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Stochastic frontier analysis of excess access to mid-trip battery electric vehicle fast charging

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ABSTRACT

This study aims to explore how factors including charging infrastructure and battery technology associate the way people currently charge their battery electric vehicles, as well as to explore whether good use of battery capacity can be encouraged. Using a stochastic frontier model applied to panel data obtained in a field trial on battery electric vehicle usage in Japan, the remaining charge when mid-trip fast charging begins is treated as a dependent variable. The estimation results obtained using four models, for commercial and private vehicles, respectively, on working and non-working days, show that remaining charge is associated with number of charging stations, familiarity with charging stations, usage of air-conditioning or heater, battery capacity, number of trips, Vehicle Miles of Travel, paid charging. However, the associated factors are not identical for the four models. In general, EVs with high-capacity batteries are initiated at higher remaining charge, and so are the mid-trip fast charging events in the latter period of this trial. The estimation results also show that there are great opportunities to encourage more efficient charging behavior. It appears that the stochastic frontier modeling method is an effective way to model the remaining charge at which fast-charging should be initiated, since it incorporates trip and vehicle characteristics into the estimation process to some extent.

Introduction

Electric vehicles (EVs) driven by electric motors instead of traditional internal combustion engines are expected to reduce fossil fuel dependency, improve urban air quality, and thus help the transition to more sustainable and environment-friendly travel. However, despite the impressive societal and environmental benefits that EVs may deliver, there are several major problems that stand in the way of promoting their greater use, and the limited range between charges is one of them. To make consumers more comfortable buying and using EVs, great efforts are currently being made to deploy a charging infrastructure and improve the storage capacity of batteries. These efforts deal with the range problem on two fronts: by providing convenient recharging opportunities and by increasing range on a single full charge. However, observation of EV usage at Tokyo Electric Power Company (TEPCO) has indicated that the remaining charge at the end of a journey decreases with the implementation of additional charging stations, even though these stations are infrequently utilized (Electrification Coalition, 2009), which suggests that drivers are recharging just to give themselves a larger margin of error to prevent

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running out of charge without a station nearby. This raises questions such as how much charging infrastructure and what battery capacity is sufficient, whether charging stations and battery capacity are being effectively used and, more importantly, how to encourage users to make effective use of charging stations and battery capacity. TEPCO's experience may suggest that charging behavior, especially the battery state of charge (SOC) at which drivers begin to charge their EVs, may provide some answers to these questions.

Exploring on refueling behavior with alternative fuel vehicles (AFVs, or vehicles with limited range like EVs) started about several decades ago (e.g. Dingemans et al., 1986; Kitamura and Sperling, 1987). Since there were few AFVs on the road, however, such studies usually entail analyzing the refueling behavior of traditional-fuel-vehicle drivers. However, driving an AFV differs dramatically from driving a traditional one, and the different refueling infrastructure will lead to different refueling patterns. With the promotion of AFV Projects around the world, refueling behavior is beginning to be explored based on real-life AFV usage data (e.g. Kuby et al., 2013; Kelley and Kuby, 2013), and so is the charging behavior of EV users (e.g. Smart and Schey, 2012; Franke and Krems, 2013c; Robinson et al., 2012). Previous studies have revealed that familiarity with refueling station locations greatly influences refueling behavior (Dingemans et al., 1986; Kitamura and Sperling, 1987; Plummer et al., 1998), there are psychological dynamics underlying charging behavior (Franke and Krems, 2013c), and refueling choice is the result of a learning process (Dingemans et al., 1986). Currently, however, the EV market is far from mature. There is an incomplete charging infrastructure, battery technology is evolving, and there is only a small number of EVs on the roads, so drivers' present charging behavior is likely to change over time as the infrastructure becomes more spatial diffusion, technical progress is made with batteries, and drivers gain more experience. Therefore, it is important to explore how charging behavior is influenced by the charging infrastructure and battery capacity based on real-life EV usage data, which is rarely involved in previous studies.

