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Abstract
This study addresses two topics relevant to the expanding research on how early adopters of hydrogen fuel cell vehicles (FCVs) evaluate stations. First, we assess FCV adopters' access to available stations near home or on the way when they adopted their FCV. Second, we analyze characteristics of geographically convenient stations that drivers did not intend to use ("unlisted stations") and compare to those they did ("listed stations"). Responses from a web-based survey distributed to FCV adopters in California indicate that nearly half lacked a station within 10 minutes' drive of home, while nearly all had one on the way. Drivers did not intend to use nearly half of their geographically convenient stations. Compared to listed stations, unlisted stations are closer to other available ones and commonly only on the way, and several neighborhood-level differences are observed. These findings are important in the context of efforts to expand FCV uptake.

Keywords: hydrogen fuel cell vehicle, station planning, network GIS

1. INTRODUCTION

Over 10,000 hydrogen fuel cell vehicles (FCVs) have been sold or leased in California since they became available in the state, supported by nearly 50 available retail public hydrogen refueling stations (HRSs) with others forthcoming [1]. Other geographic regions interested in learning best practices on FCV roll-out and diffusion, especially the northeastern United States, are paying attention to initial adoption and station use in California. Research on California's FCV adopters has found that drivers enjoy the competitive driving range of FCVs relative to conventional vehicles, lower subsidized costs relative to other alternative fuel vehicle (AFV) types, fast refueling times, and appeal to tech-savvy and environmentally conscious consumers [2-5]. However, in addition to supply, demand, and institutional barriers, refueling infrastructure remains a key inhibitor to more widespread FCV diffusion [6,7].

The need to address the infrastructure barrier has motivated a wealth of literature that recommends how to arrange a network of stations to encourage adoption in different ways [8-12]. Consistent with research on uptake and use of other AFVs, recent surveys of FCV adopters in California have corroborated the long-held notion that drivers would value stations' convenience to home, work, and frequently traveled routes [13-15].

A key limitation to this recent work, though, is the uncertainty about how many drivers even had access to stations near home or conveniently along the way at the time of adoption, which might in part influence why they prioritized the geographic criteria they did. Additionally, it is unknown to what extent drivers were *not* planning to take advantage of stations near home or on the way at the time of adoption, and the common characteristics of such eschewed stations. These previously unexplored considerations carry important implications for hydrogen station planning. If stations near home or on the way were available at the time of adoption but drivers did not intend to use them, it could suggest that focusing just on these criteria may be too narrow of a planning scope. However, it may also signal that early adopters may be systematically avoiding stations in certain areas despite their geographic convenience as a result of characteristics of the station, characteristics of the surrounding neighborhood, or both. Avoidance of stations associated with certain neighborhood characteristics could carry implications for recent efforts in California to more equitably site infrastructure in order to encourage AFV adoption in disadvantaged areas [16,17]. Lower use of stations in such areas could limit the longevity of stations there and inhibit AFV uptake nearby. Assessing how convenient station avoidance aligns with both station and neighborhood characteristics could assist in the development of better strategies, regulations, and policies that can help encourage AFV uptake from broader segments of the population [18,19].

The California Energy Commission (CEC) recently announced a plan to provide $115 million to help co-found the construction of 94 new HRSs in the state and upgrade 4 existing ones, and the CEC, the California Air Resources Board (CARB) and station developers are exploring how best to locate hydrogen stations in underserved and disadvantaged areas [15]. This investment would help enhance the network of nearly 50 stations in the state, of which half are in the greater Los Angeles area, roughly a quarter in the San Francisco Bay Area, with the remainder elsewhere in the state. As part of California Assembly Bill 8 passed in 2013, CARB provides regular assessment of station network status, use, and FCV uptake through its annual reports. These routinely highlight FCV drivers' desire for more stations, which frequently cite station unreliability and concerns about sustainable hydrogen production as barriers to greater uptake [15]. While the CEC's recent funding announcement promises more stations to meet refueling demand, it uncertain how geographic criteria will be prioritized in locating new stations, including in disadvantaged communities, nor is it clear how early adopters might consider or prioritize stations in these areas. In this context, then, it is important to gain a better understanding of the kinds of stations drivers intend to use at the time of adoption and how they compare to those they do not.

To address these topics, we ask the following research questions: 1) to what extent did early FCV adopters have publicly available hydrogen stations either near home or on the way – the two most common criteria considered in the station planning literature – when they adopted their FCV?; 2) for those who had stations that satisfied these criteria, to what extent did respondents intend to use them?; and 3) If there were geographically convenient stations that drivers did not intend to use at the time of adoption, what were the characteristics of these stations and their surrounding neighborhoods, and how did these compare to stations drivers did intend to use? Using 129 responses collected from a web-based survey distributed to FCV adopters in California, we asked which stations drivers intended to use at the time of adoption. Using network GIS analysis, we evaluate all available stations' convenience to home or frequently traveled routes and then identify if drivers listed these stations or not. We then compare station-level and neighborhood-level characteristics between stations they listed in the survey as those they intended to use ("listed stations"), and those geographically convenient ones that they did not intend to use ("unlisted stations"). We analyze differences between listed and unlisted stations using a series of logistic regression models.

This study is the third in a series of papers from the same survey that collected information about stations that FCV adopters in California intended to use at the time of adoption [14,20], though we explore key phenomena untouched by the earlier papers. These previous studies focused entirely on stations that drivers intended to use, whereas this paper investigates the opposite set, namely those stations that were available at that time but which they were not intending to use. This study contributes new insights into the availability (or lack thereof) of stations that are near home and/or on the way for individual early adopters, and the common characteristics of stations that drivers eschewed at the time of adoption, despite their geographic convenience.

