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Public electric vehicle charger access disparities across race and income in California

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ABSTRACT

Widespread electric vehicle (EV) adoption is crucial for achieving California's climate goals. The inclusion of marginalized populations in this process is important and will require that they have access to charging infrastructure. Public EV charging stations may help reduce the EV adoption barriers affecting these populations. This study combines public charging station location data with American Community Survey data at the census block group level in California, finding that public charger access is lower in block groups with below-median household incomes and in those with a Black and Hispanic majority populations. These public charger access disparities are more pronounced in areas with a higher proportion of multi-unit housing, where they are critical for EV operation due to a lower likelihood of residential charger access. Controlling for distance to the nearest highway or freeway, multi-unit housing unit rate, and median household income, we find that Black and Hispanic majority block groups are the only race and ethnicity group that is significantly less likely to have access to any public charger in their block groups compared to the rest of the state. The odds of having public charger access for the group is 0.7-times that of the no majority reference group. The access gap is even larger for the publicly-funded charging stations where Black and Hispanic majority block groups are approximately half as likely as the no-majority reference group to have access. Hence directing a larger portion of the funding to underserved communities and further government involvement in filling the public charger access gap can be crucial in achieving widespread and equitable EV adoption.

1. Introduction

1.1. EV adoption barriers

Electrifying the transportation sector, along with the high penetration of renewable energy sources, is required to meet California's climate mitigation goal (Williams et al., 2012). The top barriers to electric vehicle (EV) adoption, including fully electric and plug-in hybrid electric vehicles, are the upfront purchase cost, the vehicle travel range, and the charging infrastructure availability (Bakker and Jacob Trip, 2013; Egbue and Long, 2012; She et al., 2017). These adoption barriers have shaped the demographics of the early and current EV owners. Survey data on EV owners and consumer preferences have shown that EV owners and those with the preference to adopt EVs have higher income, higher education, and tend to live in single-family homes they own (California Clean Vehicle Rebate Project, 2015; Carley et al., 2013; Farkas et al., 2018). The higher cost of EVs has been identified as a more significant barrier to consumers than EV range (Adepetu and Keshav, 2017), but EVs are projected to reach price parity with conventional vehicles within five to 10 years (Baik et al., 2019; Lutsey and Nicholas, 2019). Many EVs in the current model years have comparable traveling range from a single charge to a conventional vehicle from a single tank of fuel. And greater numbers of EVs are entering the secondary market making EV adoption more economic and operational for a broader customer base. However, unlike the EV upfront purchase cost and battery range, which are similar across markets, charging infrastructure can present a localized barrier depending on the local deployment.

EV charging infrastructure, which increases the ease of operation, is correlated with the EV adoption rate both at the national and municipal levels (Egnér and Trosvik, 2018; Sierzchula et al., 2014). Although home chargers are the most important and the most used type of chargers in EV adoption and operation, public chargers are crucial for residents without off-street parking and home chargers (Dunckley and Tal, 2016; Funke et al., 2019). Apartment residents, having less off-street parking or private garages, have lower home charger access (Axsen and Kurani, 2012). Installing home chargers is also more challenging in rental residences as renters are less likely to bear the cost of an upgrade to a home they do not own and owners are less likely to bear the cost of a charger they will not use. Additionally, Kester et al. (2018) documented experts in more developed EV markets suggesting that the public fast-charging infrastructure is both a primary need for the EV drivers and can

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facilitate uptake by alleviating range anxiety.

The state of California and many of its cities have aggressive goals for achieving high EV penetration in the market and on the road in a relatively short time. For example, the City of Los Angeles aims to have 80% of its vehicle fleet electrified by 2035 (City of Los Angeles, 2019). The City of San Francisco has a 2030 goal to make EVs 100% of all new vehicle sales (San Francisco Electric Vehicle Working Group, 2019). However, California currently has less than 40% of the charging infrastructure needed by 2025 to support the projected EV fleet (Nicholas et al., 2019). How charging infrastructure is deployed going forward can have lasting impacts on who will be able to reap the full benefits of EV adoption.

Up to this point, there is a strong correlation between public EV charger deployment and the current and projected EV ownership. While this is rational, it can also lead to socioeconomic inequities among Californians. If the planning of public EV charger infrastructure lacks a focus on social equity, it will amplify existing inequities, causing harm to the excluded population (Wells, 2012). In such a scenario, lower-income communities—having fewer current and projected EV drivers—would likely attract less infrastructure investment. This would make them less desirable residential locations and traveling designations for current EV owners and would disincentivize EV uptake among current residents, creating a local technology lock-in that could last decades. The lack of infrastructure support could result in missed opportunities to reap the benefits of EV adoption at both the household and community levels. This includes the environmental and health benefits of enabling low or zero-emissions transportation and reducing local air pollution (Pan et al., 2019), ownership cost savings compared to internal combustion engine vehicles (Hagman et al., 2016; Palmer et al., 2018), and regional and local power grid ancillary services such as local voltage support (Knezovic et al., 2017; Rei et al., 2010). In order for these benefits to be shared by everyone, equity in public charging infrastructure planning is paramount.

1.2. Government's role in promoting a transition to EVs

The government plays a vital role in technology transition by generating early market momentum through research and development, disseminating information, and facilitating coordination among the market and industry actors (Pietruszkiewicz, 1999; Rotmans et al., 2001). Increasing consumer awareness and sustaining outreach actions are also a key role of the government during the early phase of EV adoption (Jin and Slowik, 2017). Specifically for EVs, the government's role in providing financial incentives and charging infrastructure has been important in increasing EV adoption (Narassimhan and Johnson, 2018). Kester et al. (2018) found that even among the leaders in the EV adoption in the Nordic region countries, government investments or subsidies for public charging infrastructure are often justified by the weak business case for public charging stations. The profitability of public chargers can be greatly increased by public funding (Nigro et al., 2019), but is especially uncertain in low EV adoption areas which in turn inhibits a widescale roll-out (Schroeder and Traber, 2012).

