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Spatial Equity Analysis of DC Fast Charging Infrastructure in Urban and Rural Areas of California

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Executive Summary

The adoption of electric vehicles (EVs) cannot be separated from the deployment of public charging infrastructure. In particular, DC fast charging (DCFC) near residential locations is expected to provide regular charging for EV owners who miss charging or cannot charge at home and facilitate long-distance driving, especially in rural areas. This study estimates spatial accessibility to estimate the spatial equity of DC fast charging between urban and rural areas in California. First, we employ a two-step floating catchement area (2SFCA) method to measure the spatial accessibility of DC fast charging in California. We then use the Lorenz curves and Gini coefficients based on measured accessibility to compare spatial equity (or inequality) between urban and rural areas.

Some key findings are as follows. First, many rural areas in California cannot access DC fast charging within 15 minutes by driving. Second, while urban centers do not have great accessibility to DC fast charging, we observe great accessibility near national highway lines crossing suburban areas. Third, increases in home-based charging capabilities lead to improved spatial accessibility. Lastly, we observe high inequality of spatial accessibility of DC fast charging in both urban and rural areas based on the Lorenz curves and Gini coefficients. In particular, rural areas are shown significant uneven spatial distribution of DC fast charging.

Keywords: Spatial equity, Electric Vehicles (EVs), DC fast charging, Two-step floating catchment area (2SFCA), Measuring inequality

1 Introduction

There are still several barriers to the penetration of electric vehicles (EVs) into a conventional internal combustion engine vehicles (ICEVs) market, such as limited public charging infrastructure, driving range, and charging time (Csonka and Csiszár, 2017; Shi et al., 2021; Iravani, 2022; Park et al., 2022). For instance, although many current EV owners conduct charging at home (Hardman et al., 2022; Iravani, 2022), not every owner can access home-based charging so they need to rely on public EV charging infrastructure. Therefore, the adoption of EVs cannot be separated from the deployment of public EV charging infrastructure which can be a primary source of charging (Gann et al., 2018; Shi et al., 2021; Li et al., 2022).

Not all public EV charging stations are the same because they have different chargers available and charging power levels, such as level 1, level 2, and DC fast charging (DCFC) (Falchetta and Noussan, 2021; Carlton and Sultana, 2022). In terms of power levels, DC fast charging is the most potent level of charge for EVs, which can fill 80 percent of batteries in around 40 minutes. The speed of public charging is important because how long it takes to charge an EV can significantly influence an EV owner's daily routine (Csonka and Csiszár, 2017). Gnann et al. (2018) argue that long charging time serves as an obstacle to EV adoption, so research and policy interests in public charging infrastructure should focus more on fast charging. Moreover, because of its short charging time, DC fast charging is also expected to substantially facilitate long-distance driving throughout the statewide. In this context, the deployment of DC fast charging near residential locations is expected to satisfy current EV owners who miss charging at home and attract more potential EV owners who cannot charge at home, as well as support long-distance travel demand. Therefore, well-planned DC fast charging networks than Levels 1 and 2 can overcome the barriers to the wider adoption of EVs. However, there are not many empirical studies investigating the spatial distribution of DC fast charging with a focus on urban and rural areas, especially in terms of spatial equity.

This study aims to explore spatial accessibility to estimate the spatial equity of DC fast charging (DCFC) between urban and rural areas in California. Spatial equity does not mean that public charging stations should be uniformly distributed because the opportunity to access public charging varies across locations. Therefore, we utilize spatial accessibility to measure the spatial equity of DC fast charging. For instance, low spatial accessibility indicates the spatial mismatch between supply and demand (Park et al., 2022), which implies spatial inequality (or an unsafe charging network for EV driving) in this study. As many existing studies have argued, spatial accessibility has a vital role in decision-making processes for the spatial equity of public services because it provides policymakers with where additional supply should be needed (Lu and Wang, 2003; Merlin and Hu, 2017; Chen et al., 2020). Therefore, our empirical results will contribute to the policy relevant to building safe EV charging networks by determining the need for potential supplements of DC fast charging. In this study, spatial accessibility of DC fast charging is measured by spatial interactions between where DC fast charging stations locate (supply) and where EV owners reside (demand), along with the travel time between them.

