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Do Battery-Switching Systems Accelerate the Adoption of Electric Vehicles? A Stated Preference Study

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Abstract

We estimate willingness-to-pay (WTP) for battery-switching electric vehicles (SEVs) by using a stated choice experiment. Our estimation results show that individuals have high WTP for SEVs, provided sufficient battery-switching stations exist. When battery-switching infrastructure represents 50% of the current number of gasoline stations, individuals are indifferent between conventional gasoline vehicles and SEVs, which have a 521 thousand yen lower price than gasoline vehicles. Moreover, the estimation results suggest that vehicle drivers may recognize SEVs as vehicles for shorter drives such as daily shopping trips and thereby have lower marginal WTP with respect to cruising range.

JEL Classification: L62, Q42, Q51

Keywords: electric vehicle, battery-switching stations, stated preference method, choice experiment, willingness-to-pay

1 Introduction

Electric vehicles (EVs) are expected to play a significant role in reducing carbon emissions from the transportation sector. More than 550 thousand EVs were sold worldwide in 2015, increasing the global stock of EVs to 1.26 million (Electric Vehicles Initiative, 2016). While these figures are promising, EVs still represent only 0.1% of total passenger cars globally. One of the major obstacles to the further adoption of EVs might be consumer anxiety about the new technology. EVs have a lower driving range compared with conventional gasoline vehicles (GVs) and a longer waiting time for fuel charging.

One solution to this problem might be investment in battery-switching systems for EVs. An EV battery-switching station allows drivers to exchange their depleted battery for a fully charged one in a few minutes. Since the driver does not own the battery in the car and is charged per mile driven, it is also possible to reduce the upfront costs that prevent people from purchasing EVs. However, the notion of battery-switching has been unsuccessful so far. Better Place, a venture company that developed battery-switching services for EVs and attracted significant attention and capital, collapsed in May 2013 (Pearson and Stub, 2013). Tesla Motors presented the idea of battery swap stations in June 2013, but it is unlikely to pursue further development at present (Korosec, 2015).

This study investigates potential demand for battery-switching EVs (SEVs) by using a stated preference survey. Since demand for alternative fuel vehicles critically depends on the availability of fuel charging stations (Ito et al., 2013), it is important to incorporate this feature into the analysis of demand for EVs. The choice experiment design used in this study allows us to investigate whether consumers evaluate SEVs differently from battery-recharging EVs (REVs). More specifically, the effect of fuel availability on willingness-to-pay (WTP) for EVs might be different between these two types of EVs. WTP for SEVs can be strongly affected by the availability of switching stations, since the attractiveness of switchable batteries critically depends on the infrastructure network specially designed for this technology. If consumers prefer SEVs to REVs, it suggests that there is still a chance for the investment in battery-switching stations as well as the development of vehicles specially designed for switching.

Several studies have investigated the potential demand for EVs by using a stated preference methodology (Beggs et al., 1981; Ewing and Sarigöllü, 1998; Bunch et al., 1993; Brownstone et al., 2000; Axsen et al., 2013; Ito et al., 2013). These studies ask respondents, by using hypothetical questionnaires, to choose their preferred alternative from a set of profiles that have different levels of car attributes. From the estimated coefficients of these attributes, one can calculate marginal WTP to improve particular attributes of EVs. Many previous studies have focused on the driving range issue of EVs. For example, Daziano (2013) found that the mean estimated WTP for a one-mile improvement in the driving range of an EV in the past studies in the United States is 100 dollars per mile. Infrastructure development for EVs has been less focused upon by previous studies even though consumers' valuation of range may be sensitive to the availability of refueling infrastructure (Dimitropoulos et al. 2013). Moreover, to our knowledge, no study has thus far examined the difference in WTP for SEVs and REVs.

The rest of the paper is organized as follows. Section 2 introduces the survey design of our stated preference questionnaire. Section 3 explains the empirical strategy for the WTP estimation. Section 4 presents the estimation results and their implications. Section 5 concludes.