California, among the U.S. leaders in EV adoption progress, has a suite of government supports for the transition. The Greenhouse Gas Reduction Fund, funded by California's cap-and-trade program, has to date provided over two billion dollars in support of the California Air Resources Board's Low Carbon Transportation program. For fiscal year 2019–2020, the Clean Vehicle Rebate Project was allocated $238 million in financial incentives for EV purchase (California Air Resources Board, 2019a). During the same time period, the Alternative and Renewable Fuels and Vehicle Technology Program—funded by vehicle registration, license plate, and smog abatement fees—allocated $95 million to install nearly 10,000 chargers (California Energy Commission, 2019a). California's Low Carbon Fuel Standard, which awards credits to providers of clean fuel, including electricity for vehicle operation, helps to improve the business case for public EV chargers as well as providing additional rebates from utilities for EV purchases. In the research and development space, the Electric Program Investment Charge program has funded charging infrastructure deployment projects and research for charging network management and power grid integration technology in recent years (California Energy Commission, 2019b, 2020).

1.3. Technology adoption in lower-income status and minority communities

Lower-income or minority communities are often lagging behind their wealthier and whiter peers in technology adoption due to cost barriers, lower availability of the technology (Dailey et al., 2010; Judge et al., 2004), and fewer programs facilitating technology uptake (Warschauer et al., 2004). Equity analysis in renewable technology deployment shows Black- and Hispanic-majority census tracts have installed less rooftop photovoltaic energy systems compared to other census tracts (Sunter et al., 2019). Canepa et al. (2019) looked at EV adoption equity in terms of ownership and charger availability in disadvantaged communities and found that disadvantaged communities have a lower rate of EV adoptions and the owners in these communities have higher income and higher education compared to the average person in a disadvantaged community. In terms of charging infrastructure, the study found similar public chargers per household between disadvantaged and non-disadvantaged communities (Canepa et al., 2019). However, disadvantaged communities are not sociodemographically homogenous and the study did not investigate the differential access of public charging infrastructure between different sociodemographic groups.

1.4. Government efforts to improve EV uptake equity

Around the U.S. cities have developed their own EV goals and approaches. Many of these have highlighted equity, including but not limited to EV and charger access, in their EV implementation plans. They emphasize close collaboration with community members and community-based organizations through activities such as collaborative community-based planning that could increase their decision-making power, bring economic opportunities to the community, and raise EV awareness (see e.g. EVolve Houston, 2019; San Francisco Electric Vehicle Working Group, 2019; Seattle Office of Sustainability and Environment, 2017).

In the State of California, to address EV adoption equity concerns, State Senate Bill 535 ("California Global Warming Solutions Act of 2006: Greenhouse Gas Reduction Fund") and State Assembly Bill 1550 ("Greenhouse gases: investment plan: disadvantaged communities") mandate that at least 25% of the Greenhouse Gas Reduction Fund has to fund state programs that seek to reduce GHG emissions in disadvantaged communities (i.e., communities exposed to a combination of economic, health, and environmental burdens) and an additional 10% to low-income households (i.e., households with income lower or equal to 80% of the statewide median). The Alternative and Renewable Fuels and Vehicle Technology Program described above had achieved approximately 40% funding allocation in disadvantaged and low-income communities as of early 2019 (California Energy Commission, 2019a). For the fiscal year 2019–2020, the Low Carbon Transportation program aimed to allocate 35% of funding to disadvantaged communities and 15% for low-income communities (California Air Resources Board, 2019a).

The California Electric Vehicle Infrastructure Project (CaleVIP), funded by the Alternative and Renewable Fuels and Vehicle Technology Program, has multiple regional EV charger incentive projects for public Level 2 and DC fast chargers, providing up to $7500 and $80,000, respectively, depending on the location of the project and whether the project site is located in a disadvantaged community. All CaleVIP regional projects have the requirement of 25% minimum spending in disadvantaged communities. The three largest utility companies in California have been approved for cost recoveries worth $197 million to provide incentives for charger installations, and of which 10–15% of the funding is required to be allocated to disadvantaged communities (California Public Utilities Commission, 2016a; 2016b; 2016c). The utility charger projects are mainly targeting multi-unit dwelling and workplace chargers and, to a smaller extend, public chargers.

The Clean Vehicle Assistance Program explicitly targets disadvantaged and lower-income communities by providing financial assistance for new and used EV purchases. California Vehicle Rebate Program has an income cap limiting rebates to individuals with $150,000 annual income or less and increased the rebate amount by an additional $2000 for qualifying low-income applicants. The administrator of the statewide EV rebate program, Center for Sustainable Energy, has a dedicated team focusing on EV and incentive education and awareness in lower-income and disadvantaged communities (California Air Resources Board, 2019b). These programs, while well intentioned and required great state efforts, have thus far yet to drive significant progress on EV uptake equity in California.

Current public EV charger distribution among the counties in California has clear socioeconomic and racial disparities between the outlier counties with much higher or lower charger deployment than their populations would suggest (Fig. 1). This study aims to understand the distribution of the current public EV charging infrastructure in California in finer details. It investigates whether 1) race and ethnicity and 2) household income are factors affecting public EV charger access across urban and peri-urban communities in California. Its results allow policy makers and stakeholders to examine the efficacy of the equity mandates in the current EV infrastructure support policies. They also highlight the public EV charger access needs of the underserved communities during the EV transition.

2. Methods

We gathered sociodemographic data from the 2016 American Community Survey (ACS) along with the census block group (CBG) boundaries and the primary and secondary roadways shapefiles from the U.S. Census Bureau (U.S. Census Bureau, 2018, 2015). Locations of 6278 public EV charging stations in California were obtained from the Alternative Fuels Data Center (U.S. Department of Energyn.d.,). A public EV charging station is defined as a location accessible to the public with one or more EV chargers, and it excludes private, residential, and workplace chargers. And an EV charger is an EV charging equipment with one or more outlets that can be plugged into EVs. The locations of 1102 publicly-funded charging stations accessible to the public, some no longer operational, were provided by the Fuels and Transportation Division at the California Energy Commission. These chargers were funded by the Alternative and Renewable Fuel and Vehicle Technology Program, as described in Section 1.2.

