€ 25,500
Fuel costs	€ 3.50 per 100 km	€ 16.50 per 100 km	€ 6.00 per 100 km	€ 11.00 per 100 km
Annual fuel costs for a travelled distance of 10,000 km	*(€ 350 per year)*	*(€ 1,650 per year)*	*(€ 600 per year)*	*(€ 1,100 per year)*
Annual fuel costs for a travelled distance of 15,000 km	*(€ 525 per year)*	*(€ 2,475 per year)*	*(€ 900 per year)*	*(€ 1,650 per year)*
Residual value after 5 years	€ 20,900	€ 9,300	€ 11,100	€ 7,700
Range	900 kilometers	750 kilometers	300 kilometers	100 kilometers
Refuel time at the station	5 minutes	5 minutes	30 minutes	5 minutes
Refuel time at home or work	3 hours	Not applicable	10 hours	4 hours
Extra detour time	No extra time	No extra time	20 minutes	No extra time
Annual road tax	No exemption from the road tax, € 650 per year from the first year	€ 650 per year	Exemption from the road tax for 4 years, thereafter € 650 per year	Exemption from the road tax for 2 years, thereafter € 650 per year

Please indicate below which option you would choose:

	Option 1	Option 2	Option 3	Option 4
Your choice	○	○	○	○

Note: In the example above, the respondent stated that his next purchase would be a new, medium-sized, petrol-fuelled car, costing €20,000–€25,000. He would drive 10,000–15,000 km per year in it.

In regard to the design of the study, we employed SSIWeb's *Complete Enumeration* method for the generation of 300 choice experiment versions.[7] In order to accommodate the attribute differences among the four propulsion systems presented to the respondents, we used an alternative-specific design and a minimal number of prohibitions between specific pairs of attribute levels. The sequence of the four alternatives was randomised, whereas the attribute sequence was fixed in order to reduce the complexity of the task for respondents. Perl and HTML scripting was extensively used in order to accommodate the alternative-specific nature of the attribute levels and to customise them in accordance with respondents' stated intentions for their next car purchase. The latter was especially relevant for the monetary attributes used, namely purchase price (and consequently residual value), fuel costs and annual road tax. Figure 1 presents an example of a choice scenario addressed by the respondents.

4. Discrete choice model results and discussion

To enable comparison with existing literature, we start by discussing the results of a basic Multinomial Logit model for the standard specification of the deterministic part of consumer's *n* utility function for alternative *i*:[8]

$$V_{in} = \alpha_i + \beta_{pp}PP_{in} + \beta_{rv}RV_{in} + \beta_{fc}FC_{in} + \beta_{ts}TS_{in} + \beta_{dr_i}\ln(DR_{in}) + \beta_{st}ST_{in} + \beta_{dt}DT_{in} + \beta_{hc}HC_{in}, \quad (6)$$

where α is the alternative specific constant, *PP* is the purchase price of the vehicle, *RV* denotes its resale value, *FC* its fuel costs, *TS* the applicable road tax savings, *DR* the driving range of the alternative, *ST* its refuel time at the station, *DT* the extra detour time required to reach the nearest station, and *HC* the time needed for home- or workplace-charging.

Choice data are analysed by the use of Biogeme 1.9 (Bierlaire, 2003). The basic MNL results are provided in the first four columns of Table 2. We find that ICE technologies rank first in drivers' preferences, followed by their closest alternative in terms of performance and refuelling behaviour, PHEVs. The average disutility suffered from FBEVs is more than twofold the one derived by PHEVs, while the one derived from SBEVs is threefold. The latter finding probably reflects drivers' reluctance to trust a battery-exchange scheme where they have only limited potential to control the state and quality of the battery with which their depleted battery is being swapped. Our estimates further show that consumers are willing to pay, on average, around €140 to have the resale value of their car increased by one percentage point, and €645 to have an amount of €1,000 deduced from their total road tax expenses. Moreover, each increase

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[7] The Complete Enumeration method (Sawtooth Software, 2008) generates a design as close to orthogonal as possible (in terms of main effects) for each respondent. This method also ensures minimal overlap between attribute levels in a specific scenario and balanced appearance of attribute levels.