2 Survey design

2.1 Vehicle attributes and their levels

The decision to purchase a car depends on various factors. In this study, we selected nine attributes based on our research objectives and the findings of previous studies. Attributes connected with refueling, refueling rate, and fuel availability are important factors that affect vehicle choice (Ewing and Sarigöllü, 1998; Potoglou and Kanaroglou, 2007). Table 1 presents the attributes and their levels used in our study. Details of the attributes can be summarized as follows:

Fuel type: To investigate potential demand for SEVs relative to other vehicles that uses different types of fuel, we considered the following four fuel types: GVs, hybrid electric vehicles (HEVs), REVs, and SEVs. GVs were treated as the base alternative that respondents were willing to purchase.

// Table 1: The attributes and levels of the choice experiments //

Body type: Respondents were asked to choose two vehicle body types out of the nine alternatives that they would consider in their next purchase decision; these two body types were used to create respondent profiles. The following nine categories of vehicle body types were included in the choice experiment: subcompact, compact/hatchback, coupe, sedan, convertible, wagon, minivan, SUV/pickup truck, and truck/bus. The body types are assumed to be unrelated to fuel types.

Manufacturer: Respondents were asked to choose one automobile manufacturer from the list of manufacturers that they would consider in their next purchase decision. The list comprised 32 manufacturers, including foreign companies. We used their choice to create profiles for the base alternative. It was assumed that only the following four representative automobile manufacturers in Japan produce HEVs, REVs and SEVs: Toyota Motor Corporation, Honda Motor Company, Nissan Motor Company, and Mitsubishi Motors Corporation.

Cruising range: Cruising range is a critical attribute for choosing alternative fuel vehicles. Cruising ranges were set as 800 kilometers for GVs; between 800 kilometers and 1,200 kilometers for HEVs; and between 100 kilometers and 300 kilometers for REVs and SEVs.[1]

Refueling rate: The total time for refueling was set as 5 minutes except for REVs. Compared with other vehicles, REVs usually take a longer time to recharge. The refueling rate of REVs were set as 10, 15, and 30 minutes. These are typical charging times for fast-charging stations that have the latest technology. When battery-switching stations are available for SEVs, the time taken to recharge is less than 5 minutes. For example, Tesla Motors announced that it takes only 90 seconds to switch batteries for EVs.[2] Respondents watched a few minutes of video that introduced how drivers can switch the discharged battery in an SEV for a fully charged one at a battery-switching station.

Carbon dioxide emissions: It was assumed that by choosing HEVs or EVs, drivers can reduce their emissions of carbon dioxide. When a respondent chooses an HEV, his or her emission levels of carbon dioxide are reduced by 20%, 30%, 40%, or 50% from

[1] The cruising range of Nissan's EV model Leaf is between 100 kilometers and 220 kilometers depending on the speed, climate, road, and so on. (Source: Nissan Leaf's website)

[2] https://www.tesla.com/jp/videos/battery-swap-event

the current levels of emissions from GVs. When a respondent chooses REVs or SEVs, it is reduced by 50%, 60%, 70%, or 80% from the current levels.

Fuel availability: Fuel availability was described in terms of the percentage of refueling stations among existing gasoline stations. Thus, the fuel availability of GVs and HEVs is 100%. The fuel availability of REVs and SEVs was set as 10%, 25%, 50%, and 75%. In Japan, there were more than 13,000 spots where a fast-charging service for EVs is available as of October 2016[3] and 32,000 gasoline stations as of March 2015.[4]

Purchase price: The purchase price for GVs was based on respondents' answers regarding the amount they will spend on their next purchase opportunity. The purchase prices for HEVs, REVs, and SEVs are represented by the increase from the price that customers will pay for GVs.

Annual fuel cost: The annual fuel costs for GVs were calculated from respondents' current number of refuels per month and the average amount they spend per refuel. The annual fuel costs for HEVs, REVs, and SEVs were indicated by the decrease in the annual fuel costs from that of GVs. Respondents were instructed to assume that the annual fuel costs include the cost of replacing the batteries of REVs. The attributes of different fuel types, refueling frequencies, and refuel stations are correlated because of the shared technological characteristics among these vehicles.

Respondents were also instructed to assume that all the other attributes that are not indicated in choice set as being identical among the alternatives. Respondents were able to obtain information regarding the above vehicle attributes by clicking a link while answering the choice experiment questions.