We compared the probability of public EV charger access, defined as having at least one public EV charging station within the boundary of a given CBG, across CBG groupings based on the sociodemographic information recorded in the ACS. The pubic charging station location data were used to determine the presence and absence variable, indicating access to public chargers within each CBG and merged with the ACS data. Although we defined EV as including both fully electric and plug-in hybrid electric vehicles, the charger access issue is more acute for fully electric vehicles, as plug-in hybrid vehicles can also be fueled by petroleum.

The CBGs included for the analysis are those entirely located within either the urban areas or urban clusters, as defined by the U.S. Census Bureau, which accounts for 74% of the state's population. The non-urban CBGs were excluded due to the larger geographic areas they encompass. The larger geographic area means a charging station located on one side of a large non-urban CBG should not be considered accessible to residents on the opposite side. Therefore, including rural CBGs could lead to overestimating the public charger access of these non-urban CBG residents. Furthermore, limiting to urban CBGs significantly reduces variation in population density across the sample. In addition to including only the CBGs in the urban areas and clusters, we

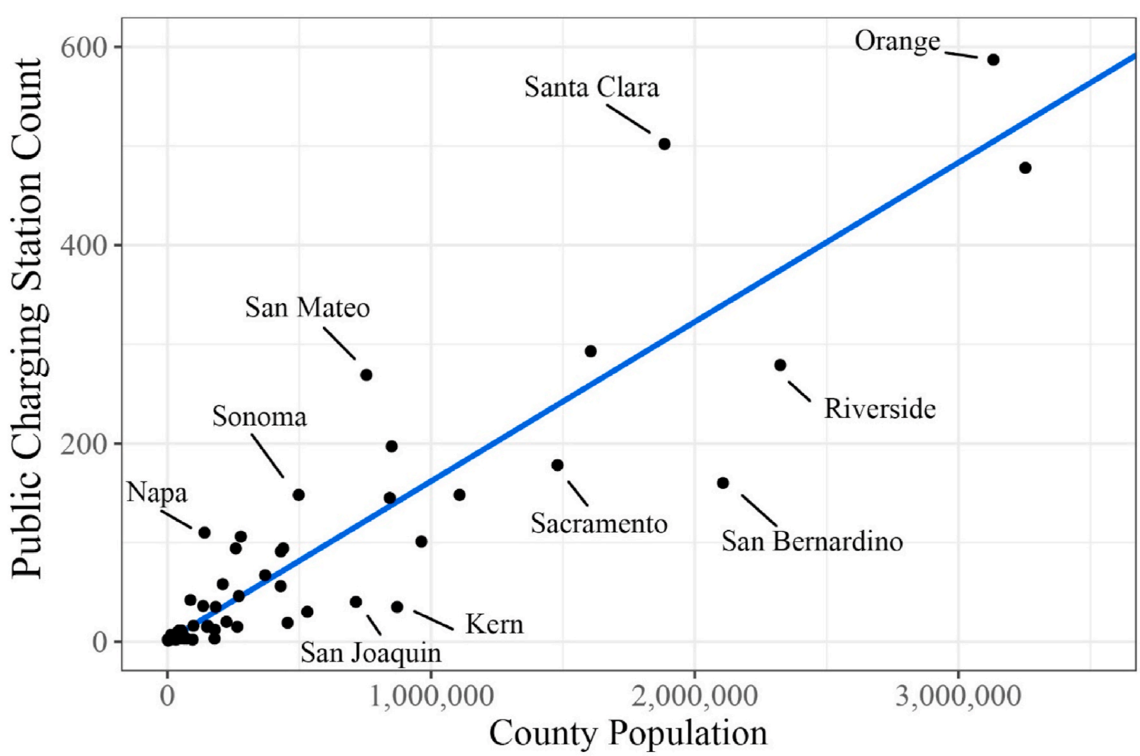

Fig. 1. County population and public EV charger count for the counties in California. The blue line represents the regression best-fit line (r-square = 0.9484). Los Angeles county, with more than 10 million population, is not shown on the figure and lies close to the best-fit line. Counties with the five most positive and five most negative residuals are labeled. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

further removed the CBGs with zero population and the final sample size of the CBGs used in the analysis is 17,837 out of the original 23,212 CBGs. And out of 6278 public EV charging stations and 1102 publicly-funded charging stations, 4292 and 679, respectively, are located in the analyzed urban CBGs.

For statistical analysis we grouped the CBGs into two sets of bins on the basis of sociodemographic variables. One analysis grouped the CBGs by median household income quartile to investigate the potential public EV charging infrastructure distribution disparity across incomes. Another analysis investigated the potential racial disparity in public charging infrastructure distribution by grouping the CBGs based on majority race and ethnicity, defined as a race or ethnicity greater than 50% of the population in each CBG. The races and ethnicities considered were Asian, Black, Hispanic, and Non-Hispanic White. CBGs without a race and ethnicity majority were labeled as having no majority and considered as the reference group.

Originally, CBGs were divided based on the majority race and ethnicities into five groups: Asian, Black, Hispanic, White, and no majority groups. However, the final results presented combined Black and Hispanic-identifying populations into a single category due to relatively low counts of Black majority CBGs compared to other groups (Table 1). The small sample size of the Black majority CBGs resulted in models with large uncertainty bands and few data points across the range of control variables. However, the Black majority CBG group had a more similar trend line to the Hispanic majority CBG group compared to all other groups. Thus, for robustness and clarity of the analysis, the new category—Black and Hispanic majority CBGs—replaced the separated Black majority CBG group and Hispanic majority CBG group.

