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Understanding the Opportunity-centric Accessibility for Public Charging Infrastructure: A Case Study of 10 Metro Areas in the U.S.

--Manuscript Draft--

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ABSTRACT

In this study, we raise the concern that traditional metrics evaluating the performances of civil infrastructure may fail to aptly address the distinct challenges emerging from the deployment of Public Charging Stations (PCSs). We believe there is a significant interrelation between individuals' charging behaviors and their day-to-day activities, and present refined conceptions of accessibility by incorporating an additional facet - the availability of opportunities proximate to PCSs. We further distinguish between two distinct scenarios: one where charging access is secondary to opportunity access and another where opportunity access is secondary to charging access. To validate our approach, we conduct a comprehensive comparison between traditional accessibility measures and opportunity-centric measures and further perform counterfactual analyses under varying PCS deployment strategies, utilizing data from over 15,000 PCSs and more than 3 million points of interest across ten major metropolitan regions in the U.S. Our analysis of accessibility-centric metrics reveals substantial inequalities in PCS accessibility across all metropolitan areas, where the PCS accessibility in the top 1% of census block groups (CBGs) can be 2.8 times better than in the bottom 50%. We also statistically confirm that an increase in PCSs will further amplify these inequalities. In terms of opportunity-based accessibility, we once again confirm a universal access disparity across all metropolitan areas. Inequalities stemming from the conventional accessibility definition are exacerbated when the availability of PCSs around major activity locations is considered. Our counterfactual analysis suggests that an equitable deployment based on the conventional accessibility definition may prove to be the least equitable when opportunities are considered. The opportunity-centric performance of PCS deployments are largely affected by pre-existing unequal distribution of opportunities in our cities. Our results underscore the complexity of locating charging stations by incorporating an opportunity-based perspective, and they provide significant insights that could inform policy-making and guide the design of nationwide charging networks for long-term sustainability.

Keywords: public charging station, accessibility, opportunity-based accessibility, equity, electric vehicles

INTRODUCTION

Reflecting a significant shift towards electrified transportation, global Electric Vehicle (EV) sales have surged tenfold, from 1 million in 2017 to 10 million in 2022 (*1*). Accompanying the growth of EVs, the rapid development of public charging stations (PCSs) plays an essential role in supporting the transition. In the U.S., motivated by the pursuit of achieving net zero emissions by 2050, states across the nation, in conjunction with the federal government, are rapidly advancing toward the implementation of EV charging stations to reach the target of 500,000 EV chargers by 2030 (*2, 3*). Beyond its obvious necessity for those without home charging capabilities, the public charging infrastructure is equally vital for those with home charging, providing essential top-ups and offering a safety net for longer journeys. Recent studies suggest that by 2030, approximately 53% of EV owners will have access to home charging (*4*), leaving a significant portion reliant solely on public infrastructure, and PCSs are projected to serve at least 30% of all charging needs. Consequently, developing an extensive, accessible, and efficient public charging network is integral to sustaining and further accelerating the global EV boom. Despite the strong momentum in EV penetration and PCS expansion, one essential research question remains open: How do we evaluate the effectiveness and efficiency of our charging station deployment?

Providing an answer to the above question is critical, as it will guide policy design that can lead to long-term community benefits. Among various metrics that could describe the multifaceted performances of infrastructure, accessibility remains a central factor. It quantifies how effectively an infrastructure plan serves the community, based on its definition "*the ease and convenience of access to spatially distributed opportunities with a choice of travel*" (*5*). Initial methods of measurement, such as distance or time to the nearest service, population-to-provider ratios, and cumulative opportunity measures, offer ease of understanding and interpretation. However, they tend to oversimplify the relationship between supply and demand regarding accessibility and fail to account for the effects of competition for the available opportunities (*6–8*). To counter these shortcomings, the class of gravity models was developed, taking into account factors like proximity, availability, and competition. While these models marked an improvement, they have attracted criticism for their complexity, interpretive challenges, and an over-reliance on the selection or empirical determination of the distance-decay function (*9, 10*). Besides these known shortcomings, we further argue that the current definition of accessibility is too generic and lacks specific adaption to fully capture the distinct attributes of charging events. To understand this, we must acknowledge the fact that, unlikely conventional travel activities, charging does not necessarily constitute a primary travel decision and, in many cases, are secondary to daily activities. To this end, we claim that the evaluation of accessibility should not only cover the physical hurdle in reaching a particular station but also embed the opportunity of engaging in activities around the charging locations.

This paper initiates an exploration into extending the definition of accessibility to PCS. It introduces new dimensions that capture the unique characteristics of charging events and provides a quantitative and qualitative assessment of the performance of the existing charging infrastructure in ten major U.S. metropolitan areas. We will explore how traditional accessibility measures present PCS performance. Moreover, our analysis will go further by connecting accessibility with increased opportunity access. We will deeply investigate two novel measures: one focusing on the convenience of charging a vehicle while simultaneously engaging in other activities - the primary emphasis here being on the activities themselves with a proximal PCS serving as a secondary benefit; the other scenario underscores the direct access to PCSs, with the supplemental advantage of conducting other activities during the charging process. Our analyses leverage a dataset of over 3 million points of interest linked to more than 15,000 PCSs across 10 metropolitan areas in the U.S., aiming to address the following primary research questions:

1. How accurate do traditional distance-based accessibility metrics characterize the performances of the public charging infrastructure?
2. Which additional perspectives related to charging behavior should be considered to guide the evaluation and deployment of charging facilities, and in what ways do traditional methods fail to adequately address these considerations?
3. How can we develop new accessibility metrics inspired by charging behavior for a quantitative evaluation of charging facility deployment performances, and what additional insights do these metrics offer that extend the conventional understanding of accessibility?
4. How can we employ counterfactual analyses for a quantitative evaluation of the U.S. deployment of charging stations, leveraging both the existing and newly proposed metrics?

By examining these research questions, our study aims to highlight the complexity in guiding and evaluating the deployment of charging stations, provide valuable insights into the factors shaping the EV charging landscape, guide the development of effective policies, and facilitate the future growth of charging infrastructure in diverse urban contexts.

