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VALUE OF PUBLIC CHARGING: UNDERSTANDING THE LINKAGE BETWEEN CHARGING NETWORK COVERAGE AND CHARGING OPPORTUNITY

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ABSTRACT

Using GPS-based travel survey data, this paper estimates the relationship between public charging network coverage and charging opportunity, defined as the probability of being able to access public charging for a driver at one of his/her stops or at one travel day. Understanding this relationship is of important interests to the electric vehicle industry and government in determining appropriate charging infrastructure deployment level and estimating the impact of public charging on market adoption of electric vehicles. The analysis finds that drivers' trip destinations concentrate on a few popular places. If top 1% of most popular places are installed with public chargers, on average, drivers will be able to access public charging at 20% of all their stops and 1/3 of their travel days; If 20% of most popular places are installed with public chargers, drivers will be able to access public charging at 89% of all their stops and 94% of their travel days. These findings are encouraging, implying charging network can be efficiently designed by concentrating at a few popular places while still providing a high level of charging opportunity.

Keywords – electric vehicle, plug-in hybrid, charging availability, charging infrastructure, market adoption

INTRODUCTION

The availability of charging infrastructure is an important consideration when consumers make purchase decisions of Plug-in Electric Vehicles (PEV), including battery electric vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV). Home is the primary location of charging, as evidenced by the EV project study finding that more than 80% of PEV charging events occurred at home (Smart, 2014). Public charging is used much less frequently, but it provides important assurance to BEV drivers, encourages them to fully utilize battery range, and alleviates so called range anxiety, i.e., the concern that a BEV might run out of battery and get stranded on road. Anegawa (2010) reported a case that electric miles increased and the fleet drivers allowed battery state of charge (SOC) to go lower after building additional fast chargers, indicating increased driver confidence and reduced anxiety. Public chargers are also beneficial to PHEVs by increasing their electric miles.

To assist efficiently allocating limited resources for charging infrastructure deployment, some fundamental questions need to be answered (NRC, 2015): how many chargers are needed, where they should be located, and what is the impact on the market adoption of PEVs. There is a growing body of research that studies the optimal location of public chargers in a given region (e.g. Frade et al.,2011; Jung et al.,2014; Nie and Ghamami,2013; Sweda and Klabjan,2011). Most of these papers focused on the mathematical formulation of underlying optimization models, which typically minimize investment cost while meeting demand or maximize the coverage of charging stations. A few studies analyzed travel survey data of conventional gasoline vehicles and examined the feasibility of replacing the fleet with BEVs assuming the same travel pattern (Pearre et al., 2011; Tamor et al., 2015). How the provision of public charging can improve BEV feasibility is also discussed. Nicholas et al. (2013) found that in California 71% of the total miles driven could be finished with an 80-mile BEV and no public charging provided, while optimized placement of 200 DC fast chargers would allow over 90 percent of miles completed. Dong et al. (2014) analyzed GPS-based travel survey data for the Seattle Metropolitan area and found that 10% of trips and 20% of miles would be missed with a 100-mile BEV and no public charging provided. The paper developed a charging station sitting model which simulates drivers' driving behavior and minimizes missed trips by optimizing the location and type of chargers. Public chargers funded at the level of $2000 per vehicle are able to reduce missed trips to 2.6% and the marginal benefits decreases with additional investment.

However, previous research hasn't studied the linkage between charging infrastructure deployment level and the probability of being able to access public charging during a driver's daily travel activities. We refer to this probability as charging opportunity. Reaching a certain level of charging opportunity may be a particularly important factor for PEVs to penetrate to the mass market, because consumers in the mass market, compared with early adopters, may be more sensitive to the lack of charging availability and less willing to adapt their travel activities for meeting the charging needs. Therefore, understanding the linkage between infrastructure deployment level and charging opportunity is an essential step toward answering the important questions of what level of infrastructure deployment is needed and what is the impact of public charging on PEV market adoption.

Using the GPS-based travel survey data for the greater Seattle Metropolitan area, this paper estimates the relationship between charging opportunity and charging network coverage level, represented by the percentage of public parking places installed with public chargers. The developed approach considers the geographical overlap between charging network and drivers' travel activity space. The analysis finds that drivers' trip destinations concentrate on a few popular places. If top 1% of most popular places are installed with public chargers, on average, drivers will be able to access public charging at 20% of all their stops and 1/3 of their travel days; If 20% of most popular places are installed with public chargers, drivers will be able to access public charging at 89% of all their stops and 94% of their travel days. These findings are encouraging, implying charging network can be efficiently designed by concentrating at a few popular places while still providing a high level of charging opportunity.