In order to visualize the public EV charging station access disparities, the access probability was compared between different ethnic and income level CBGs by controlling for potential confounding variables. The two control variables used are distance to the nearest freeway or highway, calculated as the shortest distance from the centroid of each CBG to the nearest freeway or highway, and multi-unit dwelling (MUD) housing unit rate, calculated as the total MUD units divided by total housing units in each CBG. The distance to the nearest highway was chosen as one of the main controls for comparing public EV charger access because charging stations are often sited along and near the major transportation corridors and roadways in order to serve the fuel demand of travelers on that roadway rather than specifically to serve residents of that location. MUD housing unit rate was chosen since higher MUD concentrations lead to a greater public charger need due to the lower access to dedicated parking and home chargers.

To compare the public EV charging station access across income and race groups, we used a generalized additive model (GAM) with the “mgcv” package (Wood, 2017) in R (R Development Core Team 3.0.1, 2013) to fit thin-plate spline curves with a binomial distribution for the binary presence and absence of public EV charging station access across variables we are controlling for. The fitted curves minimized the expected squared error using the restricted maximum likelihood approach (RMEL). Smoothing curves with RMEL in GAM, similar to the locally-weighted scatter plot smoothing (LOWESS) method used by Sunter et al. (2019) with census data to detect disparities in rooftop photovoltaic solar deployment, does not need a global function to describe the whole data sample. But in addition, GAM in the “mgcv” package can fit local polynomial relationships, as opposed to local linear relationships in LOWESS, and has built-in likelihood-based selection method (i.e., RMEL) that selects the optimal smoothing parameter by balancing between goodness-of-fit and model smoothness.

Table 1
Census block group groupings based on race and ethnic majority.

Original groupings	Count & proportion	Final groupings	Count & proportion
Asian	1121 (4.8%)	Asian	1121 (4.8%)
Black	247 (1.1%)	Black and Hispanic	8557 (37.0%)
Hispanic	6988 (30.2%)	White	9547 (41.2%)
White	9547 (41.2%)	No Majority	3926 (17.0%)
No majority	5248 (22.7%)		

Finally, to isolate the race and ethnicity factor, we generated two multivariable GAM models with all of the variables described above for 1) all the public EV charging stations in California and 2) the publicly-funded charging stations in California. The model covariates included majority race and ethnicity, distance to the nearest highway or freeway, median household income, and MUD housing unit rates of the CBGs. The model allowed the comparison among the odds ratios of public charging station access across different race and ethnicity majority CBGs by adjusting for all other variables.

3. Results

3.1. Public EV charging station access disparities across median household income and majority race and ethnicity groupings

Proximity to highways or freeways is positively correlated with the presence of at least one public charging station in a given CBG (“Public charger access probability”). Across all CBGs in this analysis, the public charger access probability is highest—at approximately 20%—directly next to the freeways or highways, trending downward with distance until flattening out at approximately 8% around 1600 m—or approximately one mile—away from the highway. This trend of increasing public charger access probability with proximity to highway infrastructure spans the socioeconomic spectrum, but is not equally distributed. The CBGs with the lowest median household income (i.e., lower than $44,000 per year) do not exhibit nearly as much of a public charger access “boost” from highway proximity as do communities in higher-income CBG groups (Fig. 2a).

This inequity is even starker across racial and ethnic lines. When compared to all other CBG groups at the same distance to the nearest highway, Black and Hispanic majority CBGs consistently have the lowest public charger access probability compared to other ethnic majority groupings (Fig. 2b). For CBGs immediately adjacent (<100m) to the nearest major roadway, those with a White majority population are almost twice as likely to have access to public chargers compared to those with Black and Hispanic majority population (i.e., approximately 13%–14% likelihood in Black and Hispanic majority CBGs compared to 25%–27% likelihood in White majority CBGs).

Since owning an EV as a multi-unit dwelling resident leads to higher reliance on public charging stations (Tal et al., 2018), it is also instructive to evaluate the effect of MUD housing unit rate on public charger access. As the percentage of MUD housing units increases, the probability of public charger access also increases (Fig. 3a & b). However, the public charger access probability increases at a lower rate for CBGs with the lowest median household incomes. Residents of high-income CBGs with high MUD density have more than twice the probability to have access to public charger than residents of the poorest CBGs with predominantly MUDs. Unlike the results grouped by different median household incomes, where there are clear public charger access differences between each of the income groups (Fig. 3a), only Black and Hispanic majority CBGs are left behind when all other CBGs have similar public charger access across different MUD housing unit rates (Fig. 3b).

We find that residents of Black and Hispanic-majority CBGs have a lower probability of public charger access compared to residents of other CBGs, regardless of distance to the nearest highway or freeway and MUD housing rate. This public charger access gap is largest at locations with higher than 20% MUD housing unit rate or less than 800 m to the nearest freeway or highway. CBGs with a median household income less than the state median of $64,000 per year also have lower public charger access compared to the higher median household income CBGs across different MUD housing unit rates and, slightly less so, across different distances to the nearest highway or freeway.

