Empirical Investigation on the Range Anxiety for Electric Vehicles

1. Motivation and Problem Description: Transportation holds the key to our sustainable future. Not only does it account for 27% of all greenhouse gas emissions in the US, it has also been one of the worst-performing sector in terms of curbing emissions growth. In the US, emissions from transportation grew by 15.5% from 1990 to 2015, compared with a 3.5% growth in total emissions by all sectors. The major difficulty in greening the transportation sector is the high growth in travel demand. For instance, the vehicle miles traveled in the US increased by over 40% from 1990 to 2015. Worldwide, governments and industry are moving toward the consensus that fundamental changes in fuel technologies will be needed. China, France, India, the Netherlands, Norway and the UK have all announced plans to completely phase out the sale of combustion engine (CE) cars by 2040 or before, in favor of zero emissions cars, and in particular, electric vehicles (EVs) which have shown the most promise thus far.

Currently, EVs only account for about 1% of the US new cars market. Toward the long-term goal of mass adoption, EVs have major hurdles to overcome. Whereas early adopters can be enticed by environmental and novelty factors, mass market consumers are unlikely to compromise on attributes such as price, performance and convenience, to switch from CEs to EVs. Among the major shortcomings of EVs on the market is the limited range and long recharging times, leading to drivers’ psychological concerns that the driving range of EVs may be insufficient to meet their needs. The direct implication of such psychological fear, called range anxiety, is that drivers are reluctant to adopt EVs unless the driving range well exceeds their travel needs.

The quantification of range anxiety has important implications on EV market development, policy design and infrastructure planning. In the near term, the present battery technology and production cost impose a hard trade-off between the EVs affordability and range. The presence of range anxiety implies that drivers would require EVs to deliver a longer range than is physically needed. Thus, statistical estimates of range anxiety can inform product line decisions as automakers design their lineups of EVs with different ranges and price points. Furthermore, in the near to medium term, adoption of EVs will heavily depend on government incentives and the provision of charging infrastructure. Developing empirical understanding of drivers’ psychological needs for EV range will guide policy design and infrastructure planning decisions.

In the longer term, the industry expects battery technology and manufacturing costs to further improve such that the range-cost trade-off will be alleviated. Nevertheless, as EV becomes mainstream, natural bottlenecks will arise in the supply chain of batteries and their components, including a number of minerals of scarce supply. Toward the long-term goal of completely electrifying the vehicle fleet, as stipulated by a number of governments worldwide, it is important to make prudent use of these elements that could become supply constrained as adoption continues to grow. Therefore, in the long run, it is important to design EVs with range that is sufficient but not excessive. Determining the range that is sufficient requires a good understanding of both the physical and psychological (i.e., range anxiety) preferences of drivers.
Despite these important implications of measuring drivers’ range anxiety, there have been few studies attempting to statistically quantify range anxiety, and the existing ones mainly focus on stated preference surveys on drivers’ preferences. Revealed preference studies, on the other hand, are difficult and costly to perform due to the high stakes involved in the car purchase decision. To circumvent this difficulty, we attempt to identify and quantify range anxiety at the decision level of making a single trip rather than purchasing a new car. Specifically, we use a novel dataset collected from an on-demand car sharing system, Car2go, that operates CE and EV fleets in different cities. Based on this dataset, we empirically identify and quantify the effect of a car’s effective driving range on its attractiveness to drivers on a single-trip basis, and contrast the findings for EVs and CEs.

2. Description of Data: Car2go operates a free-floating car sharing service in a number of cities worldwide. In each city, Car2go deploys a fleet of cars in a defined service region, within which users can flexibly start and end their rentals anywhere, and users are charged a fee based on the duration of the rental. Through tracking the locations of available fleets as reported on the Car2go website, we identified all trips occurring within a period of 210 days. For each trip, we record the unique vehicle identification number (VIN), GPS coordinates and street address of the starting and ending locations, and fuel levels (in %) at the beginning and end of the trip.