This study utilizes detailed data of EV charging station locations in California from the Alternative Fuels Data Center (AFDC) and vehicle registration data in 2020 from the Department of Motor Vehicles (DMV) in California. To understand spatial equity (or inequality) in the opportunities to access DC fast charging infrastructure, we first employ a two-step floating catchment area (2SFCA) method to measure the spatial accessibility of DC fast charging in California. The important meaning of this study is to find spatial equity (or inequality) by combining the supply side of DC fast charging with the demand side of EVs using the 2SFCA method. We then use the Lorenz curves and Gini coefficients based on measured accessibility to compare spatial equity (or inequality) of DC fast charging between urban and rural areas.

2 Data and Method

To measure spatial accessibility, we need data for supply (DC fast charging), demand (EVs), and mobility (travel time) to use input variables. For the supply side, we utilize the detailed data of public EV charging station locations in California from the Alternative Fuels Data Center (AFDC) to measure the number of DC fast chargers. As mentioned, public EV charging stations have different chargers available and charging power levels, such as level 1, level 2, and DC fast charging. In this study, we focus only on DC fast charging because it is expected to substantially increase to provide regular charging for EV owners who miss charging or cannot charge at home and to facilitate long-distance driving, especially in rural areas. For the demand side, we utilize vehicle registration data in 2020 from the Department of Motor Vehicles (DMV) in California to measure the number of EVs in each census tract.

Figure 1 shows the spatial distribution of the supply and demand variables; that is, there are 1,711 DC fast charging stations and 8,473 DC fast chargers, and 333,205 Battery Electric Vehicles used in this study.

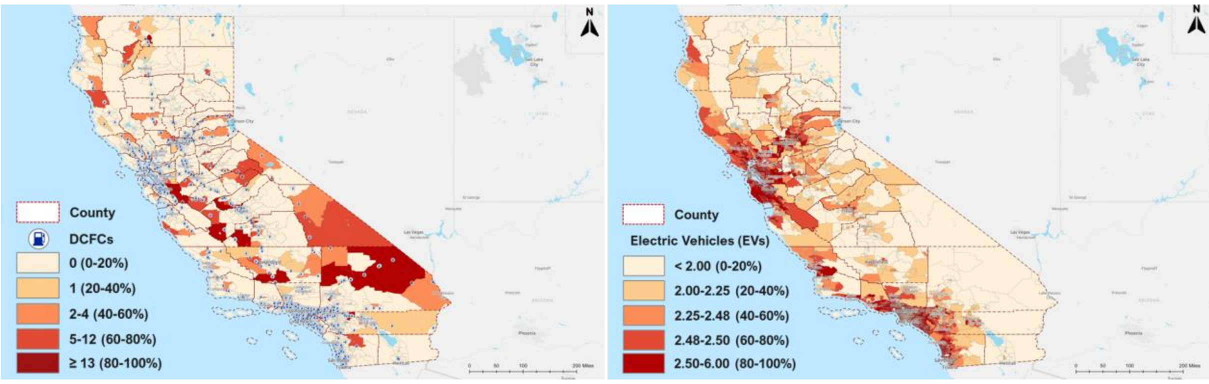

Figure 1. Spatial Distribution of DC fast charging (left) and EVs (right)

Accessibility refers to the relative ease with which the location of public services can be reached from a given area (Lu and Wang, 2003). Accessibility has been used as a key indicator of spatial efficiency and equity in an urban spatial structure to support planning policy toward sustainable cities (Kelobonye et al., 2020). Several methods have been developed and improved to measure spatial accessibility, and the cumulative opportunities measure is widely used in urban and transportation planning (Lu and Wang, 2003; Kelobonye et al., 2020; Park et al., 2022). In this study, we employ a two-step floating catchment area (2SFCA) method to measure spatial accessibility of DC fast charging throughout the statewide.