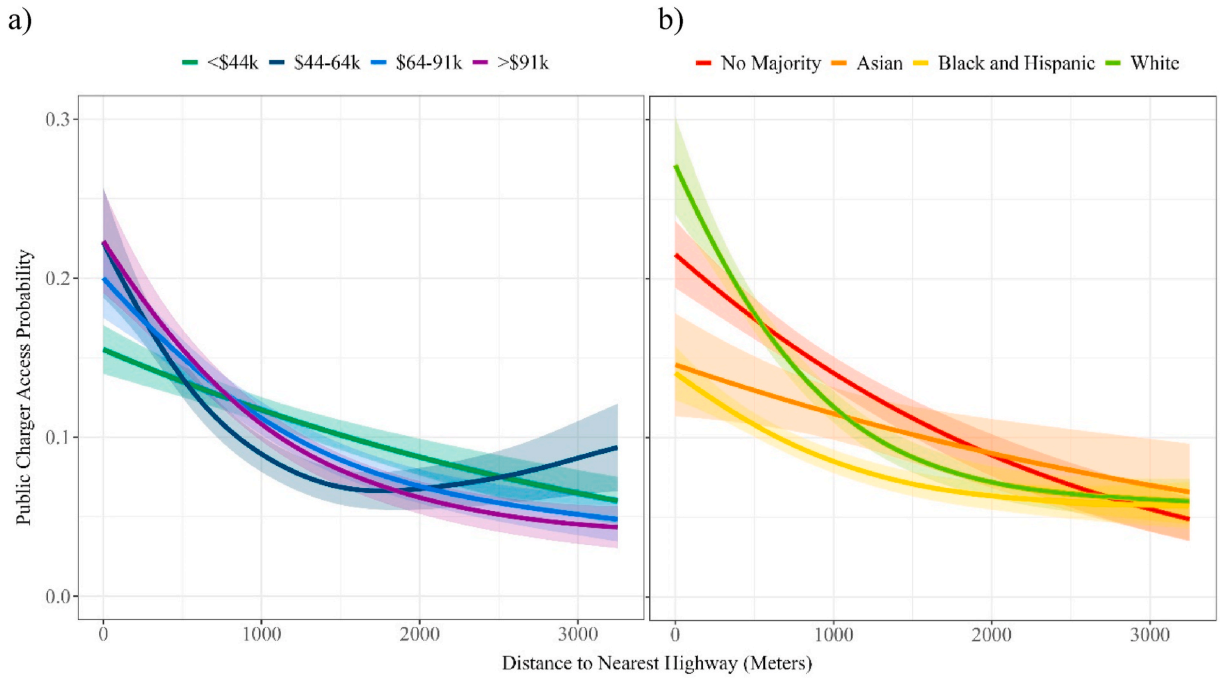

Fig. 2. Comparison of public EV charger access between CBGs grouped by sociodemographic factors across different distances to the nearest freeway or highway. (**a**) Public charger access probability as a function of the distance to the nearest highway or freeway by different income groups. (**b**) Public charger access probability as a function of the distance to the nearest highway or freeway by different majority race and ethnicity groups. The semi-transparent bands represent the 90% confidence interval.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

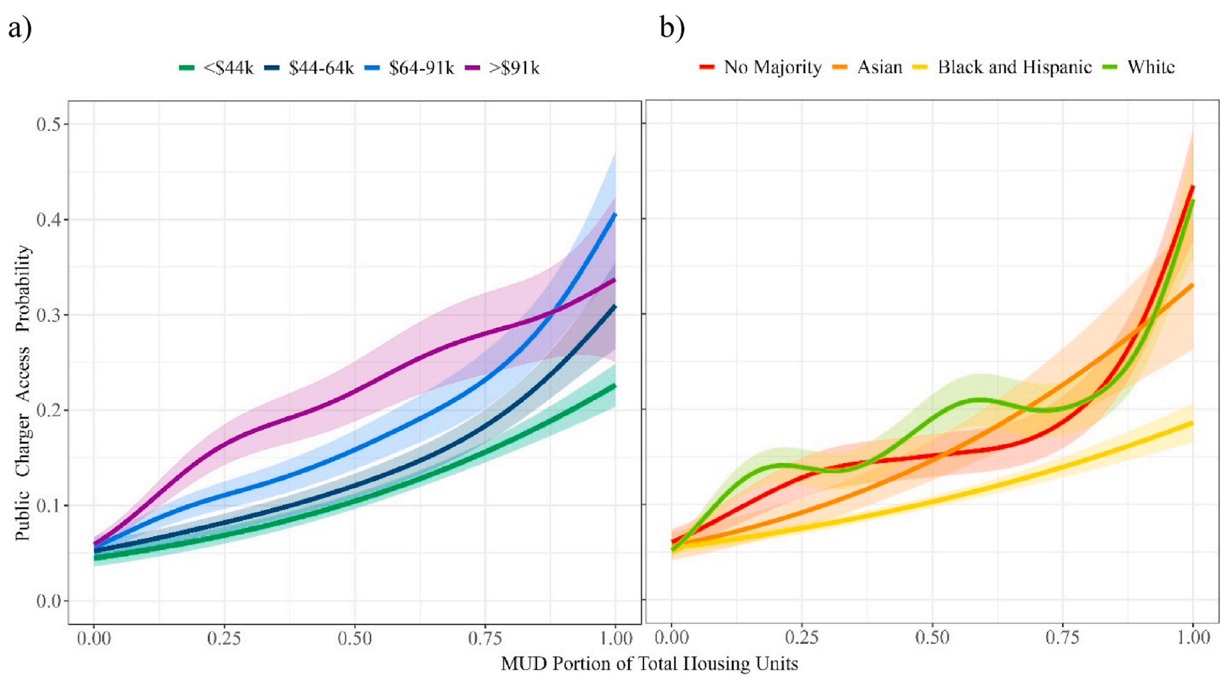

Fig. 3. Comparison of public EV charger access between CBGs grouped by sociodemographic factors across different MUD housing unit rates. (**a**) Public charger access probability as a function of the MUD housing unit rate by different income groups. (**b**) Public charger access probability as a function of the MUD housing unit rate by different majority race and ethnicity groups. The semi-transparent bands represent the 90% confidence interval.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Focusing on race and ethnicity

The above comparisons are useful in illustrating the stark disparities in public EV charger access across socioeconomic and ethnic groups. However, demographic interactions such as socioeconomic trends across ethnic groups make this approach unable to isolate the effect of single CBG characteristics on public charger access. To directly evaluate the access disparity across race and ethnicities in California, we used a multivariable GAM model to compare the public charger access probability between different race and ethnic majority CBGs while controlling for median household incomes, distances to the nearest freeway or highway, and MUD housing unit rates. As described in Section 3.1, the prevalence of MUD housing units and the proximity to the nearest freeway or highway have similar effects on public EV charger access. The similarity of the trends may be explained by a correlation between the two variables, but we found that correlation to be weak ($\tau b = -0.136$, $p < .001$) and should not constitute multicollinearity.