BACKGROUND

Public Charging Stations in Metropolitan Areas

EV charging infrastructure plays a crucial role in the U.S.'s ambitious efforts to combat climate change, mainly by removing a main long-term challenge and creating a positive loop that enforces EV adoption (*11*). At the same time, while home location chargers are currently the main used and proffered charging venue, where more than 50% of charging sessions occur, followed by work location charging, public chargers remain indispensable for EV users who lack access to home charging or face limitations in this regard (*12*). This is particularly the case for residents in densely populated urban areas, where off-street parking and private garages are less accessible and the installation cost of chargers in multi-unit dwellings (MUDs) is prohibitively high (*13, 14*). Thereby, given the crucial role of public charging stations (PCSs) in facilitating EV adoption, it becomes imperative that failure to ensure an equitable deployment may perpetuate existing socioeconomic disparities and hinder the widespread realization of EVs' benefits.

Deployment of Public Charging Stations Performance

Recent studies have identified a strong correlation between the placement of public EV charger installations and the ownership of electric vehicles (*15, 16*). However, while rational for the early stages of charging infrastructure development, such an approach can also lead to or amplify the existing socioeconomic inequities among population groups. Consequently, as EVs become more affordable and offer longer driving ranges, the layout of public charging infrastructure can have significant and lasting implications for determining which segments of the population can benefit from the advantages of EV adoption (*17*). In this regard, several studies have investigated the socioeconomic equity concerns surrounding the distribution of charging stations within communities (*15, 18–22*). For instance, a study conducted in California examined the presence of charging stations in different census block groups and revealed disparities in public charging access, particularly in lower-income block groups (*15*). The research also highlighted that areas with a higher concentration of multi-unit housing, where residential charger access is less common, experienced more pronounced disparities in public charger availability. Current data also reveals the local benefits associated with offering more charging opportunities to be unequally distributed. For instance, using 14 million housing transactions for almost three decades showed that charging infrastructure can be capitalized into property values where the average price premium for houses with PCSs within 0.5 km compared with houses without proximate PCSs (*22*). Others have highlighted the potential ramifications of inadequate charging infrastructure support among communities, leading to missed environmental and health benefits at both the household and community levels. These include reduced local air pollution, cost savings compared to traditional internal combustion engine vehicles, and advantages of leveraging regional and local power grid ancillary services, including localized voltage support (*23–25*).

Despite the growing evidence of disparities in charging station deployment, there remains a gap in the availability of a robust analytical approach to assess the performance of such deployments. Such an analysis requires consideration of the intricate dynamics involved in achieving an equitable deployment, taking into account the complexities of urban planning and the organization of human activities. This complexity arises in part from the need to consider the spatial arrangement of various locations and their interaction with the unique characteristics of neighborhoods and road networks within the local area and in part due to the users charging behaviors that are closely entwined with their day-to-day activities (*11, 26*). Furthermore, examining the deployment of PCSs requires special attention to the interplay of factors such as installation incentives and policies, user behaviors and the underlying business strategies driving the deployment process, which can vary greatly in different regions.

EV Charging Infrastructure Policies

At the forefront of the investments in the U.S. charging infrastructure is the Bipartisan Infrastructure Law (BIL) funding up to $7.5 billion for 500,000 new publicly accessible charging stations, mainly via the $5 billion National Electric Vehicle Infrastructure (NEVI) formula program (*27, 28*). NEVI sets a baseline for charging infrastructure development to ensure *"providing the traveling public with reliable expectations for their EV charging experience anywhere that NEVI Formula funds, including the Federal-aid highways"* (*29*). In doing so, deployed charging stations by states are mandated to meet specific criteria, including a minimum number of ports, types of connectors, accepted payment methods, and customer support service requirements (*29*). Nonetheless, the program's addressing of equitable charging infrastructure deployment relies on a broader set of suggested tools centered around the geospatial analysis of locating underserved communities (*30–32*). This absence of a standardized process leaves the assessment of the fairness of the deployment layout to individual states, leading to different approaches to identifying the "charging gap areas" (*33–35*). At the same time, states have already acknowledged major risks and challenges in deploying charging infrastructure in areas with a lower rate of EV users due to (1) inadequate EV use rates that may hinder investment returns, leading to (2) chargers to be abandoned beyond the required term of the agreement if utilization is not high enough, and (3) potential challenges related to power supply and communication stability (*36*). When considering the overall picture, the resulting charging is potentially influenced by risk-averse considerations, leading to the placement of charging infrastructure near businesses and activities to increase the likelihood of a returning investment. This can translate into a substantial diverge from achieving an equitable layout over time, further emphasizing the critical need for a uniform and thorough evaluation of the underlying deployment strategies. To date, the policy and guidelines for deploying charging stations significantly rely on historical frameworks that are generically applicable to other types of civil infrastructure while inadequately addressing the unique nuances and complexities associated with electric vehicle charging behavior - a shortcoming that potentially hampers the effectiveness of these initiatives. This imposes a pressing need to develop specific performance metrics for charging infrastructure and conduct comprehensive comparisons to gain a deeper understanding of the multidimensional complexity of developing a nationwide charging network.

DATA

Data Collection and Processing

We use multiple datasets to conduct our analysis. The identification of public charging stations is based on the DOE's Alternative Fuels Data Center (AFDC) as the most comprehensive station locator in the U.S. (*37*). The dataset includes over 54,000 public charging stations and more than 140,000 Electric Vehicle Supply Equipment (EVSE) as of June 2023. Sociodemographic data for the communities are sourced from the 2016-2020 American Community Survey (ACS), providing detailed information on population and income status at the census block group (CBG) level (*38*). To gather information on the location and activity categories of various places, we leverage the SafeGraph Global Points of Interest (POIs) data (*39*). The dataset comprises information on more than 12.5 million unique places spanning across the United States as of the end of 2022. Specifically, along with the geometric coordinates, the dataset includes brand affiliation and two levels of category tags for each place. Using the place tags from the original dataset, we are able to classify the places into the following main categories:

- Stores (e.g., Clothing Stores, Department Stores, Bookstores & News Dealers - brands such as Old Navy, and Barnes & Noble)
- Community and Government (e.g., Civic & Social Organizations, Continuing Care Retirement Communities, Elementary & Secondary Schools, and Religious Organizations - organizations like Rotary Club or KinderCare)
- Services (e.g., Wired & Wireless Telecommunications Carriers, Postal Service - brands such as T-Mobile, and USPS)
- Health (e.g., Offices of Physicians, Offices of Dentists, Outpatient Care Centers - establishments like Health Street, and Western Dental)
- Leisure (e.g., Hotels, Amusement Parks & Arcades, Theaters - venues like Holiday Inn, and Starlight Cinemas)
- Auto (e.g., Automotive Parts/Accessories & Tire Stores, Automobile Dealers - brands like AutoZone, and Enterprise Rent-A-Car)
- Food & Beverage (e.g., Restaurants & Other Eating Places, Drinking Places - brands like Subway, and Starbucks)
- Grocery (e.g., Grocery Stores - brands like Kroger, Whole Foods Market, and Trader Joe's)
- Construction & Real Estate (e.g., Building Material & Supplies Dealers, Lessors of Real Estate - brands like The Home Depot)
- Finance (e.g., Commercial Banking - entities like Western Union)
- Convenience Stores (e.g., Gasoline Stations with Convenience Stores - brands like 7-Eleven,

and Circle K)

Next, the datasets are mapped onto the block group level within the major metro areas by using geometric boundaries from the 2020 TIGER urban shapefiles (*40*). Our definition of metro areas aligns with the U.S. Census delineations of a Metropolitan Statistical Area (MSA) (*41*). For instance, the New York, NY metro area corresponds to New York–Jersey City–Newark, NY–NJ, and the Los Angeles, CA metro area corresponds to Los Angeles–Long Beach–Anaheim, CA. Finally, the road network within the metro areas is generated using OpenStreetMap and later used to capture the travel time between the places, stations and CBGs (*42*).

FIGURE 1: Selected Metro Areas with Number of Public Charging Stations

Selection of Metro Areas

We narrow our analysis of the U.S. charging infrastructure by focusing on major metropolitan areas rather than state or regional levels. This decision is based on two reasons. Firstly, a noticeably higher rate of EV adoption and deployment of EV infrastructure is evident in larger metropolitan areas compared to smaller urban or rural regions. This distinction allows for a more meaningful analysis of accessibility and the interaction between activities and charging facilities located in close proximity to each other. Second, even in CBG resolution, rural areas have larger geographic units with considerably less road network coverage. This can impact the accuracy of our accessibility analysis, as a charging station located on one side of a block group may not be accessible to the other side. Therefore, our analysis focuses on the ten major metro areas in the U.S., which boast an extensive charging infrastructure network and are distributed across different regions. Figure 1 displays the selected metro areas. Among the selected metros (and the nation), the Los Angeles metro area has the largest existing charging infrastructure, comprising 4526 publicly available charging stations and 11869 EVSEs. Portland metro area has the lowest number between the selected metro areas, with 432 PCSs and 1098 EVSEs.

METHOD

We describe several metrics to evaluate the effectiveness of public charging station layouts, incorporating traditional accessibility aspects along with opportunity measures for CBGs. We then proceed to introduce our counterfactual analysis and the alternative installation scenarios.

Metrics

Accessibility Measures

Our metric on the CBGs' accessibility to the public charging stations is based on the gravity model of measuring accessibility, a widely utilized approach in the urban accessibility literature (*43, 44*). In our case, gravity models enable us to quantify the degree of CBGs' accessibility to public charging stations within their catchment area (defined as the nearest 20 stations from their centroid). For brevity, *we will use CBG accessibility to refer to the gravity model-based accessibility measure*, with the mathematical expression below:

$$A_i = \sum_{j \in S} \mathbb{I}_{ij} \times N_j \times e^{-\beta t_{ij}}, \quad \forall i \in Z \tag{1}$$

where A_i represents the accessibility score of a CBG i, $\mathbb{I}_{ij}$ is an indicator variable that takes the value of 1 if station $j \in S$ is within the catchment area (nearest 20 stations) of CBG i, and 0 otherwise. N_j denotes the number of EVSEs available at charging station j, and t_{ij} indicates the travel time on the shortest path between the centroid of CBG i and charging station j in the road network. The impedance factor β influences the rate at which the accessibility score decreases with increasing distance and is set to $\beta = 0.08$ (*44*).

In addition to accessibility from CBG to charging stations, we further define the service coverage of a station j, measured as the summation of CBGs accessibility within the catchment area of station j, as below:

$$C_j = \sum_{i \in Z} A_i = \sum_{i \in Z} \mathbb{I}_{ij} \times N_j \times e^{-\beta t_{ij}}, \quad \forall j \in S \tag{2}$$

which helps to measure the cumulative level of accessibility for surrounding CBGs, where a higher value of C_j indicates that the station j covers a greater proportion of the population.

Opportunity Measure and Opportunity-based Accessibility Measures

The above accessibility measures characterize spatial impedance to and from a charging station but fall short of considering EV users' access to additional opportunities while charging their vehicles. In many cases, users are willing to sacrifice travel time in pursuit of engaging in additional activities around the charging station. This asserts the need to examine the number of points of interest (POIs) nearby a charging station as a proxy for additional activity opportunities.

We begin by first introducing the POI opportunity score of a station j for POI category c, P_j^c, written as:

$$P_j^c = \sum_{k \in K^c} \frac{\mathbb{I}_{kj}}{|K^c|} \tag{3}$$

where K^c is the complete set of POIs in category c, $\mathbb{I}_{kj}$ is an indicator variable and takes the value of 1 if a POI k is associated with (within 200 meters from) the charging station j and 0 otherwise. We note that this measure is scale-invariant by diving the size of the set K^c, so that the measure is comparable across different metro areas despite the differences in the total number of POIs. P_j^c, in this case, provides additional opportunity insights beyond traditional accessibility measures, which will shed light on if certain groups of activities are (disproportionally) concentrated deployed charging stations and allow us to examine the disparities in accessing opportunities across all PCSs.