DATA DESCRIPTION

The data set used in this paper comes from a household travel choice study by Puget Sound Regional Council (PSRC, 2008). This Study (PSRC, 2008) recorded driving activities of 275 volunteer households in the Seattle metropolitan area for approximately an 18-month period (from November 2004 to April 2006). Among the participating households, 45% of the households own one vehicle, 48% own 2 vehicles and 7% own 3 or more vehicles, resulting in a total of 445 gasoline vehicles. The participant vehicles were installed with GPS devices, which are automatically turned on/off when the engine is turned on/off. This allows for continuous collection of vehicles' daily travel activities. On average each vehicle makes 4.8 trips and travels 30 miles per day.

The raw dataset contains the time-stamped spatial information (the latitude and longitude coordinates of the vehicle) at the resolution of 4 records per minute. We are only interested in trip level information, such as the start and end location of each trip, as well as the dwell time between two consecutive trips. Ideally, a trip's start location should match the end location of the previous trip. However, gap exists in some cases. This is because, when it is turned on, a GPS device might need some time to warm up before working properly. Therefore, the end location of a trip is more reliable and considered as a "stop" in this paper. Around 700,000 trips were collected by the survey. Table 1describes the data fields of trip records used in this paper

In the raw dataset, the locations of trips are recorded by the latitude and longitude coordinates. As a driver may not always park at the same spot in a parking lot, some nearby latitude-longitude coordinate pairs might be associated with the same activity destination, such as a shopping mall or the driver's workplace. Moreover, if a charger is available near a PEV driver's destination, he/she might be willing to park at the charging station and walk a few minutes to the destination. Therefore, instead of using the exact latitude and longitude coordinates, each trip end is assigned to a grid cell. When a charger is placed in the grid cell, the driver can charge the PEV at the stop if necessary. In the downtown area, each grid cell covers 0.5 by 0.5 miles; in suburbs, each grid cell covers 1 by 1 mile; and in outer suburbs, each grid cell covers 5 by 5 miles. As a result, the entire Seattle metropolitan area is divided into about 4000 grid cells, containing all the trip ends. Figure 1 shows the map of the survey area. The home locations of the instrumented vehicles and the popular destinations such as shopping malls are plotted on the map.

Table 1 GPS Travel Data Description

Data field	Description
Vehicle ID	The unique ID of the vehicle
Travel day	The date when the trip was recorded
Trip number	Trips taken by an individual on a travel day are numbered sequentially by a trip number
Start time	The start time of the trip
End time	The end time of the trip
Start location	GPS coordinates of the starting point of the trip
End location	GPS coordinates of the end point of the trip
Travel distance	Vehicle miles traveled on the trip
Dwell time	Time spent at the destination while the vehicle is parked