The floating catchment area (FCA) method measures the service area of public services by a threshold travel time or distance (Lu and Wang, 2003; Park et al., 2022). Since the underlying assumption that services are fully available to residents within a catchment area is obviously faulty, Radke and Mu (2000) developed the decomposition method, a two-step floating catchment area (2SFCA). The 2SFCA method is linked to the tradition of FCA method and calculated as follows:

Step 1: For each DC fast charging location j, search all EV location (k) that are within a threshold travel time (d_0) from location j (i.e., catchment area j), and compute DC fast charging to EVs ratio R_j within the catchment areas:

$$R_j = \frac{S_j}{\sum_{k \in \{d_{kj} \le d_0\}} P_k}$$

where P_k is the EVs of track k which centroid falls within the catchment (that is $d_{kj} \le d_0$), S_j is the number of DC fast charging at location j, and d_{kj} is travel time between k and j.

Step 2: for each EV location i, search all DC fast charging location (j) that are within the threshold travel time (d_0) from location i (i.e., catchment area i), and sum up the DC fast charging to EVs ratio R_j at these locations:

$$A_i^F = \sum_{j \in \{d_{ij \le d_0}\}} R_j = \sum_{j \in \{d_{ij \le d_0}\}} \left(\frac{S_j}{\sum_{k \in \{d_{kj \le d_0}\}} P_k} \right)$$

where A_i^F represents the accessibility at EV location i based on the two-step floating catchment area (2SFCA) method. A larger value of A_i^F means a better accessibility at a location than other locations.

Figure 2 shows an example to illustrate the 2SFCA method, assuming a threshold travel time of 30 minutes (10-mile radius).

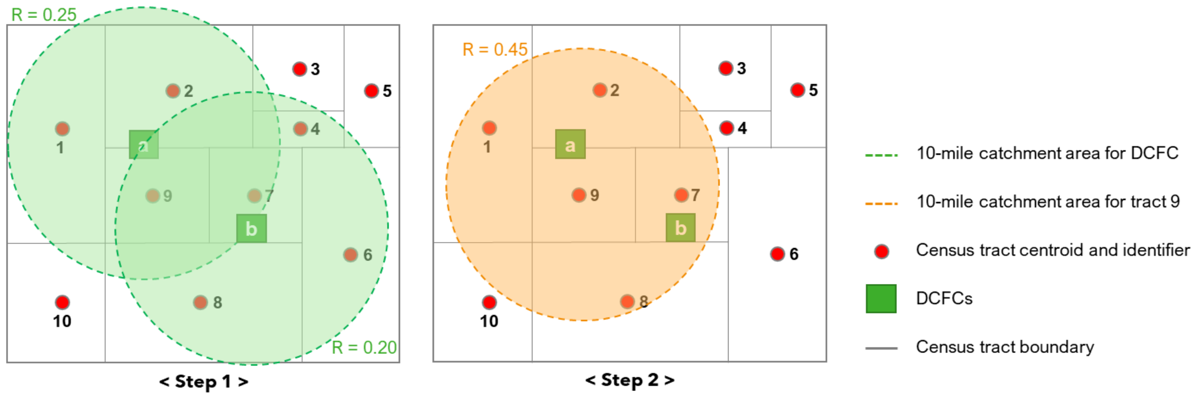

Figure 2. Two-step floating catchment area (2SFCA) method

For instance, as can be seen in Figure 2 (Step 1), if there is an DC fast charging *a* and four EVs within the catchment area (i.e., 1, 2, 7 and 9), then DC fast charging to EVs ratio R_j for *a* is 0.25. Similarly, DC fast charging to EVs ratio R_j for *b* is 0.20. As shown in Figure 2 (Step 2), EVs at 9 are located in an area overlapped by catchment areas *a* and *b*, and have access to both *a* and *b*. Therefore, accessibility to charging for EVs at location 9 is 0.45.

As with any methodology, the 2SFCA method is not without limitations. One of the limitations is to utilize the circular-shaped buffers as a threshold travel time or distance. Since circular-shaped buffers are likely to be inaccurate in areas with natural and built features, such as rivers, cliffs, railways, and poor street connectivity (Oliver et al., 2007), we utilize a road network buffers to define a catchment area using 15-minute driving time (Figure 3). As shown in Figure 3, using network buffers has different numbers of DC fast charging and EVs (tract centroids) as compared to those using circular-shaped buffers.