Fig. 4 shows how each of these predictor variables is impacting the public charger access. The trends between the public charger access probability and the predictor variables (i.e., median household incomes, distances to the nearest freeway or highway, and MUD housing rates) are similar to the single variable visualizations shown in Section 3.1. The median household income and the MUD housing rate positively impact the public charger access, while the distance to the nearest highway or freeway negatively impacts the public charger access. The wide span of confidence limits in Fig. 4b is due to the small number of urban CBGs located approximately 3000 m or more from major roadways.

Comparing across all sampled CBGs, both Asian majority CBGs and Black and Hispanic majority CBGs have lower odds of public charger access relative to the no majority CBGs (Table 2). However, the difference is significant only for Black and Hispanic majority CBGs (Fig. 4 & Table 2). The odds of having access to public chargers in Black and Hispanic majority CBGs are only 0.72 times that of the no majority CBGs. And compared to Black and Hispanic majority CBGs, White majority CBGs have 1.5 times the odds of having access to public chargers when incomes, highway or freeway distances, and MUD housing unit rates are controlled for.

Table 2
Estimated effect for each race and ethnicity majority on public EV charger access probability. The estimate column shows the relative difference compared to the no majority reference case.

	Estimate (Natural log of odds ratio)	Standard error	Odds ratio	95% Confidence interval of odds ratio	*P*-value
Reference (No majority)	−2.083	0.055	NA	NA	<0.001
Asian	−0.117	0.115	0.889	0.709–1.115	0.308
Black and Hispanic	−0.325	0.072	0.723	0.625–0.837	<0.001
White	0.051	0.066	1.052	0.924–1.198	0.443

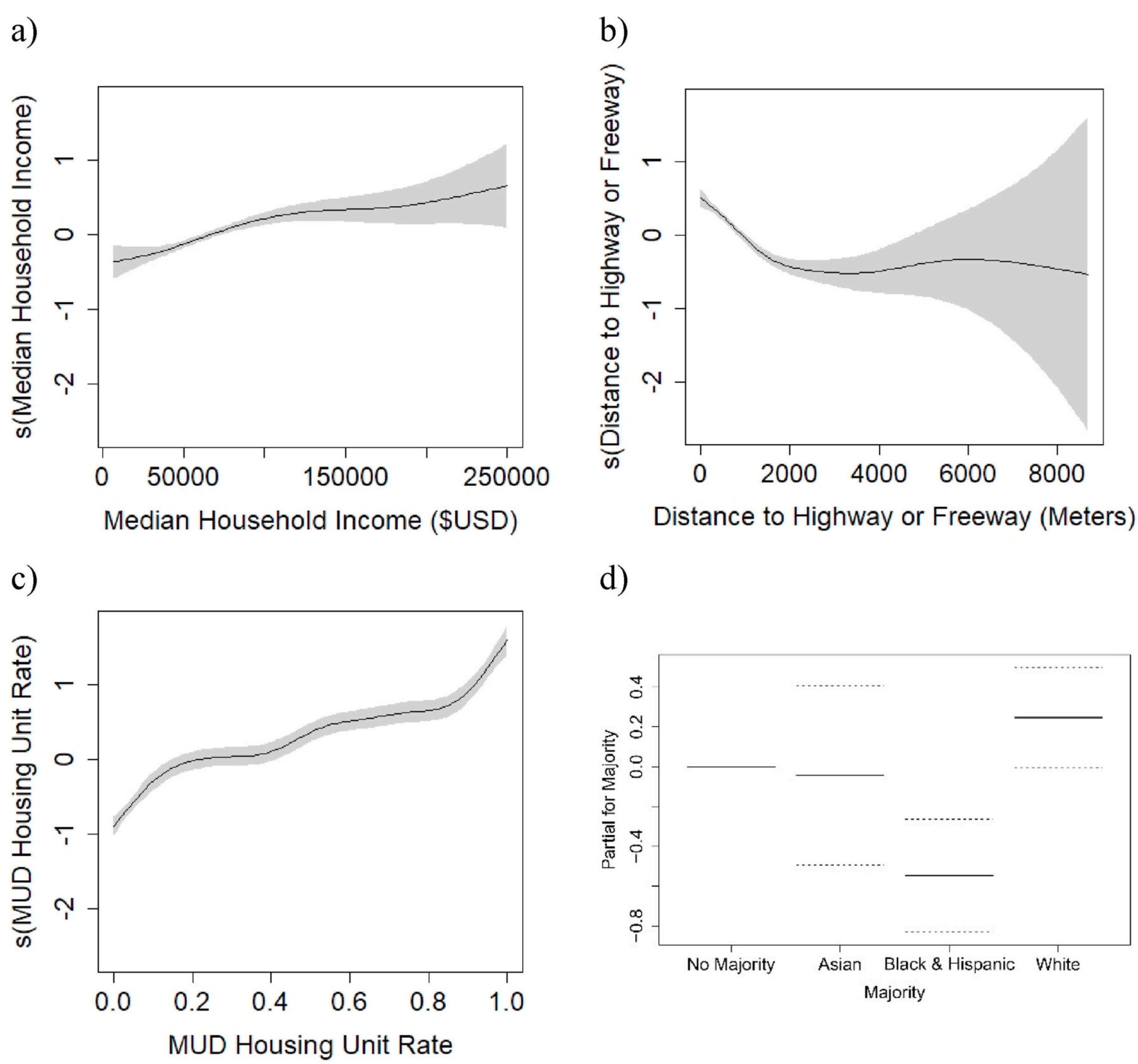

Fig. 4. (**a, b, c**) Estimated smoothness of median household income, distance to the nearest freeway or highway, and MUD housing unit rate on public EV charger access probability; y-axis is the partial effect of the variable and not on the same scale as the response variable (i.e., charger access probability); grey bands represent the approximate 95% confidence limits. (**d**) Estimated effect for each race and ethnicity majority on public charger access probability. The effect of no majority, shown as zero, is used as the reference.