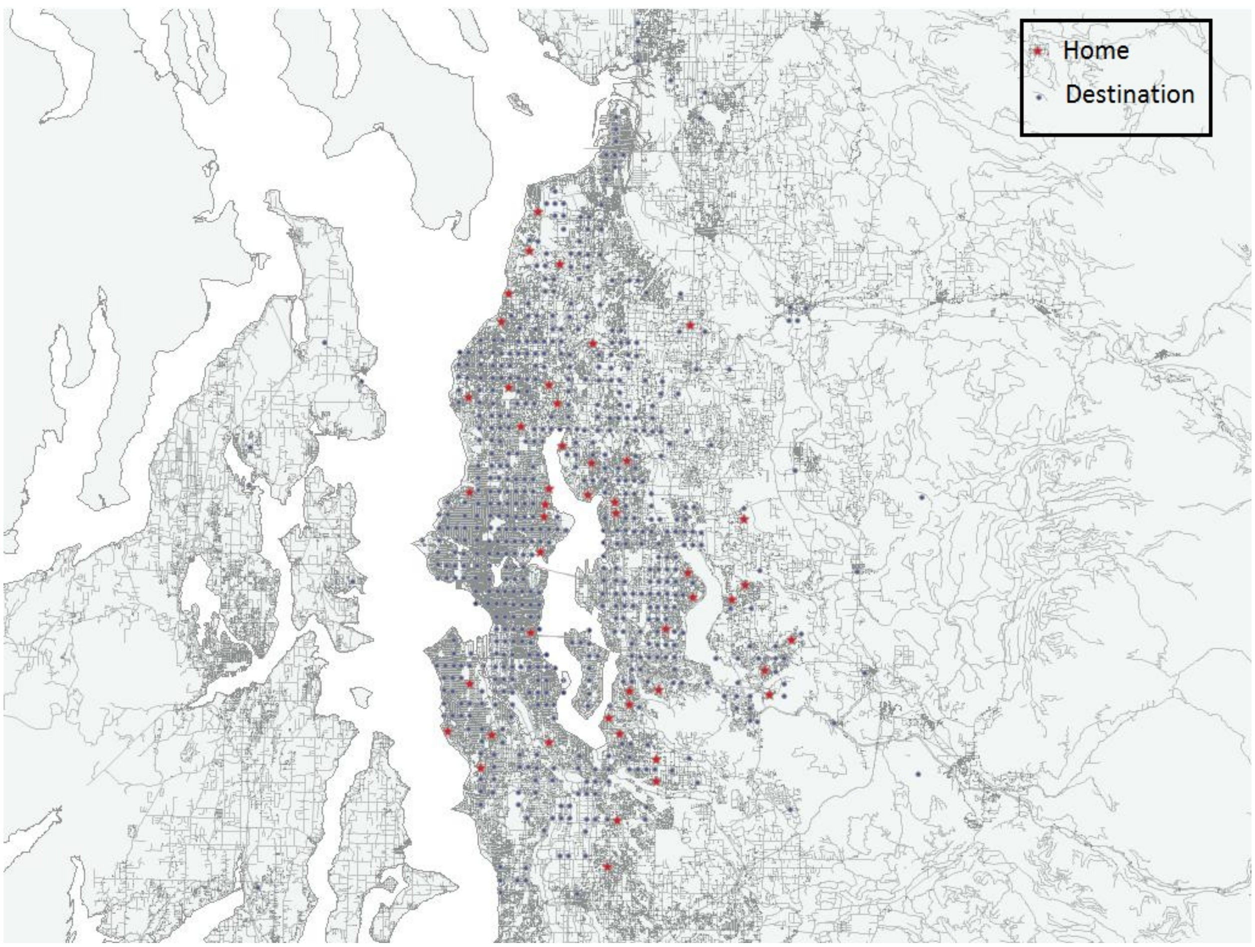

Figure 1 The greater Seattle metropolitan area map.

ANALYSIS APPROACH AND RESULTS

The goal of the analysis is to estimate charging opportunity, given a certain level of public charger coverage. The analysis is based on travel activity data collected from participant conventional gasoline vehicles. We assume that the drivers' travel pattern will not change when switching to PEV technologies. This assumption is made not only for simplicity but also for its policy relevance. First, PEV drivers may adapt their travel behavior to the limited range of BEVs and long charging time, but there is no consensus now regarding how they are going to adapt. Assuming no behavior adaptation provides an objective reference point and facilitates scenario comparison and policy discussion. Second, this assumption is particularly relevant under today's context of bringing PEVs to the mass market. Compared with early adopters, Consumers in the mass market are more sensitive to inconvenience cost associated with travel behavior adaptation. Thus it makes sense to understand their travel patterns and meet their charging needs without forcing behavior adaption in order to reduce total ownership cost of PEVs.

Charging opportunity can be regarded as the probability of encountering public chargers at trip destinations. It reflects the degree of overlap between the charging network and a driver's activity space, i.e., all trip destinations excluding home and workplaces. In theory, charger placement can be determined using one of the optimization models reviewed in Introduction Section. As the focus of this paper is on charging opportunity estimation, we use a heuristic method to quickly determine charger placement. Define public trips of a driver as the set of trips not ending at his/her home or workplace. The grid cells in the network are ranked by the number of public trips that end in the grid. Public chargers will be placed in top *k%* of grids if the desired coverage level is *k*%.

We consider two ways of estimating charging opportunity, stop-based approach and daily trip chain-based approach. We will present the details of the two approaches and relevant results in the following sections.