[3] The data is from CHAdeMo. http://www.chademo.com/wp/
[4] http://www.meti.go.jp/press/2016/07/20160712003/20160712003.html

2.2 Design of choice sets

The number of alternatives in each choice set was set as four. An example of a choice set is presented in Figure 1. The profile for vehicle 1 (GVs) was created on the basis of respondents' answers regarding their next purchase opportunity. Throughout the eight choice sets that each respondent faced, vehicle 1 was fixed as the base alternative.

The profiles for HEVs, REVs, and SEVs were created by using orthogonal arrays for 10 attributes and four levels. In total, 64 profiles for each alternative fuel vehicle were constructed; therefore, 192 (64 × 3) profiles of alternative fuel vehicles were compiled. The profiles of GVs were the same between choice sets. Then, two profiles from the alternative fuel vehicles were randomly drawn and matched with the GV profile; hence, 128 choice sets and 16 versions of a series of eight choice sets were created. One of the 16 versions was randomly assigned to each respondent.

// Figure 1: Example of a choice set //

2.3 Data

We carried out a web-based survey between February 21 and 25, 2011. The clarity of the questionnaire was checked by a pretest conducted in December 2010. We sent e-mails to invite registered monitors to the online survey and 53,066 people aged between 19 and 69 responded. The response rate was 17%. Table 2 reports the summary statistics.

// Table 2: Summary statistics of respondents' characteristics //

3 Discrete choice model

We adopt a random utility model to analyze vehicle purchase behavior (McFadden, 1974). The utility of the respondent *k* choosing alternative *i* is denoted by:

$$U_{ki} = V(x_{ki}, t_{ki}) + \epsilon_{ki} \tag{1}$$

where $V(\cdot)$ and ϵ_{ki} are the observable and unobservable terms, respectively, $x_{ki}$is the attribute vector, and t_{ki} is the price of alternative *i*. The probability of choosing alternative *i* from the choice set *C* is represented by

$$\begin{aligned} P_{ki} &= \Pr(U_{ki} > U_{kj}, \forall j \in C, j \neq i) \\ &= \Pr\left(V_{ki} - V_{kj} > \epsilon_{kj} - \epsilon_{ki}, \forall j \in C, j \neq i\right). \end{aligned} \tag{2}$$

Assuming a Gumbel distribution for the difference in the unobservable error terms, the probability of choosing alternative *i* can be represented by the conditional logit model as:

$$P_{ki} = \frac{e^{V_{ki}}}{\sum_j e^{V_{kj}}}. \tag{3}$$

The parameters of the utility function were estimated by maximizing the following log-likelihood function:

$$\ln L = \sum_{k=1}^{K} \sum_{i=1}^{J} \left\{\delta_k^i \ln P_{ki}\right\}. \tag{4}$$

where δ_k^i is a dummy variable that takes one when respondent *k* chooses an alternative *i*, and zero otherwise. Marginal WTP to increase a level of each attribute is calculated by dividing the estimated coefficient of an attribute variable by the estimated coefficient of a price variable.

4 Estimation results

4.1 Main results

The estimation results of the conditional logit model are shown in Table 3. We include the quadratic terms for cruising ranges and establishment of infrastructure in the model to capture the diminishing effect of these factors on vehicle choice. The estimated results for each coefficient of the explanatory variables used in our models are as follows:

Alternative specific constants (ASCs): There are five ASCs in our model: HEVs, REVs (three refueling rates), and SEVs. All ASCs except for SEVs are positive and statistically significant. This means that an individual prefers HEVs and REVs to GVs provided that all other vehicle attributes are the same. On the contrary, the ASCs of SEVs is not statistically significant. This means that an individual is indifferent to the choice between SEVs and GVs. SEVs should be more attractive in terms of price, environmental friendliness, and other attributes. The difference between the coefficients of REVs with different recharging times indicates the utility increase by reducing the time required for recharging at a station. For example, an individual is willing to pay 127.5 thousand yen (about 1,100 US dollars) to reduce the recharging time from 30 minutes to 15 minutes.