[8] We suppress the subscript for each choice scenario, *s*, to facilitate discussion.

of fuel costs by €1 per 100 km is valued at €1,290, implying duration of vehicle use of around 8 years at the sample average of ca. 16,400 km travelled per year.

Table 2: MNL results for attributes-only vehicle choice models

Variable	Coefficient		Willingness to pay		Coefficient		Willingness to pay	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
Electric: fixed battery [FBEV]	*-0.9505****	(0.1018)	*-€ 12,280****	(1378)	*-2.372****	(0.103)	*-€ 30,759****	(1594)
Electric: swappable battery [SBEV]	*-1.2647****	(0.0801)	*-€ 16,339****	(1157)	*-2.855****	(0.122)	*-€ 37,020****	(1922)
Plug-in hybrid [PHEV]	*-0.4189****	(0.0457)	*-€ 5,412****	(633)	*-0.669****	(0.067)	*-€ 8,672****	(930)
Purchase price (€ 1000)	*-0.0774****	(0.0023)	-	-	*-0.077****	(0.002)	-	-
Resale value (%)	*0.0109****	(0.0010)	*€ 141****	(14)	*0.011****	(0.001)	*€ 140****	(14)
Fuel costs (€/100km)	*-0.0999****	(0.0048)	*-€ 1,291****	(71)	*-0.099****	(0.005)	*-€ 1,282****	(71)
Road tax savings (€ 1000)	*0.0499****	(0.0095)	*€ 644****	(124)	*0.049****	(0.009)	*€ 641****	(124)
logarithm of Driving range (kms)	*0.5182****	(0.0317)	*€ 13****	(1.0)	-	-	-	-
Refuel time at the station (mins)	*-0.0065****	(0.0025)	*-€ 84****	(32)	-	-	-	-
Extra detour time (mins)	*-0.0129****	(0.0023)	*-€ 167****	(31)	-	-	-	-
Home-charging time (mins)	*-0.0004****	(0.0001)	*-€ 4.6****	(1.6)	-	-	-	-
Driving range: ICE 600 → 750 kms	-	-	-	-	*0.039*	(0.048)	*€ 507*	(616)
Driving range: ICE 600 → 900 kms	-	-	-	-	*0.041*	(0.048)	*€ 526*	(622)
Driving range: PHEV 500 → 700 kms	-	-	-	-	*0.157****	(0.052)	*€ 2,036****	(673)
Driving range: PHEV 500 → 900 kms	-	-	-	-	*0.236****	(0.052)	*€ 3,060****	(677)
Driving range: FBEV 100 → 300 kms	-	-	-	-	*0.542****	(0.083)	*€ 7,030****	(1089)
Driving range: FBEV 100 → 500 kms	-	-	-	-	*0.798****	(0.079)	*€ 10,342****	(1061)
Driving range: SBEV 100 → 300 kms	-	-	-	-	*0.745****	(0.118)	*€ 9,661****	(1565)
Driving range: SBEV 100 → 500 kms	-	-	-	-	*1.238****	(0.114)	*€ 16,046****	(1533)
Detour time: FBEV 10 → 20 mins	-	-	-	-	*-0.119*	(0.077)	*-€ 1,542*	(994)
Detour time: FBEV 10 → 0 mins	-	-	-	-	*0.161***	(0.073)	*€ 2,094***	(944)
Detour time: SBEV 15 → 30 mins	-	-	-	-	*-0.252***	(0.098)	*-€ 3,263***	(1279)
Detour time: SBEV 15 → 0 mins	-	-	-	-	*0.131*	(0.091)	*€ 1,697*	(1178)
Fast-charging time: FBEV 30 → 45 mins	-	-	-	-	*-0.169***	(0.075)	*-€ 2,187***	(979)
Fast-charging time: FBEV 30 → 15 mins	-	-	-	-	*0.029*	(0.073)	*€ 381*	(949)
Home-charging time: PHEV 3 → 5 hours	-	-	-	-	*0.011*	(0.050)	*€ 143*	(654)
Home-charging time: PHEV 3 → 1.5 hours	-	-	-	-	*0.111***	(0.050)	*€ 1,441***	(651)
Home-charging time: BEVs 8 → 10 hours	-	-	-	-	*-0.013*	(0.059)	*-€ 171*	(760)
Home-charging time: BEVs 8 → 4 hours	-	-	-	-	*0.082*	(0.057)	*€ 1,067*	(742)
Observations	12,112				12,112			
R^2	0.257				0.258			
R^2-adjusted	0.256				0.256			
Log-likelihood	-12,483				-12,464			

Note: Robust standard errors in parentheses. ***,** and * indicate that the parameter is statistically significant at the 1%, 5% or 10% significance level respectively.