Based on the POI score, we extend the conventional accessibility measure by concurrently examining the physical impedance to reach a PCS and the opportunity cost when charging at the PCS. Nevertheless, we need to acknowledge the difference between two distinct scenarios: (1) an EV user visiting a place as the primary decision and charging at that location as a derivative activity, and (2) an EV user visiting a charging station as the primary decision and engaging in extra activities as the derivative decision. This gives rise to two distinct opportunity-based accessibility measures as detailed below:

Activity-Induced Charging Accessibility (AICA): This metric corresponds to scenario (1) and measures how PCSs are easily accessible/available when EV users engage in their daily activities from their home locations (the centroid of CBG in our case). For example, EV users can utilize associated charging stations at their workplaces. Mathematically, we express the AICA of a CBG i as:

$$AICA_i^c = \sum_{k \in K_i^c} \sum_{j \in S} \mathbb{I}_{kj} \times N_j \times e^{-\beta t_{ik}} \tag{4}$$

where K_i^c is the set of the nearest 20 POIs in category c to CBG i and $\mathbb{I}_{kj}$ is the indicator variable that takes the value of 1 if a PCS j is within 200 meters of POI k and 0 otherwise. $AICA_i^c$ agglomerates both physical impedance from a CBG i to nearby activity locations $k \in K_i^c$ and the availability of accessing a charging port at PCSs associated with each POI.

Charging Induced Activity Accessibility (CIAA): This metric corresponds to scenario (2) and measures the number of opportunities in category c when EV users from CBG i access nearby PCSs (nearest 20). Mathematically, we express CIAA as:

$$CIAA_i^c = \sum_{j \in S} \sum_{k \in K^c} \mathbb{I}_{ij} \times \mathbb{I}_{kj} \times e^{-\beta t_{ij}} \tag{5}$$

where $CIAA_i^c$ combines the physical impedance from CBG i to the nearest 20 PCSs and accumulates the number of POIs in category c associated with each PCS. As a consequence, this metric considers the scenario when an EV user selects to charge at PCS j and gauges the availability of engaging in additional activities rather than waiting in the vehicle.

Counterfactual Analyses

Merely quantifying the accessibility score, regardless of whether considering opportunities or not, does not paint a complete picture that enables the quality assessment of a PCS deployment plan.

This must be supported by comparing the current deployment plan with feasible alternatives so that both quantitative and qualitative assessments can be made. In this regard, we conduct counterfactual analyses to compare the existing PCS layout in major metro areas with four alternative scenarios representing four different planning philosophies using the above metrics. The four baseline planning philosophies are detailed below:

1. **Uniform**: Under the uniform strategy, current PCSs are reassigned spatially uniformly across the metro area. This approach allowed us to establish a baseline for comparison, providing insights into the distribution of stations when no particular factors other than a uniform spatial coverage were taken into account.
2. **Population-based**: In the population-based strategy, current PCSs are redistributed proportional to the population density of CBGs, with more PCSs in CBGs with higher population density.
3. **Profit-based**: The profit-based strategy involves reassigning existing PCSs based on the combination of median-household income and the population of CBGs. By examining this scenario, we seek to investigate the potential disparities that may arise from prioritizing economically advantaged areas.
4. **Equity-based**: The equity-based strategy reallocates PCSs to make accessibility to PCSs equitable across all CBGs. This approach aims to understand the gains and losses of equity-driven charging station deployment that may arise because of additional opportunity considerations. The equity-based reallocate is achieved by solving the integer linear assignment problem with the objective function being $\text{Max}\,\text{Min}_{i \in Z} A_i$ and is subject to the total number of PCSs in the current plan.

RESULTS

In line with our research questions, we present the results in the following order: First, we analyze the CBGs' accessibility to PCSs and the accessibility of individual PCSs. Next, we examine the distribution of the places around PCSs, shedding light on the role of opportunities around stations and major differences between metro areas. Finally, we explore performances in terms of the proposed opportunity-based accessibility metrics, CIAA and AICA, followed by our counterfactual analysis revealing the performance level of the current deployment layouts.

Accessibility to Public Charging Stations

We first present the results regarding the CBGs' accessibility to PCSs in Figure 2. The figure visualizes the complementary cumulative density function (CCDF) for the distribution of PCS accessibility across ten metro areas in a log-log scale, where each line visualizes the proportion of CBGs, $P(x > A)$, that has an accessibility measure greater than A. As a consequence, the further each line stretches towards the right, the greater the variance of accessibility across all CBGs. We observe a notable difference in the accessibility of CBGs to PCSs both within and between metro areas. For each metro area, we observe that the tail of the accessibility distribution (e.g., top 10 percentile of CBGs accessibility scores) can be well approximated by the power-law distribution, $y \propto x^{-\gamma}$, with γ in the range of 3.29 (LA) to 9.99 (Phoenix) for the ten metro areas and the R-squared values at least 0.98. This signifies that a very small proportion of CBGs have a high accessibility score to PCSs, whereas the majority of the CBGs have poor access to the PCSs (*45*). As an example, 1% of the CBGs in San Francisco have an accessibility score at least 2.8 times higher than 50% of the CBGs. To gain further insights, we also visualize the income distribution of the CBGs that has the highest (top 10%) and lowest (bottom 90%) accessibility scores. The results suggest that for the majority of the metro areas (7 out of 10) CBGs with higher PCS accessibility are associated with a disproportional amount of the high-income population, highlighting notable inequality in accessing PCSs given the current charging infrastructure deployment.

To further compare the outcomes of different metro areas, we perform an Ordinary Least Squares (OLS) regression, using the power-law exponent parameter (γ) as the dependent variable and the number of EVSEs (X) as the independent variable. The results suggest that $ln(\gamma) \sim -0.35 ln(X)$, with p-value=0.03 and R-squared value=0.45. This indicates that a 1% increase in the number of EVSEs will result in a reduction in 0.35% reduction in the power law coefficient γ and the relationship is statistically significant at the 0.05 level. As such, we conclude that the expansion of PCSs will lead to a slower decay for the CCDF of the accessibility score, hence resulting in greater inequality for the PCS accessibility among all CBGs.