Fuel availability: The coefficient of Station is positive, whereas that of Station squared is negative. These results are consistent with our expectations that the marginal utility of expanding stations for refueling is diminishing. The interaction term between SEVs and Station is positive and statistically significant. This means there is a higher benefit in expanding stations for SEVs than that for other vehicles.

Cruising range: The estimated coefficient of cruising range and its squared term represent their marginal utilities in the utility function. As expected, the coefficient of cruising range is positive and the squared term is negative. These results indicate that marginal utility for a longer cruising range is diminishing. We also estimated the parameters of the cross terms between REVs or SEVs and the square term of cruising range. The coefficients of these cross terms are negative, which means that the marginal WTP for the cruising range of REVs or SEVs is lower than that for HEVs. Note that the cruising ranges of HEVs are different to those of EVs.

Body types: The coefficients of coupe, sedan, minivan, and wagon are negative, whereas the coefficient of SUV/pickup truck is positive. These results indicate that although WTP for HEVs, REVs, and SEVs decreases when the body type is coupe, sedan, minivan, or wagon compared with subcompact, compact/hatchback, convertible, or truck/bus, it increases when the body type is SUV/pickup truck.

Manufacturers: The coefficients of Toyota, Honda, Nissan, and Foreign are significantly positive and the coefficient of Mitsubishi is not significant. These results indicate that although WTP for HEVs, REVs, and SEVs increases when the manufacturers are Toyota, Honda, Nissan, and foreign automobile manufacturers compared with other automobile manufacturers, there is no difference in it between Mitsubishi and them.

// Table 3: Estimation results //

4.2 Establishment of infrastructure

The estimated coefficients suggest that infrastructure development for EVs is positively evaluated by individuals; however, there is a maximum WTP value with regard to the percentage of stations relative to the current gasoline stations. WTP to expand recharge stations for REVs by as much as X% of the current number of gasoline stations from the situation of no recharge stations is calculated by

$$WTP_{REV\_STATION} = (\beta_s X + \beta_{s2} X^2)/\beta_p, \tag{5}$$

where β_s is the coefficient for Station, β_{s2} is that for Station squared, and β_p is that for price. The WTP to expand battery-switching stations for SEVs is calculated by

$$WTP_{SEV\_STATION} = (\beta_s X + \beta_{s2} X^2 + \beta_{SEV} X)/\beta_p, \tag{6}$$

where β_{SEV} is the coefficient of the interaction term between SEVs and Station. Since this is positive and statistically significant, the expansion of SEV stations is evaluated as being higher than the expansion of stations for other alternative fuel vehicles.

Figure 2 shows WTP to build infrastructure for REVs and SEVs, with the percentage compared with current gasoline stations on the horizontal axis. For example, WTP to build infrastructure as much as 50% of current gasoline stations is 36.4 thousand yen (about 330 US dollars) for REVs and 52.9 thousand yen (about 4,80 US dollars) for SEVs. Under a realistic assumption,[5] the price of SEVs must thus be 521 thousand yen lower than GVs for consumers to be indifferent when the number of battery-switching

[5] We assume Range=800km, Station=100%, and Emission reduction=0% for GVs and Range=200km, Station=50%, and Emission reduction=50% for SEVs.

stations is half the number of current gasoline stations. Since the relationship between the WTP and refuel station is quadratic, a maximum WTP value exists for expanding infrastructure. WTP for REV or SEV infrastructure reaches the maximum value when refuel stations represent 62% or 78% of current gasoline stations, respectively.

// Figure 2: WTP to build the infrastructure of REVs and SEVs //

4.3 Cruising range of EVs

Figure 3 shows WTP for the cruising range of alternative fuel vehicles. Similar to the relationship between WTP and refuel stations, marginal utility diminishes with respect to cruising range. WTP for the cruising range of HEVs is higher than that of REVs or SEVs. For example, WTP for a cruising range of 1,000 km with regard to HEVs is 2,810 thousand yen (about 25,500 US dollars). On the contrary, WTP for a cruising range of 200 km with regard to REVs or SEVs is 731 thousand yen (about 6,600 US dollars). The cruising range of REVs or SEVs is shorter than that of HEVs; hence, drivers may recognize REVs or SEVs as vehicles for shorter drives such as daily shopping trips. In that case, the results might indicate that the difference in the purpose of use decreases marginal utility with respect to cruising range.