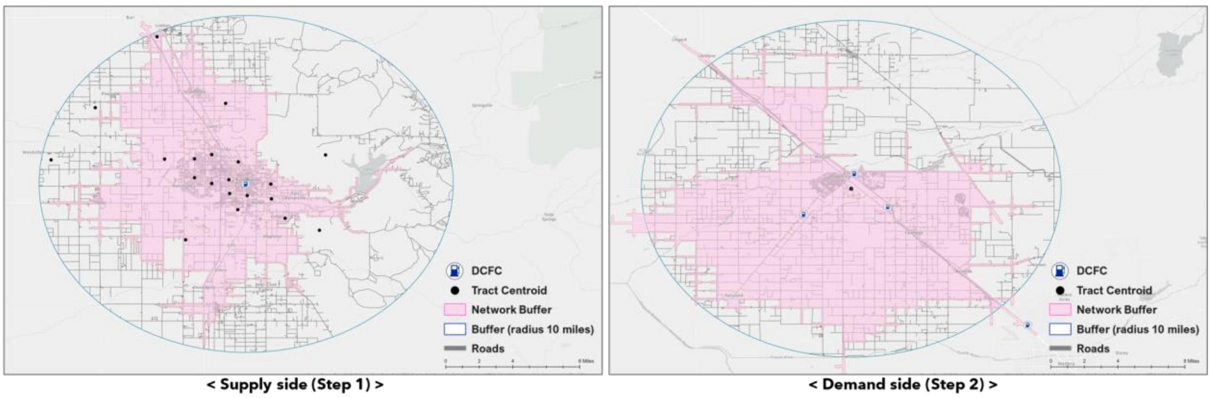

Figure 3. Examples of road network buffers

Based on measured spatial accessibility, we use the Lorenz curves and Gini coefficients to compare spatial equity (or inequality) of DC fast charging between urban and rural areas. In economics, the Lorenz curve is a graphical representation of the cumulative distribution function of wealth (or income) across the population used in the analysis of economic inequality and redistribution (Jang et al., 2017). The Lorenz curve is a visual representation of equality, and the Gini coefficient is a simple mathematical metric that indicates the overall degree of inequality.

The Gini coefficient has a value between 0 and 1. Zero represents perfect equality, while 1 denotes perfect inequality. The mathematical calculation of the Gini coefficient can be approximated using the following equation:

$$G = 1 - \sum_{k=1}^{n} (X_k - X_{k-1})(Y_k + Y_{k-1})$$

where G represents the Gini coefficient, X indicates cumulative proportion of the accessibility for $k = 0 \ldots n$, with $X_0 = 0$, $X_n = 1$, and Y indicates cumulative proportion of census tracts for $k = 0 \ldots n$, with $Y_0 = 0$, $Y_n = 1$.

3 Results and Discussion

To understand spatial equity (or inequality) in the opportunities to access DC fast charging infrastructure, we measure spatial accessibility using a two-step floating catchment area (2SFCA) method. As mentioned earlier, most EV owenrs conduct charging at home (Hardman et al., 2021; Iravani, 2022). According to the U.S. Department of Energy, 80 percent of EV charging happens at home. Therefore, we assume 80 percent of home charging capabilities as a fundamental input value, which means that 80 percent of EV charging is covered by home-based charging, and 20 percent requires DC fast charging infrastructure. In other words, 20 percent of EVs in each census tract are used as the demand for DC fast charging in the 2SFCA method.

Figure 4 presents the spatial accessibility of public EV charging in California.