Currently EVs have three types of charging: level 1, 2, and 3. Level 1 charges at 120 V while level 2 at 240 V, which have been standardized in SAE J1772 (Electric Vehicle and Hybrid Electric Vehicle Conductive Charge Coupler, 2010), but have slight national differences given the differences in utility voltages among countries. Level 3 has not been standardized but it typically operates at 480 V or higher voltage. In Japan, Level 1 and 2 charge at 100 V and 200 V respectively, and collectively referred to as normal charging, which require several hours to completely charge a fully depleted battery and can be performed at home. While level 3 is known as fast charging (also known as quick or rapid charging) with CHAdeMO technology (CHAdeMO, 2010), which provides an 80% charge in 30 min, making an effective complement to normal charging. Normal charging usually receives special attention because it is most frequent, but although most charging can be done while stationary, fast charging plays an important role in long-distance trips or when an unexpected emergency arises. An battery electric vehicle (BEV) field trial in Japan (Successful Applicant, 2012) showed that it is rare for a car to require fast charging every day, but seen over a period of a couple of weeks or months nearly all cars need to use fast charging. In addition, Christensen et al. (2010) pointed out that a fast-charging infrastructure is the most important need if EVs are to come into widespread use.

This study investigates fast-charging behavior in consideration of charging infrastructure and battery capacity. As of the end of this field trial, the charging infrastructure has been expanded in 47 prefectures across Japan to encourage use of EVs. These charging stations have a maximum of four chargers, each with or without normal chargers, but more than 98% have one fast charger. This widespread availability of fast chargers but with limited numbers probably results from the understanding that fast charging is needed by most vehicles but only very rarely. In addition, about 47.3% of fast charging stations are located at workplaces and leisure places, and the remaining 52.7% are located at car sales shops (40.4%), parking lots (4.8%), motorways (2.8%), convenience stores (2.5%), and gas stations (2.2%). This layout generates three types of fast-charging events: beginning-of-trip, mid-trip and end-of-trip. Beginning-of-trip and end-of-trip fast-charging occurs respectively at the origin and destination of trips, while mid-trip fast-charging takes place after leaving the origin and before arriving at the destination. Although the focus is on fast charging, it is mid-trip fast-charging events that are of interest rather than beginning-of-trip and end-of-trip events. Because we think mid-trip fast-charging represents the intended demand for fast charging, while beginning-of-trip and end-of-trip fast-charging does not seem to represent intended demand for fast charging. For instance, some EV drivers typically plug in their vehicles for fast charging prior to departing from or when parked at a charging location regardless of the vehicle's SOC and their upcoming driving plans. This type of fast-charging event does not happen during trips.

Personality trait has been shown to affect EV range utilization (Franke and Krems, 2013a), which may results in a complicated pattern of SOC at the initiation of fast charging. For example, a risk-averse driver will probably choose to fast charge at a higher remaining charge in order to avoid the risk of running out of charge; in an extreme case, such a driver may charge whenever there is a fast-charging station available. Such excessive "just-in-case" behavior would require a high density of charging stations that would be unnecessarily wasteful. On the other hand, the most adventurous driver will charge only on the realization that the remaining charge cannot support the rest of the trip. Planning for this behavior would, inversely, require a lower density of fast-charging stations leading to greater risk of stranding and might discourage some customers from buying an EV. This means it is better to estimate charging behavior on an individual level.

Thus, this paper aims at developing a methodology for effectively representing the relationship between remaining charge when mid-trip fast charging is initiated and the charging infrastructure, taking into account the charge capacity of the vehicle. A stochastic frontier model is used for the analysis, using real-life BEV usage data collected in Japan, and each individual's remaining charge at fast-charging initiation is taken to be a function of the characteristics of charging stations, BEV's charge capacity, travel patterns, and the familiarity with charging infrastructure.