2. LITERATURE REVIEW

Most studies on HRS locations and station use fall into two broad categories: models for station location planning, and studies of FCV driver refueling preferences. Preference studies are essential for better understanding early adopter driving and refueling behavior, and for determining what types and metrics of geographic convenience should be prioritized in station location models.

2.1 HRS Location Planning Models

Most of the HRS location literature uses operations research models for optimizing one or more mathematical objective functions subject to some constraints, to recommend locations for HRSs in a geographic area of interest [8,11]. Other models use geographic information system (GIS) methods for detailed modeling of site suitability, including the use of supply and demand surfaces [9,21,22].

HRS location models can also be categorized based on how they represent the geographic demand for stations relative to early adopters: points/nodes, arcs/links, paths/ routes/trips, or tours/trip chains. Each of these approaches assume a certain definition of geographic convenience and attraction for drivers. First, point-based models generally assume that drivers desire stations near home. Many models have adopted a p-median approach that minimizes total time or distance traveled from residential neighborhoods to their nearest station [23,24], thereby satisfying refueling demand, while others employ a covering approach based on a maximum travel time or distance considered to be sufficiently convenient for drivers to reach stations [25]. The median and covering approaches have been combined [26] and extended to the need for neighborhoods to be served by a cluster of two or more stations [27,28].

The other types of station location models all assume in various ways that drivers access HRSs while driving along frequently traveled routes. Arc-based models assume that traffic volumes on network links best represent the demand for fuel and locate stations convenient to busy roads. While the average annual daily traffic (AADT) volume data needed for these models is readily available from transport agencies, these models face challenges in ensuring that drivers' origin-destination (O-D) trips can be completed without running out of fuel. To address that issue, another on-the-way modeling approach starts with a less-easily obtained matrix of origin-destination trip volumes as the demands to be served. Flow-refueling location models (FRLM) aim to maximize the number of round trips that can be successfully completed on shortest paths or with reasonably short deviations without exceeding a safe driving range of FCVs [29-32]. Finally, tour-based models also assume on-the-way refueling but recognize that drivers frequently visit several stops on a sequence as part of a trip chain. Refueling could be accomplished on any part of such a tour to guarantee that it can be completed [33]. An implicit assumption of the arc, path, and tour models is that drivers are willing to refuel at stations conveniently on their regular driving routes, though not necessarily near their homes. A second implicit assumption is that any single driver is served by different stations that are part of a HRS network across a region, on different arcs, trips, and tours that they drive on.

Some GIS and operations research models consider both point-based and on-the-way refueling demand simultaneously [15,25,28,34]. Studies that have compared the demand satisfaction capabilities of different models have generally found that it is possible to serve a larger fraction of drivers across a wider area with a small number of stations and less wasted travel time *assuming* driver willingness to refuel conveniently on their way but not necessarily near home [35]. Thus, it is important to know how drivers actually evaluate and utilize stations they consider to be geographically convenient when planning an initial network of stations in order to encourage FCV adoption in a region.

2.2 HRS Location Preference Studies

Drivers' preferences for station locations have been studied in several ways through both stated and revealed preference approaches. Numerous studies have asked drivers where they would prefer stations to be located [36,37] and whether they would hypothetically be willing to adopt a vehicle under various assumptions about station availability [4, 38-40] In general, stated preference studies tend to show that drivers most prefer stations near where they live, with less willingness to refuel on regular driving routes. This may be due to extrapolating from their gasoline and diesel driving experience, where the density of stations means there are often several stations near their home that are on their way regardless of which direction they are headed [41].

With the introduction of FCVs and HRSs in California in 2014, it became possible to study how FCV drivers actually evaluate and prioritize station convenience relative to these and other geographic criteria of interest. Studies have surveyed early adopters about their station patronage [13,15,20] and the stations they were planning to use when they purchased their FCV [14,20], interviewed consumers at test-drive clinics [42], and used in-depth ethnographic methods with early FCV adopters [3,5,43]. Taken as a whole, these studies generally find that early adopters considered convenience to home as the most desirable and impactful factor, followed by stations near work and on the way, with some evidence of drivers learning through experience about the availability and convenience of stations that are farther from home but on frequently used routes and eventually using them [20].

Importantly, among both stated and revealed preference studies, most have focused on the driver's "primary" station. Few drivers, however, depend entirely on a single station to meet their driving and refueling needs [14]. To capture this, some stated preference studies have asked drivers to evaluate hypothetical maps of multiple stations when weighing whether to adopt an FCV [44]. A few revealed preference studies have also taken the perspective of drivers considering or using a portfolio of stations when deciding to adopt, which together cover a broader range of geographic criteria, including stations for long-distance travel [3,5,14,20]. Several studies have also highlighted problematic stations, mostly for reasons related to reliability, congestion, and risks imposed by large commercial vehicles using the stations [3,5,10,45]. There is a gap in the literature, however, when it comes to systematic studies of geographically convenient stations that are left out of drivers' portfolios of stations that they could reasonably have included, which this paper aims to address.