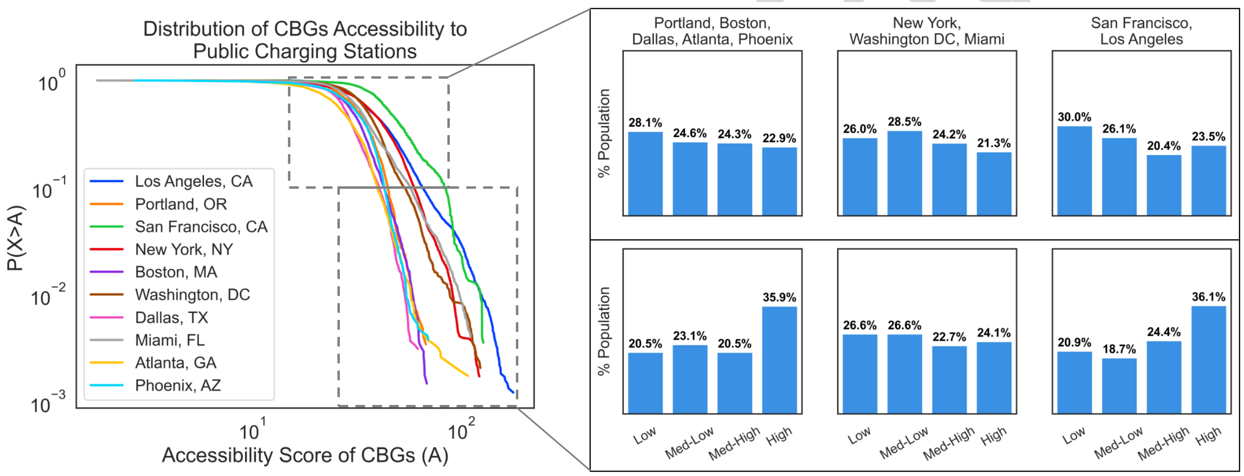


FIGURE 2: Census Block Groups' Accessibility to Public Charging Stations

Service Coverage of PCSs

In addition to CBG's accessibility to PCSs, we further compare the CCDFs of PCS service coverage across the metro areas and the results are shown in Figure 3(A). Similar to accessibility scores, we observe that the tail of the CCDFs of service coverage scores among PCSs also resembles the power-law distribution for each metro area. As such, there is also a notable variation in each metro area where a small number of PCSs greatly cover a disproportionally high amount of the population, which may imply a high charging demand for a few charging stations. Among the metro areas, New York exhibits the most unequal distribution of PCS coverage, while Boston stands out for comparatively more equal charging load among the PCSs. While the skewed outcomes of unequal PCS service coverage may be attributed to already skewed spatial population distribution in each city, we further compare in Figure 3(B) the service coverage of the current PCS layout versus the ones following a spatially uniform distribution. The results indicate that the two service coverage distributions are statistically different and the current PCS layouts are notably more right-skewed. As a result, the current PCS deployment intensifies the inequality of charging load distribution because of its spatial layout, and the results are consistent across the metro areas. If we take a further investigation into those PCSs with the highest service coverage values (top 10%), as shown in Figure 3(C), we reveal that the covered population by these PCSs are primarily low and medium-low income groups. This, together with the results for CBG accessibility to PCSs, highlight the inequity issues of PCS deployment with respect to people's economic statuses.

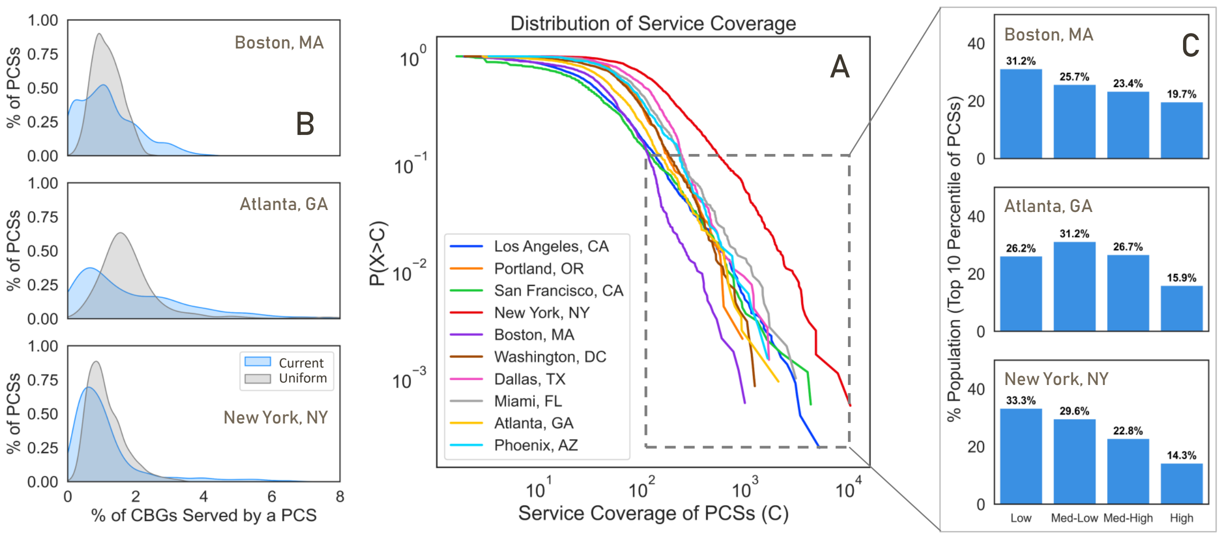


FIGURE 3: Public charging stations' service coverage and its community implications

When connecting the results of CBG's accessibility to PCSs and the results of PCSs' service coverage, an important concern may arise due to their unequal distributions. That is, how will people's accessibility to PCSs degrade if PCSs with top service coverage are out of service? To examine this issue, we conduct a sensitivity test by removing PCSs with the top 10% service coverage and reevaluate the change in CBG's accessibility score to PCSs, and show the results in Figure 4. In Figure 4(a), we examine if there is a disparity in access reduction across CBGs of different median household incomes. The results indicate striking and consistent differences across all metro areas: households with lower income levels are more prone to degraded accessibility due to possible service outages of PCSs. We further examine this relationship using an OLS regression, with the change in accessibility as the dependent variable and the median income level of CBGs as the independent variable. As shown in Figure 4(b), the coefficients are negative for 9 of 10 metro areas and they are all statistically significant at 0.05 level. This suggests that an increase in household income will experience less accessibility degradation due to PCSs outages. The only exception is Miami, with a positive coefficient, but the estimates are found to be statistically insignificant (p-value > 0.1).