Stop-Based Analysis

The stop-based approach looks at all the stops that a driver or a set of drivers make in public places with a dwell time longer than half an hour. A stop is said to be covered if it is within a grid cell installed with public chargers. Charging opportunity is estimated as the ratio of the number of covered stops and total number of stops in the dataset. Figure 2 plots estimated charging opportunity as a function of charger coverage level, i.e., the percentage of grid cells installed with public chargers. An easy way to obtain a plot like Figure 1and Figure 2 is first to count the number of public trips end in each grid cell and then rank the cells by the number of ending trips. If top 1% of cells are installed with public chargers, all public trips ending at these cells are covered. Charging opportunity is just the ratio of the number of public trips ending at these cells and total number of public trips.

Figure 2 shows a strong pattern of stops concentrating at a few popular places. If only top 1% of most popular places are installed with public chargers, on average, drivers will be able to access public charging at 20% of all their stops; If 20% of most popular places are installed with public chargers, drivers will be able to access public charging in 89% of all their stops. Note that Figure 2 reflects average charging opportunity for all drivers. If a driver's frequent stops happen to be within those 80% of grid cells not installed with chargers, his charging opportunity will be low. Charging opportunities among consumers are heterogeneous. We shall come back to this issue later.

Another observation is that the shape of the plot suggests decreasing marginal benefits of installing additional chargers.

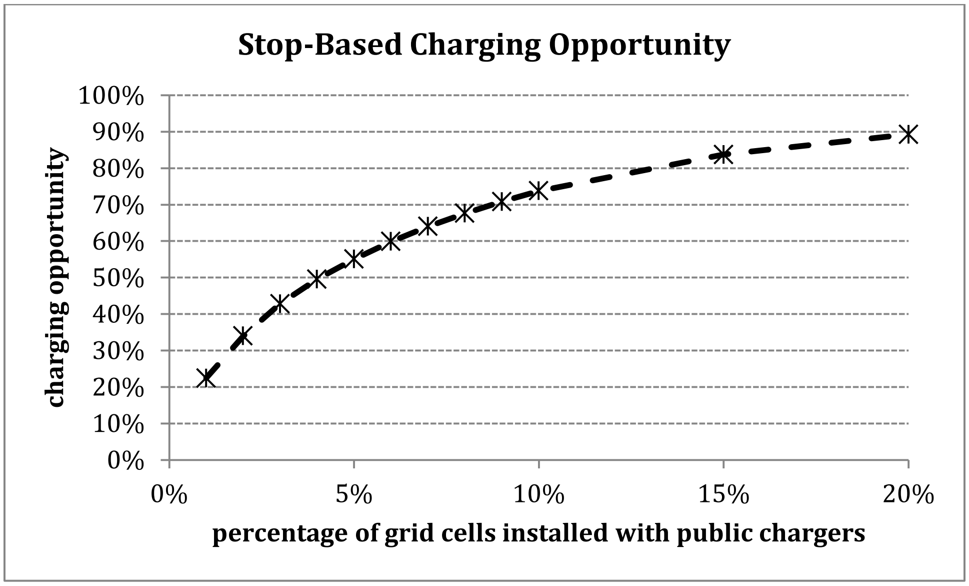

Figure 2 Charging opportunity estimated by the stop-based approach

Daily Trip Chain-Based Analysis

The daily trip chain-based approach aggregates trip-level data to daily trip chains. A travel day is said to be covered if public chargers are placed in at least one stop of the daily trip chain. As in the stop-based approach, we only consider stops with dwell time longer than half an hour. Charging opportunity is then estimated as the ratio of the number of covered travel days and total number of travel days in the dataset. The estimated charging opportunity against charger coverage level is plotted in Figure 3.

Again we observe the strong pattern of trip concentrations. If only top 1% of most popular grid cells are installed with public chargers, on average, drivers will be able to access public charging in 1/3 of their travel days. If 20% of most popular grid cells are installed with chargers, the charging opportunity rises to more than 90%, meaning drivers will be able to access public charging in most of their travel days, though charging may not be needed. Similar to findings from the stop-based approach, the marginal benefits of installing additional chargers decrease.