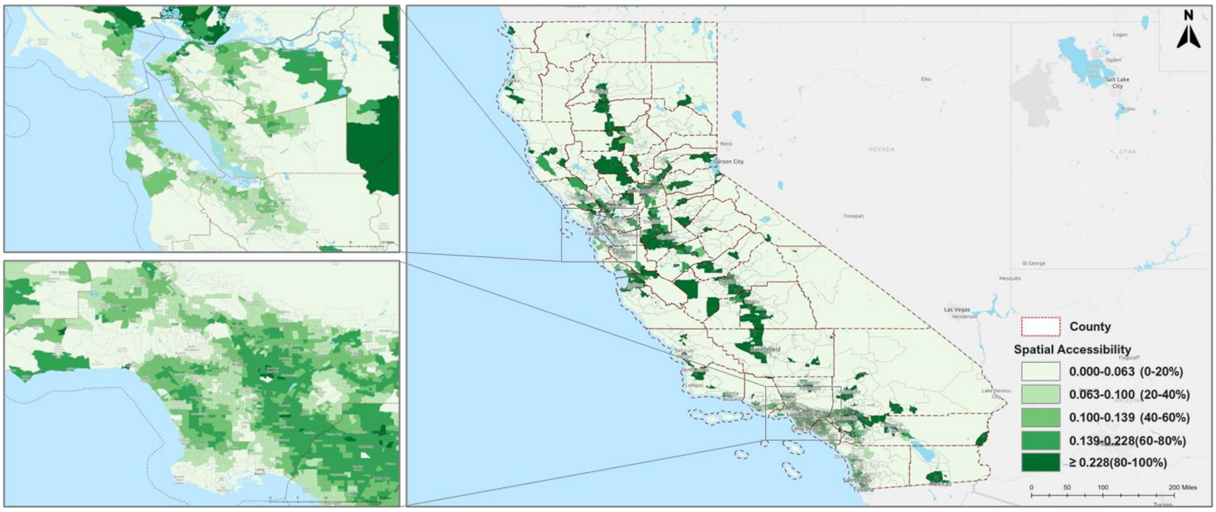

Figure 4. Measured spatial accessibility (home-based charging 80%)

As can be seen in Figure 4, many rural areas cannot access DC fast charging within 15 minutes by driving. This means that EV owners in rural areas may not be satisfied with public charging infrastructure because they cannot access public charging or need much time to charge when they miss charging or cannot charge at home. In addition, since DC fast charging is also expected to facilitate long-distance driving throughout the statewide, low spatial accessibility may indicate an unsafety net for EV driving.

When we look at the San Francisco and Los Angeles, urban centers do not have great accessibility to DC fast charging. On the contrary, we observe great accessibility near national highway lines crossing suburban areas.