Drivers value increases in driving range and reductions of fast-charging and detour time rather highly, whereas reductions of home charging time are not equally appreciated. Willingness to pay (WTP) for driving range is estimated at €13/km, at the mean range value of 513 kilometres. In line with our expectations, drivers' value of detour time is substantially higher than (about twofold) the value of fast-charging time, while their value of home-charging time is considerably lower. In particular, 30 minutes of charging at the station are valued by consumers 14% more than 8 hours of charging at home. It is worth noting that even though we tested for interaction effects between refuelling time at the station and extra detour time or driving range, the effects were statistically insignificant at a relatively high significance level.

Columns 5-8 of Table 2 present an alternative model specification, where we explore non-linearities in the levels of BEV driving range, refuel times, and detour time. To this end, we employ a dummy-coded specification for these attributes. We find that preferences for driving range and refuelling-related attributes are largely alternative-specific, as well as that consumers' utility is non-linear in range, refuel times and detour time. In all cases, drivers' WTP for driving range decreases in the considered range levels. Consumers do not seem to value increases in the range of ICE cars in the examined interval (600-900 kms), as well as increases in driving range over 700 kilometres in general. The discrepancy between the valuation of range between PHEVs and BEVs can probably be largely explained by the fact that the attribute levels applicable to the two technologies are substantially different. Interestingly, valuation of range is also different between the two BEV technologies, despite the fact that the same attribute levels are used. Not only is consumer WTP for driving range higher for SBEVs at all examined levels, but it also diminishes in driving range levels at a slower pace. This is pronounced in that WTP per kilometre falls by 53% between 100 to 300 kilometres and 300 to 500 kilometres for FBEVs, while by only 34% for SBEVs. In the interval 300-500 km, WTP per kilometre for SBEV driving range is almost twofold the WTP for FBEV driving range.

WTP for reductions in fast-charging time is increasing in charging time. A reduction from 45 to 30 minutes is valued around €146/minute, while consumers' WTP for a decrease from 30 to 15 minutes is statistically insignificant. A similar pattern is found for consumer valuation of extra detour time to reach the nearest battery-swapping station. A decrease from 30 to 15 minutes of extra detour time is valued at €218/minute, whereas a reduction from 15 minutes to no extra detour time does not have a significant value. The opposite pattern is observed for the extra detour time required to reach the nearest fast-charging station; consumers are indifferent between detouring for 10 or 20 minutes, while they value reductions from 10 minutes to no extra detour time at €210/minute. These findings have important implications for refuelling infrastructure policies, as they entail that consumers are more willing to detour for a few more minutes to reach a battery-swapping station rather than to reach a fast-charging facility. Considering that the costs of constructing and operating a battery-swapping station are around twentyfold the ones of installing and maintaining an AC fast-charging facility, it is important to acknowledge that consumers are willing to sacrifice some detour time to benefit from substantial refuel time savings.

On the other hand, reductions in home-charging time in the examined intervals do not have a significant effect on consumers' utility. For BEVs, drivers' WTP for a change from 8 to 4 hours is statistically insignificant, while for PHEVs only reductions from 3 hours to 90 minutes are valued by consumers. Unless breakthroughs in EV standard charging time occur, our results show that there is limited potential to attract more consumers to EV technologies by providing reductions of standard charging time.