3.3. Access to publicly-funded chargers

We also used the same multivariable GAM method described above to evaluate the equity of distribution of publicly-funded charging infrastructure accessible to the public specifically. The result shows a similar overall pattern of access disparities between the race and ethnicity groups, but the access gap is *larger* than that found for public chargers overall. Controlling for the median household income, the distance to the nearest freeway or highway, and the MUD housing rate, Black and Hispanic majority CBGs again were the only race and ethnicity group that has significantly lower access to publicly-funded charging infrastructure compared to the no majority CBGs ($p < .001$). The odds of having publicly-funded charger access in Black and Hispanic majority CBGs is less than half of that in White-majority CBGs (Table 3). Compared to the analysis in Section 3.2 on the access to public chargers, Black and Hispanic majority CBGs have even lower odds to have access to publicly-funded charging infrastructure. The effects of distance to the nearest freeway or highway and prevalence of MUDs on access to charging infrastructure are similar for publicly-funded charging stations (Fig. 5b and c) and public charging stations overall (Fig. 4a and c). However, income seems to have less impact on access to publicly-funded chargers compared to public chargers (Figs. 4a and 5a).

4. Discussion

This study found significant public charger access disparities based on the racial and ethnic majority, and the median household income of the CBGs. Public charging stations have primarily been deployed at, and more accessible to, wealthier and whiter CBGs; the similar demographics as the early EV adopters. The underserved groups—majority Black and Hispanic population CBGs and lower median household incomes CBGs—are less likely to have access to public charging infrastructure within their neighborhood across a range of proximities to major roadways and MUD housing unit rates. This may have been rational up to this point, as fueling infrastructure followed the demand for EVs, however, government action may be needed to make sure these inequities do not become self-reinforcing.

New car buyers, especially new EV buyers, generally have higher income (Muehlegger and Rapson, 2019). The result suggests the public charger investment are going into higher income markets—where there are more EVs being purchased. The current used EV market offers early EV models with a relatively limited range. If buyers in lower-income markets, who tends to purchase used vehicles, were to adopt EVs, they would likely have higher reliance on public chargers due to the limited range of the used EVs. However, the current trend suggests that they have lower public charger access compared to the higher income markets. The compounded effect of limited range EVs and lower charger access further stresses the value of charger access and a used battery replacement program such as the one mandated in the California State Assembly Bill 193 ("Zero-Emission Assurance Project").

Table 3
Estimated effect for each race and ethnicity majority on the probability of access to publicly-funded chargers. The estimate column shows the relative difference compared to the no majority reference case.

	Estimate (Natural log of odds ratio)	Standard error	Odds ratio	95% Confidence interval of odds ratio	*P*-value
Reference (No majority)	−3.775	0.109	NA	NA	<0.001
Asian	−0.042	0.225	0.959	0.616–1.491	0.852
Black and Hispanic	−0.546	0.141	0.579	0.439–0.764	<0.001
White	0.246	0.125	1.279	1.001–1.635	0.049

The inequity of public charger access at high MUD housing unit locations (i.e., greater than 50% of all housing units), where the access gap is the largest, is further compounded by the differences in the amenities available at MUDs serving higher versus lower-income households. Not only are the residents of higher income luxurious MUDs more likely to have access to public chargers as shown in the results above, they are also more likely to have dedicated parking structures and private dedicated EV chargers. Conversely, the lower-income MUDs, where there are fewer private chargers available, would likely have a higher reliance on public chargers. However, these locations currently have lower public charger access.

The public charger access gap at locations with higher MUD housing unit rate can potentially become a lasting barrier for the underserved communities to adopt EVs. In these locations, access to public chargers is crucial for EV adoption and operation as residents in MUDs have less off-street parking or parking garages leading to greater challenges in installing the more convenient and less expensive home chargers. Current EV drivers living in MUDs in low income and Black and Hispanic majority CBGs would likely experience higher operating costs as the lower public charger availability in proximity means more fueling would need to be completed using more costly fast chargers elsewhere. This infrastructure barrier could deter EV adoption within underserved communities, further depressing infrastructure deployment at these locations in a negative feedback further exacerbating existing inequities.

Public charger construction has up to this point followed the early adoption of EVs and the demographic factors that are associated with that adoption. However, this has led to significant inequities in public charger access as shown in this research, which will only reinforce EV uptake disparity if not addressed. Where markets fail to deliver either economically or socially-optimal outcomes, governments can step in to shift the trend.

The state of California has recognized this, and has made an effort to encourage investment in public chargers in disadvantaged communities. As such, we expected to find publicly-funded charging stations to be more equally distributed among race and ethnicity groups. However, we found the access gap in publicly-funded chargers in California to be *larger* than that for public chargers overall. This finding may reflect the purpose of early EV infrastructure funding, which sought to enable and support EV adoption for the early adopters in the early market. Furthermore, in the current policies, what constitutes a disadvantaged community is based the status designation by CalEnviroScreen. It identifies disadvantaged communities by census tracts based on an array of health and sociodemographic factors. But a census tract is not sociodemographically homogenous; designating funding for a disadvantaged census tract does not guarantee the funding for disadvantaged neighborhoods, businesses, or a census block groups—the unit of analysis in this study. For example, when applying for the public funding designated for disadvantaged communities, a private charging network company likely still aims to develop a good business case by identifying the part of the disadvantaged census tract with more EV owners, commercial activities, and vehicle traffics. A property owner applying for such public funding would also consider the return of the charger investment based on the potential charger utilization.