Compared with stop-based approach, trip chain-based approach considers all stops in one day and as long as one of these stops is installed with public chargers, the travel day is assumed to be covered. Thus daily trip chain-based approach is more lenient in defining charging opportunity and estimated charging opportunity values are undoubtedly higher. But the seemingly high charging opportunity comes with a price. The trip chain-based approach will require some moderate planning from drivers. Drivers need to look ahead at all stops in the day and be clear about the location of public chargers. This requirement is probably not a big burden if PEV drivers are given a little time to experience and learn. By contrast, the stop-based approach has no such a requirement. If the estimated charging opportunity for a driver was 100%, it implies that the driver will be able to charge at all his/her stops.

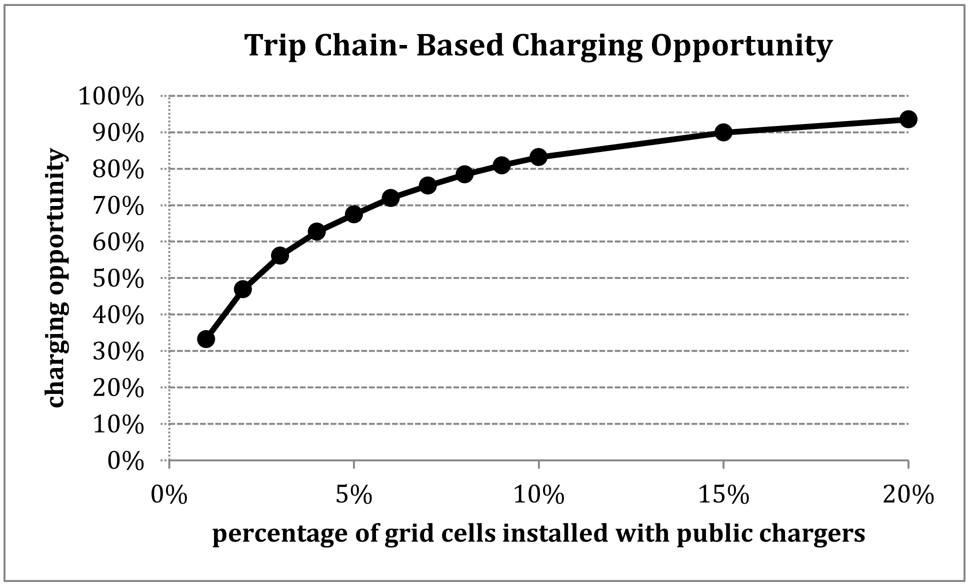

Figure 3 Charging opportunity estimated by the daily trip chain-based approach

Driver Heterogeneity

As we discussed previously, if a driver's frequent stops don't fall in those most popular grid cells with chargers installed, his charging opportunity will be low. In this section, we use the stop-based and daily trip chain-based approach to estimate individual driver's charging opportunity. The approaches are similar, except that for stop-based approach we calculate the ratio of covered stops for an individual driver and the total number of stops made by this driver and for trip chain-based approach we calculate the ratio of covered travel days for this driver and his/her total number of travel days. We estimated charging opportunity for all 445 drivers at different charger coverage level and calculated means and standard deviations.

Figure 4 and figure 5 show charging opportunity heterogeneity among drivers. The central line is the mean of charging opportunity over all drivers and the error bar describes ± one standard deviation. Note that the mean charging opportunities in these two figures are close to the values in Figure 2 and Figure 3 but not exactly the same. We can observe that charging opportunity variation among drivers is large, whose standard deviation is in the range of 15% to 20% at low charger coverage level and decreases when more chargers are installed. The 95% percentile for charging opportunity at 20% charger coverage level is 98.5% and 99.6% for stop-based and trip chain-based approaches respectively; The 5% percentile at 20% charger coverage level is 71.5% and 77.6% for stop-based and trip chain-based approaches respectively.