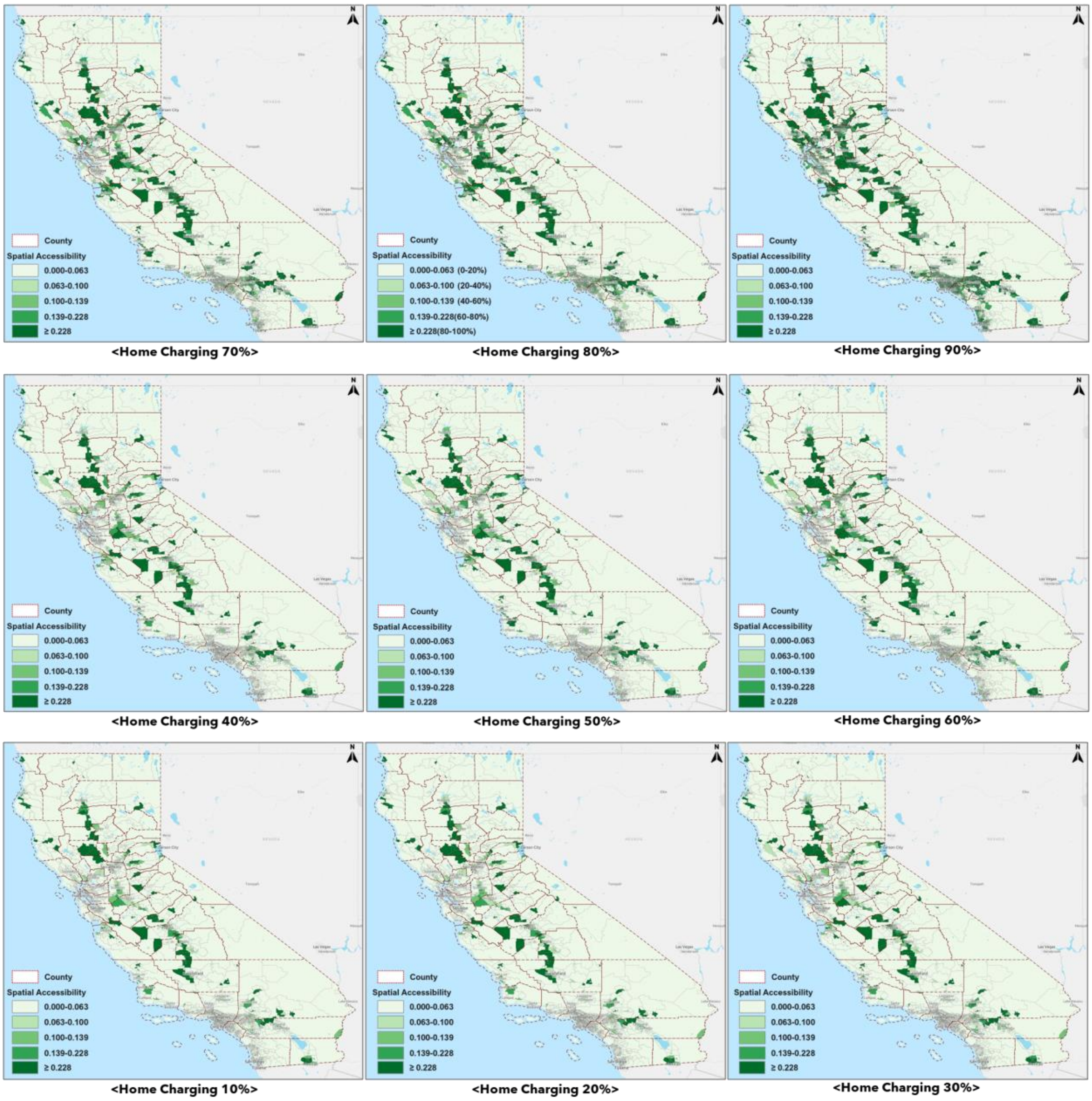

Figure 5. Measured spatial accessibility (using different home-based charging capabilities)

As mentioned, different home-based charging capabilities have different demands for public EV charging. Figure 5 shows the different spatial accessibility when using different home-based charging capabilities of 10 to 90 percent. We observe an increase in home charging capabilities lead to improved spatial accessibility.

We then use the Lorenz curves and Gini coefficients based on measured spatial accessibility to compare spatial equity of DC fast charging between urban and rural areas. In general, a Gini coefficient under 0.20 indicates low inequality, whereas a coefficient above 0.50 is considered high inequality (Jang et al., 2017). Figure 6 shows the Lorenz curves and Gini coefficients for accessibility between urban and rural areas.

As shown in Figure 6, Gini coefficients are 0.61 in urban and 0.96 in rural areas, which indicates high inequality of accessibility. In particular, the Lorenz line in rural area denotes significant uneven distribution of accessibility to DC fast charging.