In San Diego, Car2go first started operating with a fleet of about 350 EVs in 2009. The fleet was homogenous and consisted of a single car model, the Smart Fortwo Electric Drive, a two seater EV with 135km of driving range on a full battery. In May 2016, the company replaced the entire fleet with about 250 CEs, also homogenous and comprised of only the Smart Fortwo car model. The electric and gasoline models are almost identical in size, engine power and appearance, with the only differences being the fuel types and driving range (135km for EV vs. 560km for CE). Through collecting the usage data before and after the fleet change, we are able to collect samples of trips for EVs and CEs, and contrast them in our analysis. There were 24,550 and 137,815 trips completed with EVs and CEs during the data collection period, respectively. As to be discussed next, we use this fleet change event as a quasi-experiment in analyzing the impact of fuel types on consumers’ rental behavior.

3. Methodology and Main Results: Our analysis consists of estimating three complementary econometric models. Our first analysis aims to identify drivers’ aggregate preferences on fuel type, as revealed by the rental demand for the car sharing service. Specifically, considering the fleet change event (i.e., the company switching its entire fleet from EVs to CEs) happening in San Diego but not other US markets, we perform a difference-in-difference (DiD) analysis with Poisson regression to model the effect of a change in fuel type (CE vs. EV) on the demand of the car sharing system. After controlling for the effects of time and geographic region of the rentals as well as the weather conditions, the Poisson regression results show that, replacing the EVs with CE vehicles in San Diego increases the demand rate by 20-25%. We used four different US major cities as the control group where only CE vehicles are operated, and the results are consistent over these different control groups.
The results from our DiD analysis suggest that fuel type has a major effect on the overall demand for a car sharing fleet, i.e., all else equal, a CE-only fleet is significantly more popular than an EV-only fleet. In our second analysis, we delve into a key attribute that may account for such difference – range. The free-floating, self service characteristics of Car2go’s service provide a unique opportunity for such analysis: Since cars are not always refueled at the end of rentals (unlike in traditional car rental businesses), the fuel levels of available cars, which translate into different effective ranges, varies over time and location. For this, we apply the probit regression model to estimate the effect of an individual car’s fuel or battery level (i.e., effective range) on its hazard rate of being rented out by drivers. An important challenge in this estimation is that the key independent variable, fuel availability, actually interacts endogenously with the dependent variable of demand rates. For example, when there is a demand spike due to a sports event that leads to hiked demand rates over a short period, the cars available for rental tend to have lower fuel levels but are more likely to be rented. To address this endogeneity problem, we use the fuel consumption of the car’s previous trip as an instrumental variable. With this, we find that the fuel level has a statistically significant effect on a single car’s demand rate for EVs only, but not for CEs. Specifically, the result shows that increasing the battery level by 10% can lead to a 3% to 6% increase in the demand of an EV, depending on the vehicle’s location and initial battery level.

Our third and final analysis focuses on drivers’ choice behavior when starting trips. Thus far, our analysis has revealed that an EV fleet are significantly less popular than a CE one, and that range has a statistically significant effect on a car’s popularity only for EVs. Our remaining step is to quantify this preference for longer range. To do so, we use a discrete choice model to estimate drivers’ preference between alternative cars with different fuel levels when starting trips. In this model, we explicitly evaluate drivers’ trade-off between a car’s fuel level versus the cost of access (using walking distance as a proxy). This provides a quantification on the willingness to pay for longer range. Our results reveal that range anxiety exists: In contrast to CEs, drivers renting EVs are willing to walk significantly farther distances—on average they would walk about 200-300 meters to obtain additional one percent of EV range, which is four to ten times as far as they would do for CEs for the same amount of additional range. Our findings also reveal that the magnitude of range anxiety increases substantially as the trip’s realized fuel consumption increases; yet, even for very short trips (e.g., consuming less than 5% of the battery), range anxiety is still clearly exhibited compared with CE vehicle users.

4. Conclusion: To support mass adoption of EVs, understanding of drivers’ preferences, particularly the range anxiety, is essential for informing product and policy design. Based on a three-step empirical approach, we identify the adverse effect of using EV fleets on car sharing demand, attribute such difference on an individual-car level to drivers’ different preferences (willingness to pay) on range for EVs versus CEs, and further quantify drivers’ preferences for additional range. These are significant findings, since they reveal that range anxiety is not merely a matter of purchase behavior, but also one associated with day-to-day usage.