// Figure 3: WTP for cruising range //

5 Concluding Remarks

Notwithstanding its expected significant role in reducing carbon dioxide emissions for mitigating climate change, the current penetration level of EVs is still very low. Battery-switching systems might greatly promote EV use by alleviating driving range anxiety and reducing the upfront cost of purchase. Our estimation results show that individuals have lower WTP for SEVs despite the existence of sufficient battery-switching stations. Under the scenario that battery-switching infrastructures represents 50% of that of current gasoline stations, individuals are indifferent between GVs and SEVs, which have a 521 thousand yen lower price than GVs. However, we should remember that the future of batteries might be different from now. For example, the estimated cost of Li-ion battery packs for EV manufacturers declines by approximately 14% annually (Nykvist and Nilsson, 2015).

The bankruptcy of Better Place and retreat of Tesla Motors from battery-switching systems lend support to the difficulty of developing a network of battery-switching stations in a profitable manner. Maintaining the system is costly, as it is required to hold more batteries than the number of EVs on the road (Avci et al., 2015). On the other hand, there is an ancillary benefit of battery-switching systems such as avoiding high peak demand and the ability to coordinate discharging back to the power grid through vehicle-to-grid technology (Widrick et al., 2016). The consideration of these costs and benefits is necessary for judging the economic rationality of adopting battery-switching systems for EVs.

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Table 1: The attributes and levels of the choice experiments

Attributes		Levels			
Fuel type		GV	HEV	REV	SEV
Body type	GV	Base 1a			
	HEV/REV/SEV	Base 1a	Base 1b		
Manufacturer	GV	Base 2a			
	HEV/REV/SEV	Base 2a	Base 2b		
Cruising range	GV	800			
(km)	HEV	800	900	1000	1200
	REV/SEV	100	150	200	300
Refueling rate	GV/HEV/SEV	5			
(minutes)	REV	10	15	30	
Fuel availability	GV/HEV	100%			
(% of the existing gasoline stations)	REV/SEV	10%	25%	50%	75%
Carbon dioxide	GV	0%			
(% reduction of a	HEV	20%	30%	40%	50%
present average car)	REV/SEV	50%	60%	70%	80%
Purchase price	GV	Base 3			
(including tax)	HEV	Base 3+10%	Base 3+20%	Base 3+30%	Base 3+50%
	REV	Base 3+20%	Base 3+40%	Base 3+60%	Base 3+80%
	SEV	Base 3−10%	Base 3−5%	Base 3+5%	Base 3+10%
Annual fuel cost	GV	Base 4			
	HEV	Base 4−50%	Base 4−40%	Base 4−30%	Base 4−20%
	REV	Base 4−80%	Base 4−60%	Base 4−40%	Base 4−20%
	SEV	60,000+ (Base4−50%)	80,000+ (Base4−80%)	100,000+ (Base4−80%)	150,000+ (Base4−80%)

Note: Base 1, Base 2, Base 3, and Base 4 are specified by respondents and differ between respondents.

Table 2: Summary statistics of respondents' characteristics

	Mean	SD	Min	Max	N
Females	0.49	0.5	0	1	2408
Age	44.622	13.220	20	69	2408
Household income (10^4 yen)	650.416	397.456	50	2250	2165

Note: N denotes the number of respondents.