(a) Income level of census block groups with and without reduced accessibility

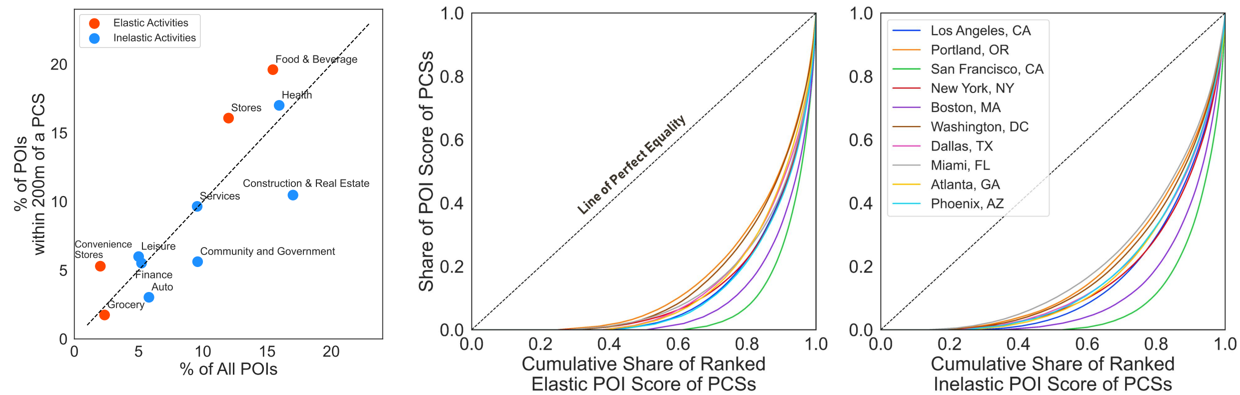
(b) OLS coefficient for the relationship between income and reduction in accessibility

FIGURE 4: Impacts of service outages for PCSs with top service coverage

Opportunity scores and opportunity-based accessibility

The above results present a comprehensive investigation of the disparities in PCS accessibility and PCS service coverage, as well as the resilience implications in maintaining the level of accessibility due to PCS outages. As mentioned earlier, conventional accessibility measures only provide a snapshot of the PCS performances, and we next shift our focus to examine if similar issues are also present for opportunity-based measures.

We first explore the distribution of POIs that are associated with PCSs. In Figure 5a, we compare how opportunities are spatially distributed around PCSs to the overall distributions of the entire metro area, and we divide the POIs into two groups of activities: elastic activities where users can easily find alternatives (e.g., food and beverage locations), and inelastic activities where users are less likely to find an alternative (e.g., church, government facilities, and workplaces). We report that there is a notable difference in the percentage of specific POI categories around PCSs compared to the overall distribution across the metro areas, and PCSs are preferentially attached to certain POI categories. Particularly, there is a greater concentration of POIs for elastic activities nearby PCSs, such as Food & Beverages, Stores, and Convenience Stores, with 26.8%, 33.9%, and 161.4% more POIs than the overall percentage of each category across the metro areas. On the other hand, there is a lower percentage of POIs that are associated with inelastic activities. As a consequence, people will be more likely to find a PCS for their daily elastic activities but will be less likely to find a PCS nearby their inelastic activity locations, and they will likely have a limited set of activities to consider when they specifically choose to charge at certain charging stations.



(a) Location of POIs (b) Lorenz curve of POIs Associated with Public Charging Stations

FIGURE 5: POIs Associated with Public Charging Stations

Besides the differences in overall POI concentration, we also observe a significant inequality in the associated number of POIs across all the PCSs, as depicted by the Lorenz curves in Figure 5b. The outcomes highlight a surprisingly high level of inequality of opportunities around all the PCSs and the same observation holds for all the metro areas regardless of elastic and inelastic activities, where a few numbers of PCSs are associated with a very high number of POIs (for all metros, more than 50% of the cumulative share of POI scores corresponds to less than 10% of the PCSs). We can further quantify the degree of inequality via Gini index (*46*), calculated as the distance of each curve from the diagonal line (line of perfect equality). The Gini coefficient ranges from 0 to 1, with 0 representing perfect equality and 1 denoting total inequality. The San Francisco metro area is found to be associated with the highest level of inequality with Gini coefficients of 0.86 for elastic activities and 0.83 for inelastic activities. Boston follows closely with Gini coefficients of 0.82 and 0.77 for elastic and inelastic activities, respectively. The Gini coefficients for all other cities are at least 0.6 (Miami). In conclusion, while it is desirable to have abundant activity locations nearby PCSs, the existing deployments saw a huge discrepancy in terms of access to opportunities. This motivates us to quantitatively assess the accessibility to opportunities by combining conventional accessibility measures with the opportunity measures for the deployed PCSs.

Similar to the results on the distribution of the accessibility scores, we visualize the CCDF for the distributions of AICA and CIAA in Figure 6(A) and Figure 6(B). We report that the tail of the CCDFs for CBGs in both metrics can be well approximated by the power-law distribution, which is indicative of inequalities of opportunity-based accessibility for different communities with few CBGs having disproportionally high opportunity-based accessibility scores. The observations hold true for all metro areas and we hypothesize such inequality issues, both in terms of conventional accessibility and opportunity-centric measures, are likely universal across major cities. Nevertheless, we observe different trends among the distributions for AICA and CIAA, respectively. This is statistically verified by fitting the power-law distributions to the CBGs with the top 10% of the scores. The fitted results show the range of γ between 2.11 (Miami) to 3.76 (LA) for AICA and a range of 1.94 (NYC) to 5.74 (Dallas) for CIAA, both with R-squared values at least 0.98 for the fitted distributions. We note that the range of γ for AICA is notably lower than both conventional accessibility measures as well as CIAA. This suggests that the CCDFs for AICA decay slower than those for PCS accessibility, and is indicative of AICA suffering greater inequality across CBGs than PCS accessibility. We believe the reason is likely due to the compounded inequality of accessing to PCSs and the unequal distribution of opportunities (POIs) in each metro area. As a consequence, the placement of PCSs nearby (existing) major activity locations will inevitably lead to inequalities in opportunity-centric accessibility measures. Moreover, the γ does not capture CBGs with low AICA scores as it focuses on the tail of the CCDF. For areas with low AICA scores, we observe significantly worse AICA as compared to accessibility measures than other areas, since there is no PCS available nearby their top 20 activity locations. For CIAA, while the inequality issues remain, the extent of which is observed to be less severe as compared to AICA distributions. This is supported by the average γ for CIAA being greater than AICA hence CCDF decays faster, and also fewer areas with nearly zero CIAA. Similar to AICC, there may be two major factors that also compoundly contribute to the inequalities associated with CIAA: (1) the unequal deployment of PCSs in the current layout which makes it harder for many CBGs to access them, with lower-income CBGs mostly relying only on a few accessible stations, and (2) the unequal distribution of POIs nearby PCSs as shown by the opportunity scores. Finally, we observe a positive correlation between CIAA and AICA values in all metro areas (from 0.33 in Dallas to 0.58 in New York), suggesting that areas with lower AICA scores are also likely to experience poor CIAA. These observations raise one important issue that requires attention for future PCS development. For EV owners in disadvantaged communities, they will be less likely to find a PCS nearby their major activity locations due to low AICA, and they will have to detour to PCSs that may be associated with minimum additional opportunities. As a consequence, they will be enforced to withstand an invisible "charging tax" as the opportunity lost in waiting for charging, whereas EV users from more affluent communities are more likely to spend their charging time concurrently with other activities.