3. METHODS

3.1 Recruitment and Survey

In January 2019, we distributed a web-based survey via email and Facebook that was completed by 129 FCV owners in California. Facebook groups that granted permission to advertise the survey included: Toyota Mirai Owners (1,900 members), Honda Clarity Fuel Cell Owners (650 members), the Hydrogen

Car Owners (4,200 members), and GM Project Driveway (600 members). Information-sharing amongst early FCV adopters in online forums and communities has been identified as important to them in previous studies [3], making these good sampling frames from which to recruit. One limitation, though, is that this strategy did not capture responses from FCV owners who do not participate in these online communities. The Institutional Review Board of the authors' universities reviewed the survey to ensure it contained minimal risk of participation to respondents before being distributed. The survey could only be completed by those who lived in California, were over the age of 18, and had an FCV when they completed the survey.

The survey prompted respondents to list the names of up to five public hydrogen stations in California that they intended to use when they decided to adopt their FCV. Drivers provided a date of acquisition of their FCV and the survey included maps of available and planned stations during each quarter-year from 2015 through 2019 for reference. See [14] for full details on survey questions and data collected from this instrument. The primary data collected from the survey that were used in this analysis are: 1) where FCV adopters lived at the time they decided to get the vehicle, 2) the geographic locations of destinations they frequented at the time of adoption, and 3) the names of public retail hydrogen stations they intended to use when they first got the vehicle. The survey did not collect information about respondent age, gender, or whether they bought or leased their FCV, instead focusing on the geographic locations of interest.

3.2 Defining and Identifying Geographical Convenience and Unlisted Stations

We use a combination of spatial analysis and survey responses to define and identify listed and unlisted stations. In this study, "unlisted stations" are those reasonably convenient to a driver at the time of adoption, but not listed in the survey by drivers as intended for use. We identify them by assessing both stations' proximity to home and deviations required to reach them from a shortest travel time path between home and a destination the driver listed in the survey. To evaluate stations' proximity to home, we use a common finding in the literature that prospective adopters would prefer stations to be within approximately 10 minutes of home at the time of adoption [36,37,42]. To measure whether a deviation to reach a station is convenient, we refer to a consistent empirical finding that AFV drivers are willing to travel up to six minutes out of their way reach stations [14,46,47]. Using these two literature-derived thresholds, we determine if stations would be considered suitably convenient under these conditions (Figure 1).

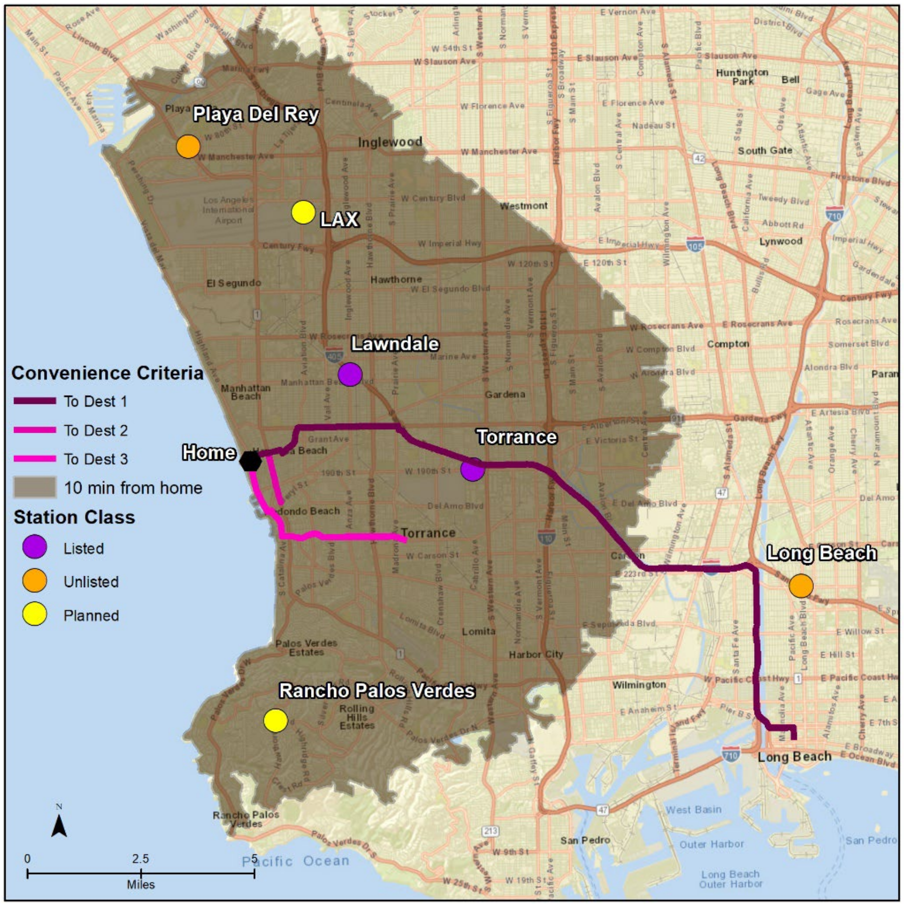

Figure 1. Example identification of unlisted and listed stations for a respondent living in Hermosa Beach. Note the stations designated as "planned" at this time, which are not considered in this analysis.

To evaluate station convenience to home, we generated 10-minute free flow travel time service areas away from all respondents' home locations provided in the survey in ArcGIS 10.7.1's Network Analyst using a detailed street network for the state of California. If an available station at the time of adoption fell inside a service area, it is classified as one "near home." We then identified whether the respondent listed that station in the survey as one they intended to use. If they did not, this is an unlisted station. We also recorded whether respondents had *any* stations within these service areas or not.

