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Abstract:
At present it is difficult for electric vehicles (EVs) and fuel-cell vehicles (FCVs) to gain significant traction in the general market. The reason for this is that the batteries and fuel cells that constitute the critical design elements of EVs and FCVs have not yet attained practical levels of performance or cost. In this paper, we present the results of simulations we have conducted to assess the cost impact of batteries on the spread use of EVs.

Keywords: penetration of new technology, battery electric vehicles

JEL codes: O14

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Projections and Sensitivity Analysis for the Spread Use of Electric Vehicles

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1. Introduction

Promoting zero emission vehicles including electric vehicles (EVs) and fuel-cell vehicles (FCVs) are expected as important mitigation measures for the climate change in transport sector. Though, at present it is difficult for EVs and FCVs to gain significant traction in the general market. The reason for this is that the batteries and fuel cells that constitute the critical design elements of EVs and FCVs have not yet attained practical levels of performance or cost for the general use.

For the projection of market penetration of new technologies, both of technological progress and user's choice have to be considered. The technology cost of batteries and fuel-cells for vehicles are expected to decline drastically at mass production stage, but its future expectation is largely uncertain. The cost and performance of these technologies directly affect the choice of them. In this paper, we develop a simulation model of the market penetration of EVs and present the results of simulations to assess the cost impact of batteries and discuss the possible policies for promoting the spread use of EVs.

Regarding the penetration of new automotive technologies, there are mainly three approaches in past studies; discrete choice theory (Bunch et al., 1993; Brownstone and Train, 1999; Ewing and Sarigollu, 2000; Potoglou and Kanaroglou, 2007; Mau et al., 2008; Axsen et al., 2009), computable general equilibrium (Schafer and Jacoby, 2006; Karplus et al., 2009), and bottom-up linear optimization like MARKAL (Ichinose and Endo, 2006; Endo, 2007; Yeh et al., 2008). These studies successfully explained how new technologies can penetrate in the market, though the future price of the technologies were given as scenario in most studies.

Main concern of this study is whether the EVs have potential competitiveness in the market under the condition of assumed cost reduction over the production, in other words cost reduction by scale economy, and the sensitivity of the potential competitiveness under the cost reduction curve variation. To clarify the potential, we employ the descrete choice theory to represent the user's behavior, and utilize a cost reduction curve for battery technology. Combining them, we assess the possibility of market penetration of EVs and the sensitivity of cost reduction curve prospect.

2. Methods

In this paper, only two types of vehicle, conventional internal combustion engine vehicles (ICEVs) and battery electric vehicles (EVs), are considered. Consumers are assumed to choose the technologies based on their economic performance and risk of out of energy. The other performance or characteristics are neglected.

The economic performance is defined as life time cost of vehicles, which consist of vehicle price and discounted fuel cost during the life time. Fuel cost depends on the travel length of consumers and fuel efficiency of the vehicles. The vehicle price and fuel efficiency of ICEVs are fixed in this paper, though those factors for EVs depend on the battery price and capacity on board. The risk of out of energy for ICEVs is assumed zero, but that for EVs is assumed to vary depending on its battery capacity and travel length of consumer.

The battery price is assumed to decline against the annual production volume of the battery. Therefore, the battery price and demand for EVs are interdependent. The market share is determined at the balanced point of battery price, in other word, at the equilibrium of supply and demand of batteries.

In the following section, the details of these factors are formulated.

2.1. Vehicle energy efficiency

The fuel efficiency of ICEVs is assumed to be fixed here, denoted as e_{ICE} (MJ/km). The efficiency of EVs depends on the amount of battery capacity because it affects the vehicle weight. The efficiency e_{EV} is formulated as follows.

$$e_{EV} = a_0 + a_1 \cdot (W_0 + \mu \cdot Q)$$

Where, W_0 is vehicle weight without battery (kg), μ is battery specific energy (kg/kWh), Q is battery energy capacity (kWh) and a_0, a_1 is parameters.