With California's aggressive EV goals, more funding will be needed in Black and Hispanic communities to prevent a situation where the early adopters continue to receive the disproportionate infrastructure support. Charger access not only influences the EV operation of the residents in the CBGs, it also affects the EV drivers elsewhere. The presence of public chargers, in addition to enabling EV operation for the local residents, also provides convenience for EV drivers elsewhere during their visits. The absence of public chargers in a CBG can harm the desirability of the destinations located there, such as the local businesses, further exacerbating an economic gap. As the EV adoption rate increases and the public charger business case strengthens, the privately-funded charging station investments are naturally going into areas with more customers (i.e., EV owners), which currently are the

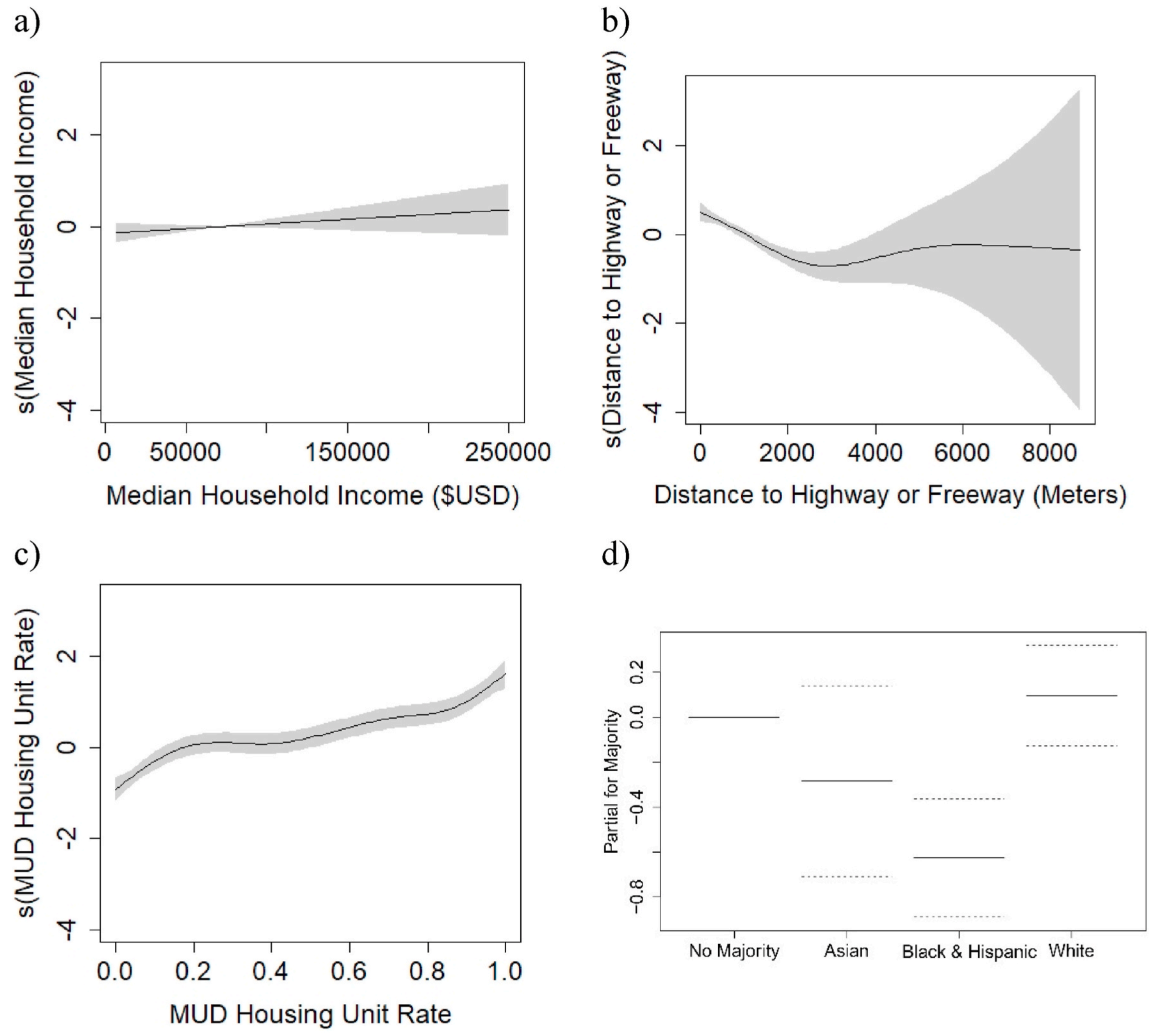

Fig. 5. a, b, c) Estimated smoothness of median household income, distance to the nearest freeway or highway, and MUD housing unit rate on the probability of access to publicly-funded chargers; y-axis is the partial effect of the variable and not on the same scale as the response variable (i.e., charger access probability); grey bands represent the approximate 95% confidence limits. **d)** Estimated effect for each race and ethnicity majority on the probability of access to publicly-funded chargers. The effect of no majority, shown as zero, is used as the reference.

wealthier and White majority neighborhoods. Public monies should be spent in communities that otherwise will be left behind and causing technology lock-in with lasting impacts.

Lastly, the results shown Figs. 2 and 3 should be interpreted with caution as the trend lines at the tail-ends (i.e., high and low) of the X-axes could be driven by the relatively small number of CBGs in those bins. However, the disparity patterns discovered are still consistent if only comparing the trend lines at locations with more and relatively similar amounts of CBGs between the different groupings.

5. Conclusion

Early charging infrastructure development tends to focus on providing geographic coverage (Wood et al., 2017), but as we can see from the results, in California public-access charging infrastructure has been slow to arrive in lower-income communities and those with Black and Hispanic majority and lower-income. Since investment in public charging infrastructure has been shown to follow EV adoption, this will further amplify socioeconomic and demographic disparities in EV uptake. As the EV market approaches price parity with conventional vehicles and the secondary EV market matures, charging infrastructure can be the primary remaining barrier, and the government should help to fill the public charger access gap for underserved communities.

In the early phase of EV uptake, it may have been seen as necessary to place chargers near early adopters to facilitate uptake without consideration of equity. California's suite of equity focused regulations is the right step in promoting an equitable EV adoption. But in the coming phases of EV transition, it will be important to further and actively direct public investment in public chargers to develop infrastructure that is equitable and future-oriented for all potential EV drivers. This is especially important in market segments that are not well-served by private investments. Cities have also been trailblazing with innovative EV charging infrastructure policies. And public charger access can benefit from synchronization between state- and city-level initiatives. The policy makers and state agencies can improve the equity guidelines and metrics used to direct the electrification and infrastructure investments. Relatedly, better data collection on inputs for the improved equity metrics will be needed. And lastly, to the extent possible, more decision making and planning power should be retained in the local communities.

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