We next identify stations conveniently on the way between home and destinations identified in the survey at the time of adoption, which we refer to as stations "on the way" hereafter in this study. To do so, we analyzed how much drivers would need to deviate from shortest travel time paths between home and their main destinations to reach stations. Using the same detailed street network used to generate the service areas, we computed shortest free flow travel time paths between home and each of the three destinations given. Then, we inserted each station available at the time the respondent adopted the vehicle as the only stop on a route between home and the destination. The difference in estimated travel time between the home-station-survey destination route vs. the home-survey destination route is the deviation. If the deviation required to reach any station along any of the three home-to-destination routes was six minutes or less, we identified that station as conveniently on the way. We then identified whether the respondent listed that station in the survey as one they intended to use. If they did not, this is also an unlisted station. We then evaluate if respondents had any stations on the way or not.

In this study, individual stations can be listed by one driver, but could be considered unlisted by another driver if that station was (a) geographically convenient, (b) available at the time of adoption, and

(c) not listed by the other driver. The unit of observation, then, is each listing or non-listing of a station by a respondent. Of interest is how the group of unlisted stations differs from two distinct groups of listed stations, which are those that are either: 1) stations listed by drivers that satisfied the same geographic criteria as unlisted stations, 2) stations listed that did not satisfy the same geographic criteria as unlisted stations. The first scenario directly compares characteristics between geographically convenient listed and unlisted stations. The second scenario helps to evaluate if there are systematic differences between convenient, unlisted stations and those listed that do not satisfy either of the two "classic" convenience criteria in the station location planning literature, but were desirable to drivers for other reasons.

Of note, all retail hydrogen stations considered in this analysis either only had H70 pumps or both H35 and H70 pumps at the station. That meant FCV drivers had access to the H70 pumps which allow for a full refuel at all stations throughout the study period. Finally, we focus only on stations available at the time of adoption for drivers instead of those planned. Planned stations carry a bit more uncertainty: some never come online as advertised, or much later than anticipated, while available stations allowed drivers the opportunity to research, visit, or more concretely consider them for use. While planned stations are certainly of interest to prospective drivers, we do not consider them further in this analysis.

3.3 Additional Respondent Considerations

Before finalizing the group of unlisted stations, we considered the number of stations each respondent provided in the survey. Since the maximum number a respondent could list was five, we removed unlisted stations associated with respondents that listed five from further analysis, as it is possible that someone might have listed one of the unlisted stations provided more room. While they may not have considered such a station as one of their five most important, they may still have intended to use it. In this analysis, we also consider survey responses to the question that asked them how confident they were in their recollection of station locations. While stated recollection is an imperfect measure, it does provide some indication of awareness of station options at the time of adoption.

3.4 Geographic Characteristics of Stations

In the survey, drivers could list up to three pre-generated reasons why they intended to use stations they listed, but equivalent responses were not collected for unlisted stations. Therefore, this analysis focuses primarily on comparisons of objectively measurable geographic characteristics between listed and unlisted stations. In addition to objective metrics regarding stations' proximity to home or frequently traveled routes, we also consider stations' 1) proximity to the nearest other available hydrogen station and proximity to freeway entrances, both of which are also derived using network analysis, 2) reliability issues, identified by whether other survey respondents who did list the station in question noted that it had such issues, and 3) neighborhood characteristics.

The neighborhood characteristics are stored at the U.S. Census Tract level in GIS and reflect two general dimensions. The first includes characteristics that have been shown to influence AFV adoption and use [39,40,48], including but not limited to those characteristics first noted by [22] specific to FCVs. All data are 2015-2019 5-year estimates from the American Community Survey [49]. For all tracts in California, we compile percentages of: population aged 18-35 (which approximate the boundaries of the "Millennial" generation), population aged 55 and over, white (non-Hispanic) residents, population with a bachelor's degree or higher, those with commutes greater than 20 minutes, households making over $100,000/year, households with two or more vehicles, households with no vehicles, occupied housing units, single-family housing units (SFH), and multi-family housing units (MFH).

The second dimension includes workplace area employment characteristics, using the most recent U.S. Census Longitudinal Employer-Household Dynamics (LEHD) data [50]. For all tracts in California, we compile percentages of high-paying jobs (earnings $3,333/month or greater), low-paying jobs (earnings $1,250/month or less), and jobs for workers aged 30 to 54. Other studies have identified that FCV adopters tend to be relatively wealthy [2], so this helps us to explore stations' convenience to relatively high-paying jobs that might employ early adopters. We additionally consider the number of residents in each tract who took advantage of the California Clean Vehicle Rebate Program through the end of 2019 [17]. We intersect station locations and respondent home locations to these tract-level data in GIS.

We use these geographic characteristics in two ways. First, we descriptively compare differences in these characteristics between listed and unlisted stations under the two scenarios of interest: geographically convenient stations vs. unlisted stations and geographically inconvenient stations vs. unlisted stations. For geographically convenient stations, we further compare differences in these characteristics in cases where these stations were either close to home, on the way, or convenient to both. Second, we use these geographic characteristics as independent variables in the logit regression analysis.

3.5 Station Locations and LISA Spatial Clusters

To determine whether listed or unlisted stations are in areas with relatively high or low concentrations of each neighborhood-level geographic characteristic noted in the previous section, local indicators of spatial autocorrelation (LISA) are computed for all characteristics for all census tracts in California [51]. Specifically, we evaluate the geographic correspondence of listed and unlisted stations and univariate high-high (HH) and low-low (LL) LISA spatial clusters for each neighborhood characteristic of interest using a first-order queen contiguity spatial weights matrix. Prior to LISA spatial cluster identification, we computed univariate Moran's I statistics to test for global spatial autocorrelation for each neighborhood-level characteristic considered throughout the state, finding moderate to strong signals of positive spatial autocorrelation for each, with the lowest score being 0.39.