In this paper, the value of e_{ICE}, W_0, and μ is given based on Malcolm et al. (2000) in which the performance is expected in 2020. The parameters are estimated based on Graham (2001). Q is set to 30kWh considering driving range and cost. These values are summarized in Table 1.

Table 1. Assumed specification of vehicles and battery

	ICEV	EV	
Weight (kg)	1136	Total w/o battery (W_0) Battery (μQ) (spec. energy; kWh/kg)	1184 984 200 (0.15)
Energy efficiency (MJ/km)	1.54	0.48 (excl. charger loss) 0.54 (incl. charger loss)	
Maximum driving range for one charge	More than 500km	180km	

Here, the efficiency is calculated for US-FTP test cycle. The efficiency of ICEV in this table is equivalent to 21.3 km/L, which is very advanced energy efficiency compared with current ICEV. EV efficiency has to be measured in two ways; excluding and including charger loss. The former is used to calculate the driving range for one charge, and latter is needed to derive lifetime cost. To ensure the designed battery cycle life, lower bound of state of charge is assumed to be 20% here, in other words, the vehicle can use 80% of the total capacity of the battery. Considering these factors, the maximum driving range for one charge is calculated to be 180km, which can be reduced due to driving pattern and electricity consumption of accessory like air conditioner.

2.2. Lifetime cost of the vehicle use

As mentioned, the life time cost of the vehicles in this paper is assumed to be sum of the vehicle price and discounted fuel cost during the life time C. It is formulated as follows.

$$C = C_0 + \sum_{t=0}^{T} \frac{c_f \cdot e \cdot L}{(1+r)^t}$$

Where, C_0 is vehicle price ($), c_f is energy price ($/MJ), e is energy efficiency (MJ/km), L is annual travel distance (km) and r is discount rate. Considering Japanese situation, energy price of gasoline is set to 3.87 US-cent/MJ and electricity is set to 2.83 US-cent/MJ. The energy efficiency is assumed in the previous section, and discount rate is set to 10% considering the expected return of private investment.

The vehicle price is also based on Malcolm et al. (2000), where the price of ICEVs is \$19,400. Regarding EVs, we assume the battery price is variable depending on its production volume. The price of EVs without battery is given as \$15,960, and the total price of EVs (C_0^{EV}) is calculated by following equation.

$$C_0^{EV} = 15{,}960 + \eta \cdot Q$$

Where, η is battery price per capacity (\$/kWh). The annual travel distance varies by consumers, and we assume it is random variable and has probability distribution of which the detail is described in the next section. In summary, the lifetime cost of ICEVs can be formulated as a function of annual travel length L, and that of EVs can be a function of L and unit price of battery η. They can be denoted as $C^{ICE}(L)$ and $C^{EV}(L,\eta)$ respectively.

2.3. Market share of EVs

We employ discrete choice theory, especially logit model for the estimation of choice probability of EVs. Without the risk of out of energy, we assume the probability is formulated as follows.

$$\Pr_C^{EV}(L,\eta) = \frac{\exp\left(\theta \cdot C^{EV}(L,\eta)\right)}{\exp\left(\theta \cdot C^{EV}(L,\eta)\right) + \exp\left(\theta \cdot C^{ICE}(L)\right)}$$

Where, θ is parameter which is negative. This formula means if the lifetime cost of EVs get cheaper comparing with ICEVs, the choice probability of EVs increases. The parameter is estimated as $\theta = -7.11 \times 10^{-4}$ (1/\$) based on the sales share of hybrid electric vehicles (HEVs) and the cost of HEVs and ICEVs in Japan, 2004.