Table 3 provides insights into socioeconomic sources of variation of driver preferences. To facilitate discussion, details about respondents' background characteristics can be found in Table II.1 in Appendix II. In agreement with other studies in the field (e.g. Beggs and Cardell, 1980; Qian and Soopramanien, 2011), we find that females have a weaker aversion towards EV technologies than men. Drivers who have already had driving experience with BEVs[9] are more inclined to opt for them than individuals who have never driven electric, while consumers who currently drive in hybrids are more willing to take a step towards PHEVs than individuals driving in cars propelled solely by ICEs. Company car drivers who reported that their next transaction would concern a car purchase are also more willing to choose a PHEV, probably positively influenced by the generous incentives provided by the Dutch government for the adoption of PHEVs in the company car market. Our estimates further reveal that consumers are more likely to be attracted by EV technologies when their choice concerns the second or third car of the household rather than when it concerns the primary car. This is an intuitively appealing finding, as households are expected to derive less disutility by the shortcomings of EVs when their choice concerns a vehicle to which lower expectations with respect to driving range and refuelling time are attached. Last, the most promising segments for BEV adoption seem to be small cars and vans.

On the other hand, drivers who intend to purchase a large car, an MPV, an SUV, a sports car or a luxury vehicle are less likely to refrain from choosing ICE-propelled EVs than drivers aiming for a medium-sized car. Interestingly, individuals who make car trips abroad more than twice a year have a stronger disutility only for fixed-battery electric cars. The fact that plug-in hybrids and swappable-battery EVs allow a refuelling behaviour closer to the one of ICE-propelled cars is of importance for these drivers. In line with intuition, we further find that drivers anticipating to travel longer annual distances with their next car derive a higher disutility from short driving ranges and high fuel costs.

[9] For instance, they have had the opportunity to use the car-sharing services (Car2Go) provided in the Netherlands or to test-drive a BEV in the framework of events for the promotion of electric mobility.

Table 3: MNL results for vehicle choice model with interaction effects

Variable	Coefficient		Variable	Coefficient	
	Estimate	Std. error		Estimate	Std. error
BEV * Female	0.399***	(0.055)	Fuel costs (€/100km)	-0.112***	(0.005)
BEV * Driving experience with EVs	0.462***	(0.108)	Fuel costs * Max annual distance	-0.033***	(0.004)
BEV * Next car will be Large / MPV / SUV	-0.539***	(0.076)	Log (Driving Range) * Max annual distance	0.075**	(0.03)
BEV * Next car will be Van	0.319**	(0.141)	Driving range: ICE 600 → 750 kms	0.041	(0.048)
Electric: fixed battery [FBEV]	-2.752***	(0.114)	Driving range: ICE 600 → 900 kms	0.048	(0.049)
FBEV * Travelling often abroad	-0.236***	(0.08)	Driving range: PHEV 500 → 700 kms	0.167***	(0.053)
FBEV * Next car will be Small	0.428***	(0.068)	Driving range: PHEV 500 → 900 kms	0.249***	(0.053)
Electric: swappable battery [SBEV]	-3.013***	(0.128)	Driving range: FBEV 100 → 300 kms	0.562***	(0.083)
SBEV * Travelling often abroad	-0.143	(0.097)	Driving range: FBEV 100 → 500 kms	0.826***	(0.08)
Plug-in hybrid [PHEV]	-0.872***	(0.075)	Driving range: SBEV 100 → 300 kms	0.749***	(0.119)
PHEV * Female	0.217***	(0.046)	Driving range: SBEV 100 → 500 kms	1.245***	(0.114)
PHEV * Travelling often abroad	-0.037	(0.052)	Detour time: FBEV 10 → 20 mins	-0.112	(0.077)
PHEV * Next car will be Large / MPV / SUV	-0.234***	(0.057)	Detour time: FBEV 10 → 0 mins	0.166**	(0.073)
PHEV * Current car is a hybrid (HEV)	0.261***	(0.069)	Detour time: SBEV 15 → 30 mins	-0.255***	(0.098)
PHEV * Current car is company car	0.227***	(0.066)	Detour time: SBEV 15 → 0 mins	0.132	(0.091)
ICE * Not primary car of the household	-0.444***	(0.056)	Fast-charging time: FBEV 30 → 45 mins	-0.166**	(0.075)
ICE * Next car will be Sports / Luxurious	0.423***	(0.159)	Fast-charging time: FBEV 30 → 15 mins	0.026	(0.073)
Purchase price (€ 1000)	-0.069***	(0.003)	Home-charging time: PHEV 3 → 5 hours	0.002	(0.051)
Purchase price * Next car will be 2nd hand	-0.029***	(0.004)	Home-charging time: PHEV 3 → 1.5 hours	0.111**	(0.051)
Resale value (%)	0.011***	(0.001)	Home-charging time: BEVs 8 → 10 hours	-0.011	(0.059)
Road tax savings (€ 1000)	0.082***	(0.011)	Home-charging time: BEVs 8 → 4 hours	0.091	(0.057)
Observations		12,112	R^2		0.273
Log-likelihood		-12,210	R^2-*adjusted*		0.270