We then identify the locations of spatial clusters. HH clusters are cases where a census tract has a high value relative to the mean value of all census tracts in California and is surrounded by tracts with values that are also higher than the mean. LL clusters are the reverse: where a tract has a low value relative to the mean and is surrounded by tracts that also have low values. In addition to the correspondence of listed and unlisted stations with these two forms of LISA clusters, we also consider their correspondence with home locations of respondents. We identify whether listed or unlisted stations fall inside high-high LISA clusters ("hotspots") or low-low clusters ("coldspots") (Figure 2). We repeat this for respondent home locations. Global and local spatial autocorrelation tests and analysis was conducted using the GeoDa 1.18.0.0 software platform.

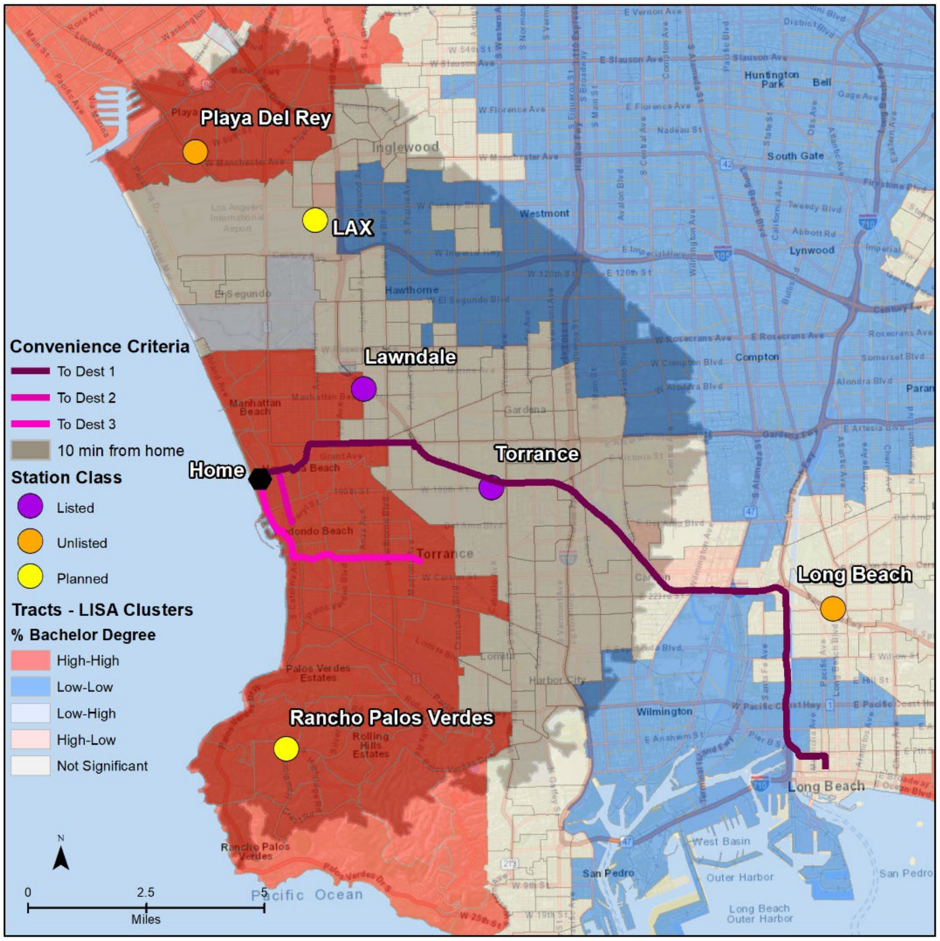

Figure 2. Example LISA cluster correspondence with a respondent's listed and unlisted stations. Note the High-High (HH) "hotspots" in red and the Low-Low (LL) "coldspots" in blue.

3.6 Statistical Analysis and Logistic Regression Models

Of primary interest are the significant differences in station-level and neighborhood characteristics between listed and unlisted stations. We consider how stations unlisted by respondents compare to those listed under the two scenarios of interest.

In both scenarios, we first compile and analyze descriptive statistics for both station-level and neighborhood characteristics for listed and unlisted stations. We then tabulate correspondence with HH ("hotspot") or LL ("coldspot") LISA spatial clusters of listed and unlisted stations, along with home locations. Next, we specify two binary logistic regression models to evaluate differences in characteristics between unlisted and listed stations in each scenario.

In both models, the dependent variable is whether the station was unlisted. Independent variables include station characteristics, characteristics of neighborhoods surrounding stations, or interactive variables that represent hotspot and coldspot cluster correspondence of stations and home locations (e.g., does the respondent live in a hotspot of those with a bachelor's degree or higher while the station is in a coldspot). Prior to entering any variables in either model, we tested for multicollinearity between independent variables, adding first the appropriate station-level and neighborhood variables using a stepwise selection approach, adding or removing variables one at a time according to their statistical contribution.

Then, for any neighborhood characteristic included in these two models, we consider whether station neighborhood characteristics alone or interactive variables best improve model performance. To do so, we compare model fitness between the model that only includes the station's neighborhood characteristic and the one that includes an interactive variable.