In addition, the maximum driving range of EVs is much smaller than that of ICEVs. It raises the risk of out of energy for the long distance drivers. Unfortunately we do not have statistics of daily travel length, therefore the probability of out of energy is calculated based on monthly travel length data by *e-nenpi* (Japanese private vehicle information service) and assumptions of variance of dairy travel as well as on road energy consumption distribution. As a result, the out of energy probability $\Pr_O^{EV}$ is assumed as cumulative function of the Gumbel distribution over the annual travel length.

$$\Pr_O^{EV}(L) = \exp\left(-\exp\left(-(L-\gamma_m)/\gamma_s\right)\right)$$

γ_m=19,473 and γ_s=7,509

The probability distribution of annual travel length $\Pr_L$ is assumed as density function of Gumbel distribution here. The parameters are estimated based on the odometer data of used car information by *carsensor.net* (Japanese web site for used car information).

$$\Pr_L(L) = \frac{1}{\varphi_s}\exp\left(-\left(L-\varphi_m\right)/\varphi_s\right)\cdot\exp\left(-\exp\left(-\left(L-\varphi_m\right)/\varphi_s\right)\right)$$

φ_m=6,955 and φ_s=4,160

Using these probability functions, the choice probability of EVs ($\Pr^{EV}$) can be estimated by following equation.

$$\Pr^{EV}(\eta) = \int_0^\infty \Pr_C^{EV}(L,\eta)\cdot\left(1-\Pr_O^{EV}(L)\right)\cdot\Pr_L(L)dL$$

In summary, the choice probability of EVs is a function of the battery price per capacity, and the share of EVs is assumed to be equal to the choice probability.

2.4. Cost reduction curve of the batteries

The cost reduction curve over the production volume of the battery is taken from the work of Duvall and Alexander (2005). These authors used data (Anderman et al., 2000) from BTAP (the California Battery Technical Advisory Panel), but also considered variations in the price of materials to obtain supply curves based on reassessments of future prices, thereby yielding price predictions for PHEVs (plug-in hybrid-electric vehicles) and EVs. The supply curve used here estimates price per unit electrical storage capacity based on annual production volumes of batteries designed for use in EVs; in contrast to typical supply curves, the price decreases as demand increases. The price curve can be formulated as follows.

$$\log\eta = \alpha_0 + \alpha_1 \log N$$

α_0=3.32, α_1= -0.168

Where, N is number of units shipped annually. According to this formula, when N is 10 thousand, the unit price is \$445/kWh, and it is \$302/kWh at N=100 thousand.

3. Simulation Results

3.1. Equilibrium penetration of EVs

Figure 1 shows battery supply and demand curves in a log-log plot calculated under the assumptions discussed above. Here the solid lines plot EV demand vs. battery price, while the dashed lines plot battery price vs. EV sales volume. From Figure 1 we see that EV demand rises as battery price falls, while battery price falls as sales volume rises. The left panel presents the estimates under the original parameter; the curves intersect at two points, corresponding to battery prices of \$540/kWh and \$170/kWh, and EV share of less than 1% and 56% respectively. Supply and demand are equal at both of these points, but the point marked **A** in the figure corresponds to an unstable equilibrium; if the battery price rises higher than its value at point **A**, the sales volume will converge to zero, while if the price falls below the value at point **A** then sales will grow until equilibrium is attained at point **B**.

The right panel of Figure 1 presents the same data as in left panel, but now calculated using a 5% larger value for the α_0 parameter in the expression for the battery supply curve. In this case, there is no intersection between the curves even in the regime of high battery price; in such a situation there can be no supply-demand equilibrium, and EVs will not become widespread.