Note: Robust standard errors in parentheses. ***,** and * indicate that the parameter is statistically significant at the 1%, 5% or 10% significance level respectively.

It is worth noting that Nested Logit models did not appear to provide significant improvements to MNL specifications. On the contrary, Table 4 presents the outcome of a Mixed MNL, where we let the parameters of the alternative specific constants (ASCs) of the basic specification vary according to the normal distribution. 5,000 Halton draws were used for the estimation of this model. The improvement in model fit in comparison with the basic MNL is considerable. The estimates of ASC standard deviation reveal that there is large heterogeneity in consumer preferences for the three EV types. Heterogeneity is largest in the case of fixed-battery EVs, while smallest in the case of swappable-battery ones. As expected, all parameter estimates are of larger magnitude than the ones of the Basic MNL (Brownstone and Train, 1998). On the other hand, with the exception of road tax savings, WTP estimates are not strikingly different between the two models. It is noteworthy, however, that when the panel nature of the data and consumer heterogeneity is taken under consideration, the divergence between drivers' mean WTP for FBEVs and the one for SBEVs becomes notably smaller.

Table 4: Mixed MNL results for attributes-only vehicle choice model

Variable	Coefficient		Willingness to pay
	Estimate	Std. error	
Electric: fixed battery [FBEV]	*-2.0779****	(0.1801)	*-€ 16,438*
Electric: swappable battery [SBEV]	*-2.2116****	(0.1562)	*-€ 17,495*
Plug-in hybrid [PHEV]	*-0.7303****	(0.0935)	*-€ 5,777*
Purchase price (€ 1000)	*-0.1264****	(0.0061)	-
Resale value (%)	*0.0181****	(0.0015)	*€ 143*
Fuel costs (€/100km)	*-0.1487****	(0.0085)	*-€ 1,176*
Road tax savings (€ 1000)	*0.1175****	(0.0161)	*€ 929*
logarithm of Driving range (kms)	*0.7469****	(0.0453)	*€ 12*
Refuel time at the station (mins)	*-0.0091****	(0.0033)	*-€ 72*
Extra detour time (mins)	*-0.0181****	(0.0031)	*-€ 143*
Home-charging time (mins)	*-0.0006****	(0.0002)	*-€ 4.4*
Standard deviations			
Standard deviation: FBEV	*2.8132****	(0.1016)	-
Standard deviation: SBEV	*2.3031****	(0.1035)	-
Standard deviation: PHEV	*2.4276****	(0.0810)	-
Observations	12,112		
R^2	0.385		
R^2***-adjusted***	0.385		
Log-likelihood	-10,319		

Note: Robust standard errors in parentheses. ***,** and * indicate that the parameter is statistically significant at the 1%, 5% or 10% significance level respectively.

5. Conclusions

The large-scale adoption of EVs has been lately considered a potentially promising means of confronting mounting concerns over environmental degradation, oil dependence and increasing petroleum prices. We find that battery electric vehicles are still far from attractive for the majority of consumers, who seek for EV alternatives whose attributes resemble the ones of ICE-propelled cars. To this end, the recently introduced plug-in hybrid and extended-range EVs have considerable potential to mitigate drivers' concerns over short driving ranges and long charging times. On the contrary, at their early introduction stage, swappable-battery EVs are not on average considered as improvements to their fixed-battery counterparts. However, their short refuelling time makes drivers more willing to suffer higher extra detour times to reach a battery-swapping station than to access a fast-charging facility. Considering that the costs of constructing and operating such a station are around twentyfold the ones of installing and maintaining an AC fast-charging facility, this finding has important implications for the potential spatial dispersion of BEV refuelling infrastructure.