4. RESULTS

4.1 Respondents and Convenient Stations

Of the 129 survey respondents, 106 listed a) both a home location and at least one frequently visited location away from home, and b) at least one station they intended to use at the time of adoption. We first note that only 58 of these 106 respondents (55%) had a station available at the time within 10 minutes of their home (Table 1), with proportions nearly identical between respondents in greater Los Angeles and the San Francisco Bay Area. This means that nearly half of respondents felt comfortable adopting an FCV without an available station within 10 minutes of home. Of these 58 respondents with stations near home, nearly all (56) listed one, reflecting the importance of stations near home for those that have them.

Table 1. Respondent Access to Stations and Frequency of Listing, by Geographic Area.*

Respondent Access to Stations	Los Angeles (n=62)	San Francisco (n=34)	Other (n=10)	Total (n=106)
Had Station Near Home	36	20	2	58 (55%)
Had and Listed Station Near Home	35	19	2	56/58 (97%)
Had Station on the Way	54	31	9	94 (89%)
Had and Listed Station on the Way	40	28	9	77/94 (82%)

*The units of observation for this table are respondents.

In contrast to the 58 of 106 respondents who had an available station near home, 94 of these 106 early FCV adopters had an available station conveniently on the way to at least one destination at the time of adoption, and of these 94, 77 listed one. Listing available stations only on the way is more common outside of greater Los Angeles and its larger number of stations. The key findings here are: 1) respondents had more access to stations on the way compared to those near home at the time of adoption, and 2) if they had stations that aligned with these criteria, respondents intended to take advantage of them, particularly stations near home.

4.2 Unlisted and Listed Stations by Geographic Convenience Criteria

In total, there were 124 unlisted and available stations at the time of adoption that were either near home or on the way, compared to 243 listed stations, of which 144 were also geographically convenient according to these criteria. We focus on the differences between convenient listed and unlisted stations first (Table 2). Over half of the convenient unlisted stations were only on the way to one destination. Of all stations conveniently on the way to only one destination, just over one-third of these were listed. Stations that satisfy every other convenience category in Table 2 were listed over half of the time.

Table 2. Frequency of Geographically Convenient Stations Listed or Unlisted by Criteria.†

Station Convenience Category	Listed	Unlisted	Total	Listed (%)
Near Home Only	22	11	33	67
On the Way to One Destination Only	57	95	152	38
On the Way to More than One Destination	18	10	28	64
Near Home + On the Way to One Destination	21	4	25	84
Near Home + On the Way to More than One Destination	26	4	30	87
TOTAL	144	124	268	54

†The units of observation for this table are listings and non-listings of convenient stations by individual respondents.

Of the 88 available stations near home at the time of adoption, respondents listed 69 of them (78%). These stations were listed more often if the station was *also* on the way to at least one destination. Similarly, stations on the way were more frequently listed if convenient either to multiple destinations or near home. One notable finding is that drivers listed stations on the way to more than one destination but *not* near home nearly as often (64%) as stations that are near home but *not* on the way (67%). What is clear is that the drivers gravitated to stations convenient to both: of the stations that are both near home *and* on the way to at least one destination, 85% are listed while only 46% of stations convenient to one are.

There are noticeable relationships between the ratios of listed and unlisted stations by these convenience criteria as the size of the market and the corresponding refueling station network increases (Figure 3). Unlisted stations outnumber listed stations for stations only on the way in Los Angeles. If respondents are fortunate to have stations convenient to both, they generally list them.

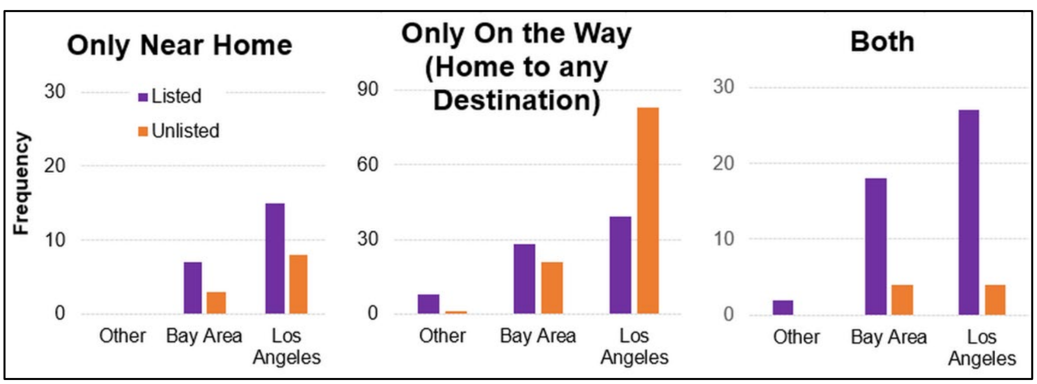

Figure 3. Relative Distribution of Unlisted and Listed Stations by Convenience Criteria and Geographic Region.

When evaluating how frequently drivers list specific stations or not, we note that in the Greater Los Angeles area there is a clear geographic boundary where the ratio of unlisted to listed stations changes (Figure 4). Most stations in the western half of Los Angeles County were unlisted more often than listed, while the reverse is true for those in Orange County. In the sparser networks of the Bay Area and those outside of the two major markets, stations are generally more frequently listed than unlisted.