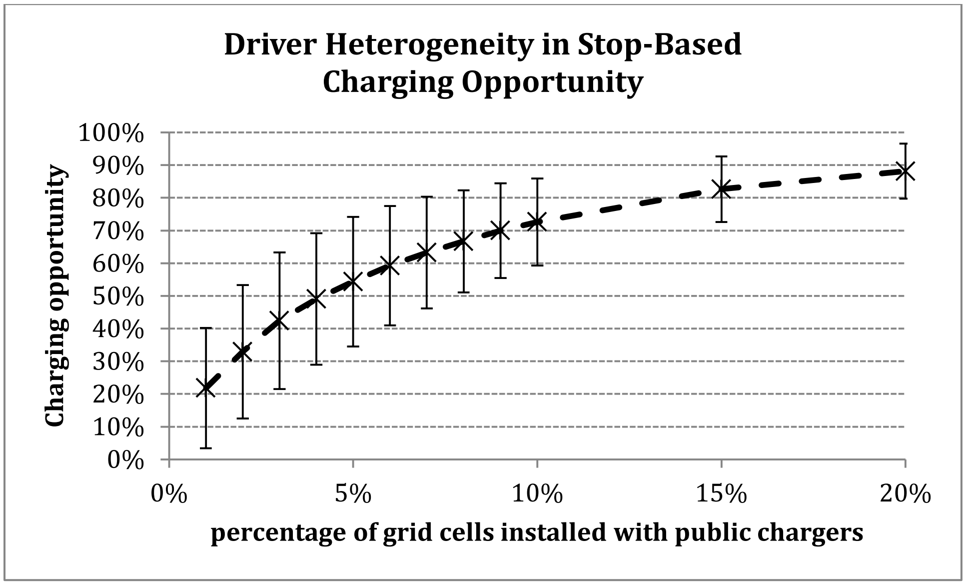

Figure 4 Driver Heterogeneity in Stop-Based Charging Opportunity

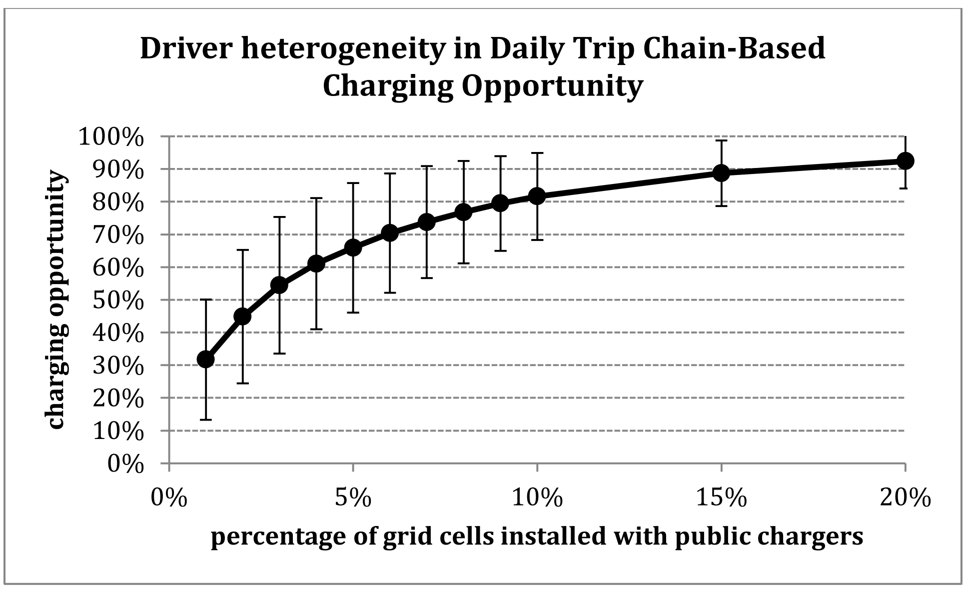

Figure 5 Driver Heterogeneity in Daily Trip Chain-Based Charging Opportunity

Charging Opportunity Weighted by Travel Distance

The focus of this paper is on charging opportunity determined by the spatial distribution of drivers' stops and charging network. Charging opportunity doesn't necessarily reflect charging needs. Supplemental to the paper's main focus, this section analyzes charging opportunity weighted by travel distance, which reflects charging needs to some extent.

The analysis framework is still similar to the one in previous sections, except that 1) each stop is weighted by the travel distance of the associated trip. The charger placement algorithm ranks grid cells by the number of weighted stops that fall within the cell and places chargers in top ranked cells. 2) The stop-based approach calculates charging opportunity as the ratio of covered stops and total number of stop, with each stop weighted by the travel distance of the associated trip. 3) The daily trip chain-based approach calculates charging opportunity as the ratio of covered travel days and total number of travel days, with each travel day weighted by the total daily travel distance. The reasoning is that travel distance indicates battery energy consumption, which may in some degree reflect the needs of recharging.