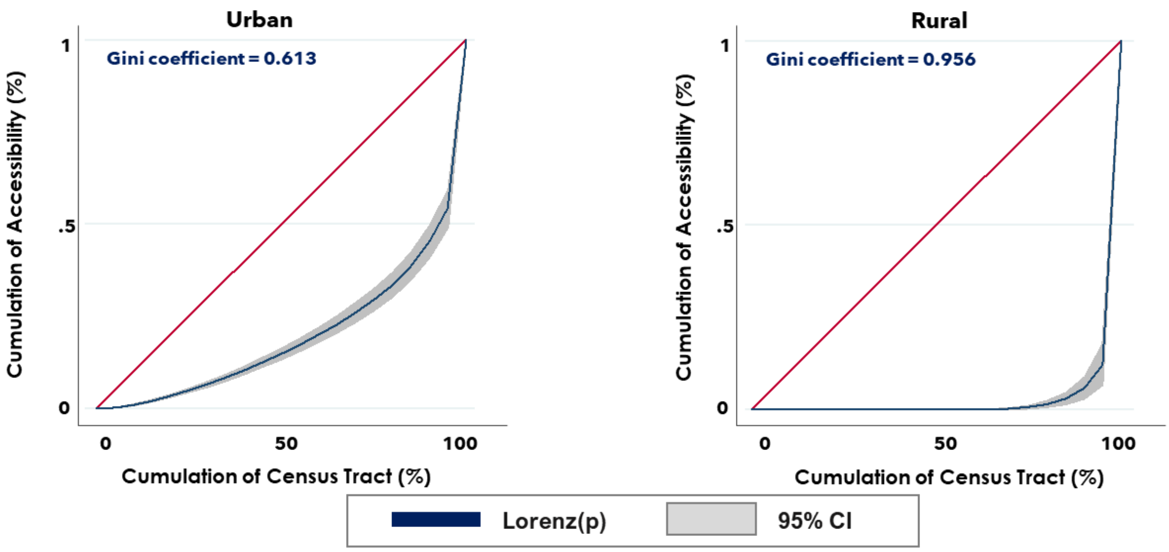

Figure 6. The Lorenz curves and Gini coefficients for accessibility between urban and rural areas

4 Conclusions

As individuals' EV adoption accelerates, demand for public charging continues to increase. In particular, DC fast charging is expected to substantially increase to provide regular charging for EV owners who miss charging or cannot charge at home and to facilitate long-distance driving, especially in rural areas. Accessibility can be a key indicator of spatial equity, which reveals basic information about the spatial distribution of public services (Kelobonye et al., 2020). This study estimates spatial equity (or inequality) in the opportunities to access DC fast charging infrastructure using spatial accessibility. Good accessibility to DC fast charging plays an essential role in promoting the use of EVs, which can support sustainable cities because of the environmental and financial benefits of EVs. Using a two-step floating catchment area (2SFCA) method, we first measured the spatial accessibility of DC fast charging. We then used the Lorenz curves and Gini coefficients based on measured accessibility to compare spatial equity (or inequality) between urban and rural areas in California.

The empirical results of spatial accessibility show that many rural areas cannot access DC fast charging within 15 minutes by driving. This means that EV owners in rural areas may not be satisfied with current public charging infrastructure, which partially implies the reason for the lower EV adoption rate of residents in rural areas. Deploying public EV charging infrastructure is still in the early stages and needs lots of additional supplies, but our empirical results should be taken carefully. Lucas et al. (2016) argues that people experiencing social exclusion have little willingness to pay for the adoption of new products. This implies that residents in rural areas may not have the opportunity to benefit from an electric vehicle as much as those in urban areas, and the gaps may increase in the future, which can be barriers to the wider adtopion of EVs. Therefore, this study suggests that deploying DC fast charging infrastructure in rural areas should be considered with respect to spatial equity.

We observe high inequality of spatial accessibility of DC fast charging in both urban and rural areas based on the Lorenz curves and Gini coefficients. Although our study did not consider Level 1 and 2 chargers, it is evident that public DC fast charging is not sufficient to spatially cover current EVs. Moreover, rural areas are shown the significantly uneven spatial distribution of DC fast charging. Since DC fast charging is also expected to facilitate long-distance driving throughout the statewide, it may imply an unsafe charging network for EV driving. Therefore, the results provide evidence suggesting that additional public DC fast charging needs to be installed throughout California.

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Presenter Biography

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Kihyun is currently a postdoctoral researcher in the Electric Vehicle (EV) Research Center at UC Davis Institute of Transporation Studies (ITS). His research extends to understanding EV users' travel behavior and charging needs, predicting charging locations, connecting with existing transportation systems, assessing spatial equity, and more.

Before coming to UC Davis, he holds a Ph.D. in City and Regional Planning from the Ohio State University, specializing in land use and transportation planning. He received his master's degree in Urban Planning and bachelor's degree in Economics from Chung-Ang University in South Korea.