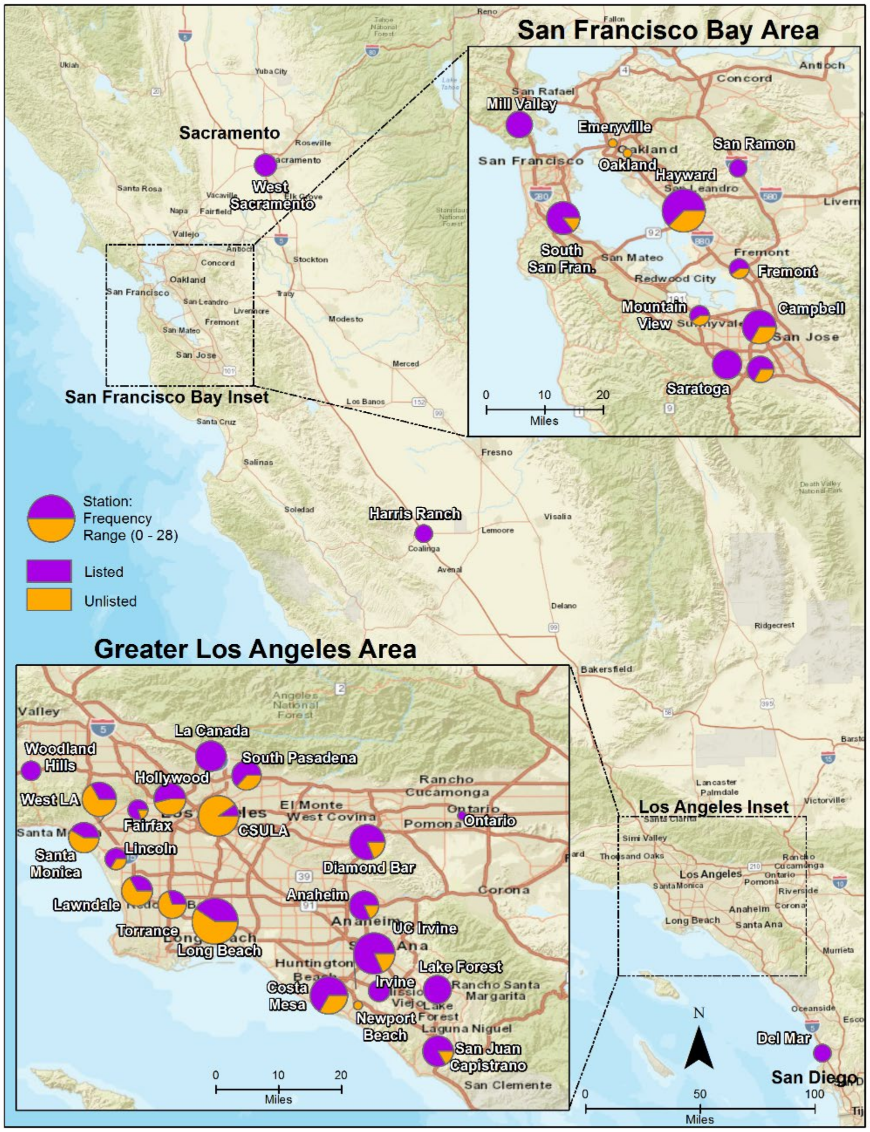

Figure 4. Frequency and Proportion of Individual Stations Listed or Unlisted by Respondents.

4.3 Descriptive Statistics of Listed and Unlisted Stations

We next compare descriptive statistics between listed and unlisted stations that were either only near home, only on the way, or both near home and on the way. In all cases, unlisted stations tend to be farther from home and nearer to other available stations, in census tracts with higher Millennial populations, and a higher percentages of residents with a 20 minute or greater commute (Table 3). Except for the near home only stations, there were fewer residents who had gotten an FCV rebate near unlisted stations. Several of these classifications produced in Table 3 include only a few station listings, making it difficult to generalize much about them, but there are some notable in some of the classifications with somewhat larger numbers.

We note several similarities in the relationships of geographic characteristic between listed and unlisted stations that were 1) both near home and on the way and 2) those that are only on the way. The resident white, non-Hispanic population is lower in areas with unlisted stations compared to those listed in each case, and even more pronounced when a station is both near home and on the way. Additionally, in each case, resident income and education levels are much higher in areas where stations were listed compared to those unlisted. Higher paying jobs are also more prevalent near unlisted stations in each case, though low-paying jobs are more common near unlisted stations compared to listed, while the reverse is true for stations both near home and on the way. Many of these differences between listed and unlisted stations neighborhoods are fairly consistent across the geographic classification types.

Table 3. Comparison Descriptive Statistics between Listed and Unlisted Stations by Geographic Convenience Classification. (All values are medians except the binary factors, which are means)