Figure 6 shows similar trend as Figure 2 and Figure 3 but with lower charging opportunity values. This makes sense because unweighted approach favors most popular destinations, such as shopping mall or restaurants, and installation of chargers in these places will be efficient in providing charging opportunities. By contrast, travel distance weighted approach factors in charging needs and put more weight in places which are less popular but may be essential to meeting the charging needs of some drivers.

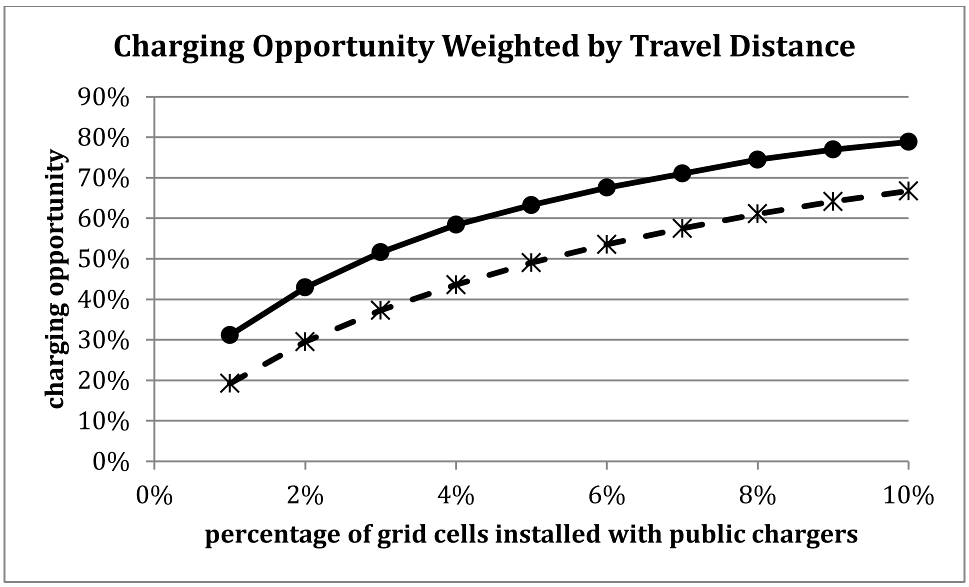

Figure 6 Charging Opportunity Weighted by Travel Distance

CONCLUSIONS AND DISCUSSIONS

Using GPS-based travel survey data, this paper estimates the relationship between charging opportunity and public charger deployment level. Understanding this relationship is of important interests to the PEV industry and government in determining appropriate charging infrastructure deployment level and estimating the impact of public charging on market adoption of PEVs. These issues are especially important under the context of expanding PEV market from early adopters to the mass market, which might be more sensitive to the lack of public charging.

The developed analysis approaches consider the geographical overlap between charging network and drivers' travel activity space and estimate charging opportunity as the probability of being able to access public charging at one of the stops or at one travel day.

Findings from the analysis are particularly encouraging. Drivers' stops concentrate on a few popular places. If only top 1% of most popular places are installed with public chargers, on average, drivers will be able to access public charging in 20% of all their stops and 1/3 of their travel days;   If 20% of most popular places are installed with chargers, drivers will be able to access public charging at 89% of all their stops and 94% of their travel days. These findings are good news to charger providers implying charging network can be efficiently designed by concentrating at a few popular places while still providing a high level of charging opportunity. On the other hand, results also show charging opportunity among drivers is heterogeneous: the standard deviation of charging opportunity is in the range of 15% -20% when the charger coverage level is low and decreases to below 10% when the charger coverage level reaches beyond 15%.

Charger coverage level is represented in this paper by the percentage of public parking places installed with public chargers. While this representation facilitates the analysis in this paper, it does not provide information on number of chargers at each site, nor does the paper intend to decide the type of chargers, e.g., AC level I, AC level II or DC fast charging. Additional work is needed if total investment cost is of interest. Another future work is to analyze travel survey data from another city if it is available in order to validate whether the findings are robust to regional variations. Finally, in view of charging opportunity heterogeneity among drivers, equity issues should also be considered when planning public charging infrastructure.

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