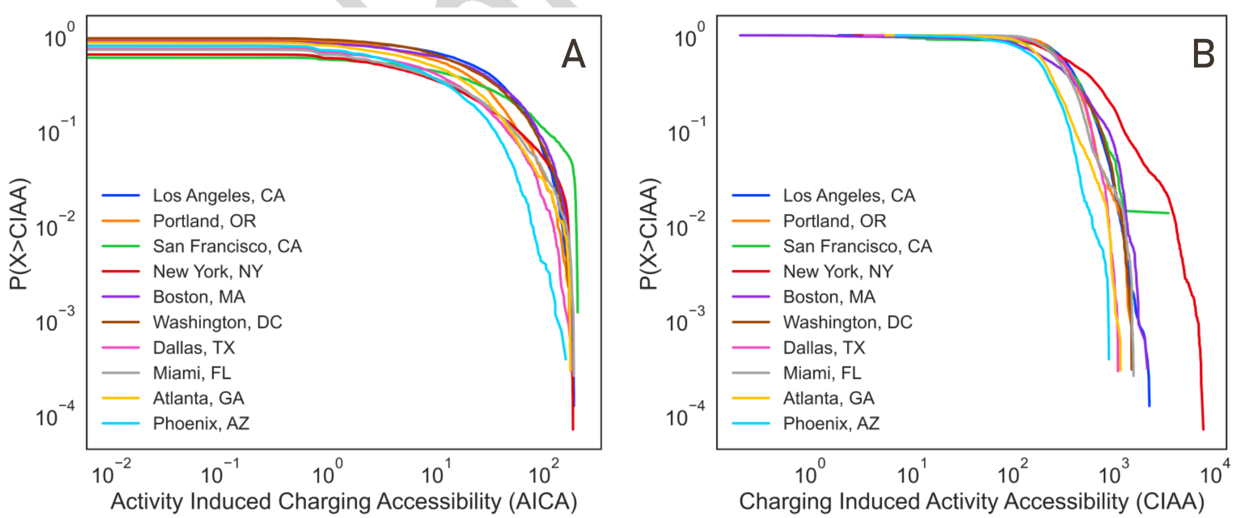


FIGURE 6: CCDF of AICA distributions (left) and CIAA distributions across CBGS in 10 metro areas

Counterfactual Analyses

With the above discussions, we next present our final results on the outcomes from the counterfactual analyses. We use radar plots to present the median performances per each metric across all metro areas and the comparisons between the current deployment layout and four other alternative strategies across five distinct dimensions are shown in Figure 7. The results in the figure are scaled performances with a value of 1 being the baseline and the lowest value of each performance metric (the innermost ring), with each outer ring representing an additional 50% improvement over the baseline. As an example, equity-based PCS deployment results in the worst CIAA performance whereas the current PCS deployment scores nearly 100% greater median CIAA. Unsurprisingly, the equity-based approach obtains the highest PCS accessibility, and uniform and profit-based distributions lead to the worst performances in this category. The current deployment, on the other hand, gives favorable CIAA and AICA measures with acceptable levels of conventional accessibility performances. The conventional accessibility for the current deployment is nearly 30% better than the baseline (Uniform) but approximately 35% worse than the best outcomes (Equity-based). The AICA measure for the current deployment is 57% better than the baseline (Uniform) and 22% worse than the best scenario (Population-based). It is worth stressing that the Equity-based approach, despite yielding the best accessibility measures, results in the worst performances for the opportunity scores, AICA and CIAA measures. In this case, purely promoting equity based on distance measures, as widely accepted in other types of civil infrastructure planning, does not lead to equitable outcomes if we consider the need to participate in additional activities while charging. Alternatively, even though the current deployment suffers apparent disparities in each city, the current deployment maintains a reasonable balance among all five measures. We conjecture that the disparities observed for current deployment may be due to the structural disparities that carry over from existing civil infrastructures (e.g., the road network and community segregation), which will require further investigation. In general, we report that the population-based planning philosophy is on average the best-performing one that is worth considering to guide the nationwide charging network development.