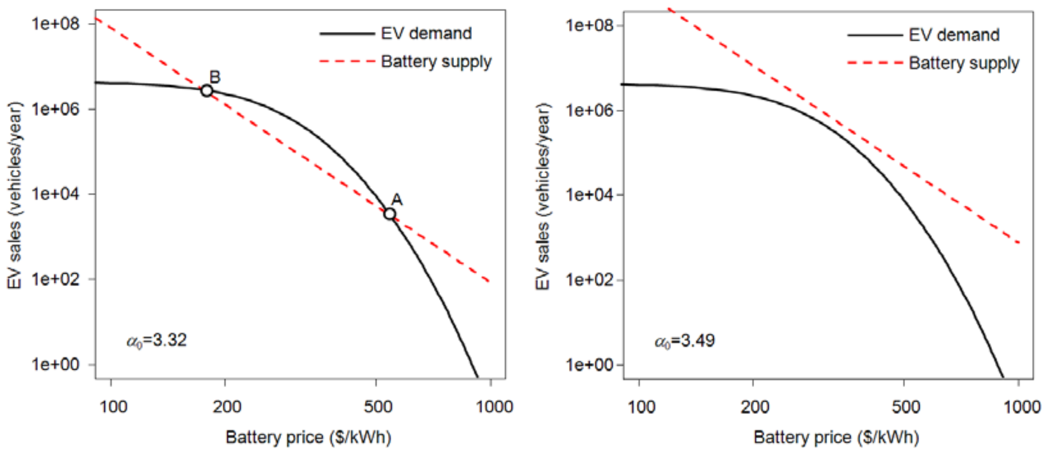
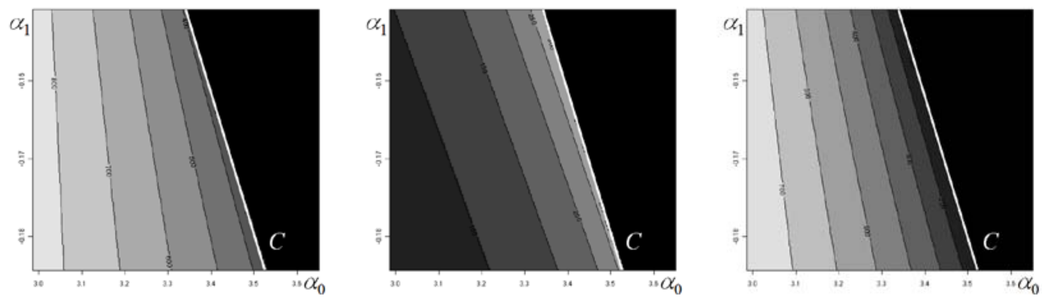


Figure 1. Relationship between battery price and EV sales volume

3.2. Sensitivity of battery price curve parameters

Figure 2 illustrates changes in the battery prices at points A and B as the two parameters in the supply curve are varied by ±10%. The horizontal and vertical axes indicate the values of the α_0 and α_1 parameters, while the color indicates the battery price (brighter colors correspond to higher prices). The blacked-out region to the right of line C in each plot is the regime in which no intersection point exists. (Line C is the equal-price curve, along which points A and B coincide.)

These figures indicate that, even if we consider only ±10% variations in the parameter values, fully 32% of the parameter space is blacked out; at parameter values falling anywhere within this region, EVs will not become widespread. As the parameter values decrease, the threshold price rises and the equilibrium price falls; in this case the difference between the threshold and equilibrium prices is large, and government policy has maximal impact. On the other hand, for parameter values lying near the vicinity of line **C**, the impact of government policies to promote the spread of the technology is minimal, even in cases where an equilibrium point exists. We thus see that small changes in parameter values can have a large influence on the efficacy of technology-promotion policies.



Left) Battery price at point **A,** Middle) Battery price at point **B**, Right) Difference in battery price between points **A** and **B**

Figure 2. Sensitivity of Battery Price to Changes in Parameter Values

4. Conclusion

In this study, we developed an assessment model for potential market competitiveness of EVs, and simulated its possible penetration in the market with consideration of consumer's choice and cost reduction curve of battery technologies. As a result, we found that growth in the use of EVs is highly sensitive to the parameters that determine the supply curve, and will thus be heavily influenced by forecasts for battery price reductions due to mass-production effects. The analysis clearly demonstrates that small variations in battery price forecasts can entirely neutralize the impact of policies to promote EVs.

It is big challenge to obtain an accurate cost reduction curve for any new technologies at mass production stage. This study suggests the importance of cost estimation of future technologies and needs for the quantitative analysis of uncertainties in the policy making of new technology promotion.

Note that, although we have not included them within our analysis here, some uncertainties inevitably exist in demand-side models and in the assumptions/ conditions we used to conduct our simulations as well, and these must not be ignored. Future work is necessary to incorporate these uncertainties into a more refined model.

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