Table 3: Estimation results

Explanatory variables	**Coeff.**	**Std. Err.**
ASCs		
HEV	0.805***	0.081
REV with a battery rechargeable in 10 minutes	1.192 **	0.480
REV with a battery rechargeable in 15 minutes	1.278 ***	0.482
REV with a battery rechargeable in 30 minutes	1.172 **	0.483
SEV	0.722	0.486
Vehicle attributes		
Range [100 km]	0.428 ***	0.120
Range^2 [10,000 km]	-0.019 ***	0.006
Station [%]	0.010 ***	0.003
Station^2 [%/1000]	-0.082 **	0.035
Emission reduction [%]	0.004 ***	0.001
Price [million yen]	-0.833 ***	0.031
Annual cost [yen]	-0.576 ***	0.034
$(\text{REV}+\text{SEV})*\text{Range}^2$	-0.043 *	0.023
SEV*Station	0.003 **	0.001
Body type		
Coupe	-0.113 *	0.058
Sedan	-0.109 ***	0.037
SUV	0.158 **	0.070
Minivan	-0.313 ***	0.074
Wagon	-0.123 ***	0.040
Manufacturer		
Toyota	0.274 ***	0.036
Honda	0.263 ***	0.040
Nissan	0.208 ***	0.043
Mitsubishi	-0.052	0.083
Foreign	0.124 **	0.050
Psuedo-R^2		0.0696
Log Likelihood		-20647.048
Observation		21672
Number of respondents		2408

Figure 1: Example of a choice set

	Vehicle 1	Vehicle 2	Vehicle 3
Fuel type	Gasoline	Battery-Recharging EV	Battery-Switching EV
Body type	SUV, Pickup	SUV, Pickup	SUV, Pickup
Manufacturer	Toyota	Toyota	BMW
Cruising range	800 km	200 km	200 km
Refueling rate	5 minutes	15 minutes	15 minutes
Fuel availability	All existing service stations	75% of existing service stations	50% of existing service stations
Carbon dioxide	Present level	60% less	70% less
Purchase price	5 million yen	7 million yen	5.5 million yen
Annual fuel cost	100 thousand yen	80 thousand yen	170 thousand yen
	⇩	⇩	⇩
Choose one vehicle			

Figure 2: WTP to build the infrastructure of REVs and SEVs

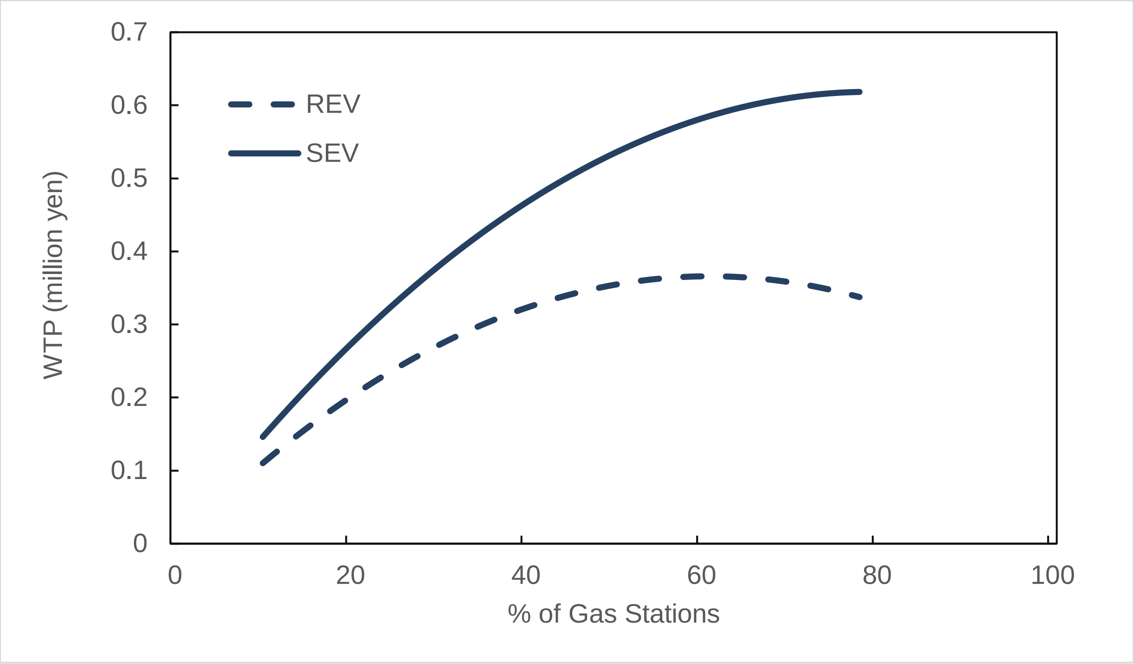

Figure 3: WTP for cruising range