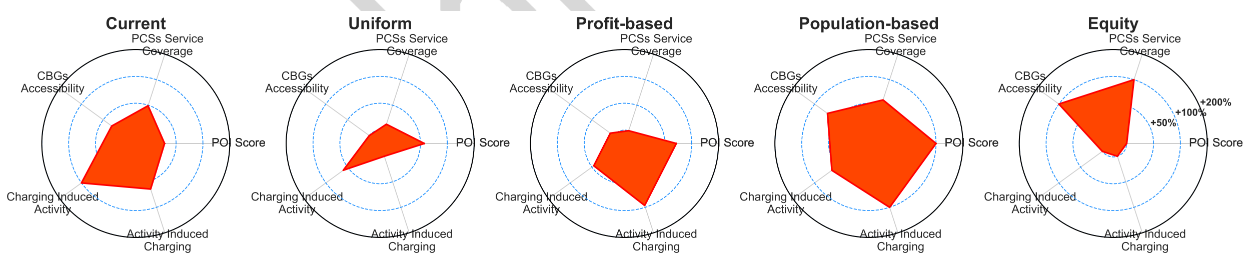
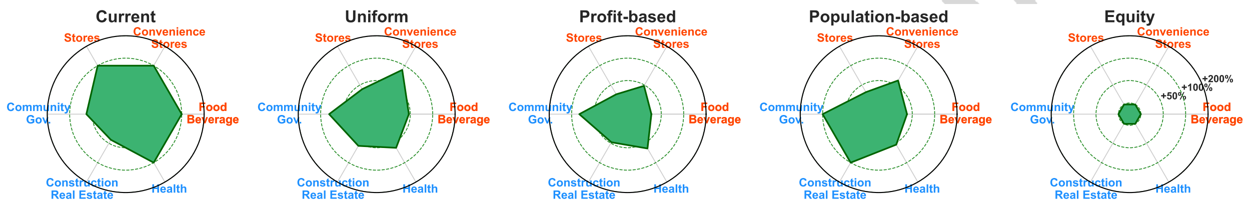


FIGURE 7: Performance Comparison of Different Deployment Scenarios

While the above results provide an aggregate view of the CIAA and AICA performances, we further break them down into individual POI categories and we show in Figure 8a the category-specific CIAA performances and in Figure 8b the category-specific AICA performances. Similar to the overall observations, we again confirm that the equity-based approach leads to the worst AICA and CIAA performances in every category of POIs. Based on the results, one very important observation is that the current deployment strategy scores well in CIAA measures but yields worse performances for AICA measures. We believe this is largely due to the current policy guidance that promotes public-private partnerships in deploying PCSs and many local businesses investing in PCSs at their locations, hence the higher CIAA measures. Nevertheless, the outcomes do not necessarily align with real-world needs if we consider the charging events being largely derived from daily activities. On the contrary, the profit-based approach gives the best overall AICA performance. This further highlights the disparities that arise from existing opportunity distributions in major metro areas. The major opportunities/POIs are more adjacent to economically advantaged communities both in terms of physical distance as well as the number of opportunities. This, together with the disparity in existing civil infrastructure, renders the planning of PCSs a highly challenging problem. Optimizing PCSs deployment purely based on distance-based accessibility or opportunity-based accessibility will lead to undesirable outcomes that may either result in a waste of resources or exacerbate existing barriers in the community. It is of great importance to balance the consideration across multiple dimensions and plan PCS proactively with the consideration of existing disparities and societal barriers, as discussed in this study, such that a PCS deployment plan for long-term community benefits can be achieved.



(a) Charging Induced Activity Opportunities

(b) Activity Induced Charging Opportunities

FIGURE 8: opportunity Measures Score of Different Deployment Scenarios

CONCLUSION

In this study, we incorporate an additional opportunity-based aspect to the traditional view of civil infrastructure deployment, which enables us to connect the links between communities, existing charging layouts, and the location of activities. Our study allows for a thorough comparison of the existing charging infrastructure with various charging deployment philosophies that might each prioritize a different aspect in addressing the complexity of the multi-faceted charging deployment problem. Our comprehensive analyses lead to four significant conclusions, outlined as follows:

1. **There are notable disparities in how accessible charging stations are for different communities.**. We observe that the tails of the CCDF for accessibility distributions across communities can be approximated by the power-law distribution. This is indicative of a few communities having significantly better access to PCS than the majority of the communities. For instance, in San Fransisco, the PCS accessibility in the top 1% of CBGs can be 2.8 times better than in the bottom 50%. Meanwhile, we observe a highly skewed PCS service coverage in the current layout, with specific stations in New York serving up to 10 times more CBGs compared to others. This raises a significant concern

where few PCSs are adjacent to majority of the population while majority of the PCSs are more accessible to selective groups of users.

2. **Opportunity-based accessibility reveals more severe inequality issues for current PCSs**. When we consider the intertwined relationship between activities and choices for charging, we notice that disparities in opportunity-based access within and between metropolitan areas are made worse. This underscores the inherent biases in where we position charging stations relative to activity hubs, which typically lean toward favoring specific areas. As a result, we see a more intense inequality in accessibility when activity locations are the primary decision factor and charging stations are secondary. This outcome highlights the need to reassess the quality of the existing charging infrastructure plan, as well as compare scenarios that prioritize different planning philosophies.
3. **Equitable deployment is not necessarily equitable**. Based on the results from counterfactual analyses, we report that the equitable PCS deployment strategy based on the conventional accessibility measure will result in the least equitable deployment outcomes with the worst opportunity-based accessibility metrics. This finding is contrary to commonly recommended practices in other civil infrastructure deployments when distance-based accessibility is often used to evaluate the quality of the infrastructure deployment. This outcome highlights the complexity of planning PCSs as compared to other public infrastructure and urges the adoption of multidimensional metrics to guide the deployment of PCSs.
4. **PCS deployments are restricted by existing inequalities in our cities.** If considering opportunity-centric accessibility as a key PCS deployment metric, we observe that the profit-based approach will result in the best overall performances in terms of CIAA and AIAA measures, but the inequalities will be exacerbated because major activity destinations are more concentrated nearby affluent communities as the outcomes of decades of urbanization process. To overturn this process, it is important to be proactive in planning PCS and activity locations concurrently, while avoiding excessively attaching new PCSs to already-popular locations.

Lastly, we suggest two future research directions that could enhance our study's findings. First, our study implicitly treats POIs within the same activity category as homogeneous. It could be beneficial to explicitly consider the heterogeneity among them. For example, examining expenditures at these POIs might provide a deeper understanding of potential inequalities in opportunity-centric accessibility measures. Second, while our study employs accessibility as a static metric to explore the spatial relationship between communities and public infrastructure, incorporating data on population movements could offer more detailed insights. This could help us better understand location-specific measures of PCSs and potentially link to EV ownership across various communities. The results of such research could then be employed to jointly analyze and craft policies that promote long-term sustainability, taking into account both EV users and PCSs concurrently.

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