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Appendix I: Description of the PHEV and EV technologies provided to the respondents

Before presenting respondents with the choice scenarios, we provided them with descriptions of the PHEV and BEV technologies. The fixed-battery EV (FBEV) was described as a car with a built-in battery pack. Due to the purchase of the battery-pack, the FBEV was usually more expensive than its ICE counterpart. However, its operational costs were much lower than the ones of the ICE car. The FBEV could be either charged at a standard charging point at home or work or at special fast-charging stations. Standard charging would take several hours, while fast-charging would bring the battery to full charge in substantially less than one hour.

The EV with swappable battery (SBEV) was different from FBEV in two aspects. First, the battery pack should be rented by the driver, as it was not built in the car. Second, while the SBEV adopter could use standard charging at home or work, fast-charging was not possible. Instead, the driver would have to exchange the depleted battery with a new one at specialised battery-swapping stations. This procedure would take the same time required now to refuel an ICE car. For their further information, respondents were offered the opportunity to watch a video of the battery-swapping procedure.

The PHEV was described as a vehicle running on both oil-derived fuel and electricity, thereby incorporating both plug-in hybrid and extended-range technologies. Respondents were informed that the PHEV could run on electricity for a few tens of kilometres. Once the battery was almost depleted, the PHEV would run solely on oil-derived fuel. No fast-charging or battery-swapping option was offered for PHEVs.

Respondents were further informed that the BEV and PHEV technologies ran on automatic transmission and that driving electric is almost silent. BEVs and PHEVs were also described as more energy efficient and as having substantially lower (PHEV) or no (BEVs) direct emissions of air pollutants, CO2 and particulate matters. Respondents were also instructed to assume that the battery packs would be recycled at the end of their lifespan.

Appendix II: Selected background data of survey respondents

Table II.1: Selected socio-demographic, car ownership and use, and car purchase intention characteristics of survey respondents

Variable	Percentage	Variable	Percentage
Demographic Characteristics		**Car ownership characteristics**	
Sex		***Number of cars in the household***	
Male	63%	1	52%
Female	37%	2	43%
Age		3 or more	5%
18-24	1%	***Intensity of use of car driven most by respondent***	
25-34	10%	Primary car of the household	86%
35-44	19%	2nd or 3rd car of the household	14%
45-54	23%	***Ownership status of car driven most by respondent***	
55-64	26%	Privately owned car	87%
65 or above	21%	Company car	13%
Education (completed)		***Fuel type of car driven most by respondent***	
Primary and lower secondary	22%	Petrol	68%
Higher secondary vocational	25%	Diesel	19%
Higher secondary professional	13%	Hybrid	11%
Bachelor	27%	LPG / Biofuels	1%
Masters / PhD	12%		
Unreported	1%	**Characteristics of the car respondent is likely to buy next**	
2011 Gross household income		***New or 2nd hand***	
Less than € 20,000	4%	New	37%
€ 20,000 - € 32,500	14%	2nd hand	63%
€ 32,500 - € 51,300	31%	***Fuel type***	
€ 51,300 - € 77,500	25%	Petrol	61%
€ 77,500 - € 103,800	13%	Diesel	14%
€ 103,800 or above	6%	Hybrid	14%
Unreported	7%	Plug-in Hybrid	4%
Household size		Electric	3%
1 person	13%	Other	4%
2 persons	47%	***Car segment***	
3 persons	14%	Small	32%
4 persons	19%	Medium-sized	41%
5 or more persons	7%	Large / Estate	12%
House ownership		MPV	7%
Own house	82%	SUV	3%
Rented accommodation	18%	Van	3%
		Sports / Luxury	2%
Car use characteristics		***Annual distance travelled***	
Previous driving experience with EVs		< 10,000 km	27%
Yes	5%	10,000 km - 15,000 km	30%
No	95%	15,000 km - 20,000 km	19%
Frequency of making car trips abroad		20,000 km - 25,000 km	11%
Less than once a year	38%	25,000 km - 35,000 km	8%
Once a year	19%	>25,000 km	5%
Twice a year	18%		
Three or more times per year	24%		