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Fast-charging station choice behavior among battery electric vehicle users

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ABSTRACT

This study explores how battery electric vehicle users choose where to fast-charge their vehicles from a set of charging stations, as well as the distance by which they are generally willing to detour for fast-charging. The focus is on fast-charging events during trips that include just one fast-charge between origin and destination in Kanagawa Prefecture, Japan. Mixed logit models with and without a threshold effect for detour distance are applied to panel data extracted from a two-year field trial on battery electric vehicle usage in Japan. Findings from the mixed logit model with threshold show that private users are generally willing to detour up to about 1750 m on working days and 750 m on non-working days, while the distance is 500 m for commercial users on both working and non-working days. Users in general prefer to charge at stations requiring a shorter detour and use chargers located at gas stations, and are significantly affected by the remaining charge. Commercial users prefer to charge at stations encountered earlier along their paths, while only private users traveling on working days show such preference and they turn to prefer the stations encountered later when choosing a station in peak hours. Only private users traveling on working days show a strong preference for free charging. Commercial users tend to pay for charging at a station within 500 m detour distance. The fast charging station choice behavior is heterogeneous among users. These findings provide a basis for early planning of a public fast charging infrastructure.

Introduction

Electric vehicles (EVs) driven by electric motors instead of traditional internal combustion engines are attracting more and more attention because they offer the potential benefits of reducing fossil fuel dependency, improving urban air quality, and thus helping the transition to more sustainable and environment-friendly travel. Battery charging is one important aspect of EV operation, while an inadequate charging infrastructure is consistently cited as a major barrier to widespread EV adoption (Bapna et al., 2002; Romm, 2006; Melaina and Bremson, 2008; Johns et al., 2009).

With the current charging technologies, the usual method of charging an EV is to plug it into a 120 V or 240 V outlet, as standardized in SAE J1772 (2010). This type of charging is referred to as normal charging, and several hours are required to

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completely charge a fully depleted battery. This type of charging can be performed at home. An EV battery can also be recharged at 480 V or higher using CHAdeMO technology (CHAdeMO, 2010). This is known as fast charging (or quick or rapid charging), and achieves an 80% charge in 30 min. It is usually performed at a charging station. Although for most usage EVs can be normal-charged during long stationary periods, fast charging plays an important role in long-distance trips or when an unexpected emergency arises. An field trial of battery electric vehicles (BEVs) in Japan (Successful Applicant for the FY, 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 owners need to use fast charging. It has also been pointed out by Christensen et al. (2010) that a fast-charging infrastructure is the most important need if EVs are to come into widespread use. However, the EV market is immature and the fast-charging infrastructure is incomplete, creating a barrier to adoption as noted above. Thus, the construction of EV fast charging stations is essential if EVs are to come into widespread use.

The optimal location of fueling stations for alternative fuel vehicles (AFVs; vehicles that run on fuels other than traditional petroleum, including electricity, biodiesel, ethanol, hydrogen, and natural gas) has in recent years been the focus of many proposed approaches and models. These studies are generally based on assumptions about drivers' preferences for refueling location. For example, *p*-median model (Hakimi, 1964) and maximal covering location model (Church and Velle, 1974) assume that drivers prefer to refuel close to home, work, or other key trip anchors; Flow Capturing Location Model (FCLM, Hodgson, 1990) and Flow Refueling Location Model (FRLM, Kuby and Lim, 2005) assume that drivers prefer to refuel en-route from origin to destination. In addition, driver's willingness to deviate from the shortest path to access a refueling station has been incorporated into modeling, such as Deviation Flow Refueling Location Model (DFRLM, Kim and Kuby, 2012) and Deviation Flow Refueling Location Model - enhanced (DFRLM-E, Yildiz et al., 2015).

Unfortunately, empirical studies on the refueling preferences of AFV users, and even of petroleum-powered vehicle users, are rare. About the refueling location, Sperling and Kitamura (1986) surveyed the refueling behavior of gasoline and diesel vehicle drivers through interviews while they refueled at selected fuel stations in northern California, treating diesel vehicles as a proxy for AFVs. They found that 56% of diesel vehicle drivers stated that convenience to home, work or school is the primary reason for selecting a fuel station. In other work, Kitamura and Sperling (1987) found that the refueling stops of gasoline vehicle drivers are clustered at the beginning or end of a trip, and close to home or work locations in particular. Kelley and Kuby (2013) updated the Sperling and Kitamura studies by interviewing drivers of compressed natural gas (CNG) vehicles while they refueled at selected stations in southern California using the same type of survey methodology. They concluded that more CNG drivers prefer fuel stations requiring the least deviation from the path between origin and destination than stations closest to home. Kuby et al. (2013) came to the similar conclusion when they investigated the refueling behavior of CNG drivers in Los Angeles. While these studies provide a general descriptive analysis of where drivers are most likely to refuel their vehicles, they fall short of providing insight about the decision-making process that drivers use. Further, these studies demonstrate that the decision of where to refuel is related to many factors, including the driver's activity program, the quantity of fuel remaining in the tank, and the location and attributes of fuel stations (Sperling and Kitamura, 1986; Kitamura and Sperling, 1987). However, the tradeoff among these factors in making a refueling location choice is left unsolved. Pramono provided some insights about the decision-making process and the tradeoff among various factors in gas station choice using a two-stage fixed-effect conditional logit model applied to data obtained by interviewing gasoline vehicle drivers while they refueled at selected stations in Bandung, the capital of West Java Province, Indonesia. About the deviation for refueling, Lines et al. (2008) conducted surveys on hydrogen rental cars at the Orlando International Airport, finding that more than 80% of respondents expressed a willingness to detour more than one mile away in order to refuel, and 46% were willing to detour more than three miles. Kelley and Kuby (2013) and Kuby et al. (2013) found that there is a sharp decay beyond six minutes of deviation for CNG drivers and the willingness to deviate is relatively consistent across stations. Pramono found that the sampled drivers are most likely to refuel at gas stations within 1500 m detour distance. However, caution is needed in mapping these data to the charging behavior of EV drivers for two reasons: first, the fast-charging of an EV takes longer than traditional petroleum vehicle and other AFV refueling; second, EVs can be normal-charged at home or in other locations where they remain stationary for some hours, in addition to fast charging at public charging stations.

With growing usage of EVs around the world, studies of charging behavior are beginning. Jabeen et al. (2013) explored EV drivers' preference for charging at work, home or public charging stations through stated choice experiments in Western Australia. In fact, this study not only covers charging location choice, but also choice of charging method, normal charging or fast charging. Arslan et al. (2014) analyzed the degrees to which plug-in hybrid electric vehicle (PHEV) drivers deviated from their shortest paths to recharge under several deployment levels of fast charging stations, using simulated trips. They found that the deviation is higher when fast charging stations are sparse. However, to the authors' knowledge, there has been almost no empirical research into choice behavior for fast charging stations.

An understanding of fast charging station choice behavior is of paramount importance in knowing how EV users trade off the relevant factors to make fast charging decisions, and will provide the basis for developing an effective fast charging infrastructure to accelerate EV market growth, which is essential for promoting EVs as societal and environmental policies. The aim of this paper is to provide insight into the process by which BEV users choose fast charging stations by exploring how various factors influence choice behavior. This paper also explores the specific distance by which BEV users in the sample are generally willing to detour to reach a fast charging station, in light of the above-mentioned findings about the detour willingness for refueling.