FACTOR	Both (n=55)		Near Home Only (n=33)		On the Way Only (n=180)	
	Listed (n=47)	**Unlisted (n=8)**	**Listed (n=22)**	**Unlisted (n=11)**	**Listed (n=75)**	**Unlisted (n=105)**
Nearest other station (mi.)	5.0	4.9	5.0	4.9	7.4	5.0
Nearest freeway (mi.)	0.5	0.1	0.8	1.0	0.6	0.5
Distance to home (min.)	5.1	6.0	6.3	9.7	23.5	41.6
Lowest deviation (min.)	1.7	1.9	10.9	10.9	2.3	2.2
Binary Factors (%)						
Extremely confident[a]	61.7	50.0	0.7	0.7	0.65	0.67
Unreliable station[b]	0.1	0.4	0.3	0.0	0.15	0.19
Neighborhood Factors (%)						
Age 18-35	24.0	29.7	20.8	53.4	22.9	27.2
Age 55 and over	22.2	24.2	10.4	19.0	23.3	23.1
White, non-Hispanic	34.7	7.2	49.4	51.4	37.4	35.7
Drive alone	74.3	64.7	75.1	74.3	74.3	72.2
Two or more vehicle household	57.7	61.1	67.0	67.0	58.9	53.1
Zero vehicle household	5.4	4.8	2.9	2.0	5.8	8.0
20 min Commute or more	63.7	68.0	57.7	63.7	63.8	64.8
Bachelor's degree	57	17.9	57.0	71.5	56.2	37.7
$100k or more	47.6	21.6	48.6	60.0	49.2	28.8
Occupied housing units	36.0	40.0	45.7	61.4	49.3	35.3
Single family households	41.7	58.3	58.2	78.4	48.7	27.3
Multi-family households	54.6	41.7	41.8	21.6	51.4	62.3
High paying jobs	30.1	58.4	17.8	23.0	23.2	36
Low paying jobs	14.3	7.8	16.0	30.2	7.4	14.3
Jobs, age 30-54	49.5	55.0	44.6	46.0	49.5	54.4
FCEV rebates	3	0	5	5	3	1

Therefore, we evaluate summary statistics for station-level characteristics and those of surrounding neighborhoods between all types of geographically convenient listed and unlisted stations, and between geographically inconvenient stations and unlisted stations (Table 4). In both cases, unlisted stations are farther from home, nearer to freeway entrances, and closer to the nearest other available station compared to listed ones. Unlisted stations were slightly more associated with reliability issues, as noted by other respondents. Most stations in this analysis were also listed or not listed by respondents who were extremely confident in their recollection of stations in the survey, though this percentage was highest for listed stations not near home or on the way.

Table 4. Summary Statistics, Station and Tract characteristics of Unlisted and Listed Stations.

Factor	Listed, Convenient (n=144)		Listed, Not Convenient (n=94)		Unlisted (n=124)	
Location Factors	**Mean**	***SD***	**Mean**	**SD**	**Mean**	***SD***
Nearest other station (mi.)	9.5	*14.0*	8.8	*12.4*	5.3	*2.6*
Nearest fwy (mi.)	0.9	*0.9*	1.4	*1.1*	0.7	*0.9*
Distance to home (min.)	32.8	*74.3*	43.3	*51.1*	51.1	*52.5*
Lowest heviation (min.)	5.9	*15.5*	30.4	*35.2*	3.0	*2.8*
Binary Factors (%)	**Mean**	***SE***	**Mean**	**SE**	**Mean**	***SE***
Extremely confident[a]	65.1	*3.9*	74.5	*4.5*	66.1	*4.3*
Unreliable Station[b]	14.7	*2.9*	16.0	*3.8*	19.4	*3.6*
Neighborhood Factors (%)	**Mean**	***SE***	**Mean**	**SE**	**Mean**	***SE***
Age 18-35	28.5	*1.3*	28.0	*1.5*	29.2	*1.2*
Age 55 and over	23.5	*0.9*	24.7	*1.1*	22.6	*0.9*
White, non-Hispanic	39.6	*1.7*	40.9	*2.3*	27.7	*1.9*
Drive alone	71.9	*1.0*	71.6	*1.1*	65.0	*1.6*
Two or more vehicle household	57.1	*1.3*	57.5	*1.7*	48.6	*1.7*
Zero vehicle household	6.9	*0.6*	6.9	*0.6*	9.7	*0.8*
20 min commute or more	58.4	*1.2*	58.5	*1.7*	59.8	*1.7*
Bachelor's degree	49.7	*2.0*	48.3	*2.2*	37.7	*2.3*
$100k or more	45.2	*1.6*	41.8	*1.6*	31.9	*1.6*
Occupied housing units	42.4	*2.2*	42.1	*2.8*	28.9	*1.8*
Single family households	47.0	*2.7*	46.8	*3.3*	37.7	*2.7*
Multi-family households	51.6	*2.7*	52.1	*3.3*	56.7	*2.8*
High paying jobs	47.6	*2.3*	48.1	*2.5*	47.3	*1.8*
Low paying jobs	11.3	*0.8*	11.8	*1.0*	13.4	*0.8*
Jobs, age 30-54	45.4	*2.1*	48.0	*2.7*	51.2	*1.9*
FCEV rebates	5.8	*0.5*	6.7	*0.7*	3.0	*0.4*

[a]Respondent was extremely confident about their memory of which stations they intended to use at time of adoption.
[b]This is identified by at least one of the survey respondents indicating that a station had reliability issues.

Neighborhood characteristics surrounding listed and unlisted stations differed in several ways. Unlisted stations are more commonly in areas with lower percentages of single-family housing units, households making $100,000 or more or with two or more vehicles, white (non-Hispanic) resident populations, and those with a Bachelor's degree or higher. Of note, listed stations are in tracts with higher levels of FCV rebate use, suggesting a relationship between nearby FCV owners and listed stations. However, these are relatively low numbers and reflect the still-growing nature of the FCV market in the state.

4.4 LISA Spatial Cluster Analysis

Table 5 summarizes the geographic correspondence of listed and unlisted stations and univariate high-high (HH) and low-low (LL) LISA spatial clusters for each neighborhood characteristic of interest. Both station and resident home locations frequently lie in hotspots where household income exceeds $100,000/year. Nearly half of respondents live in hotspots where residents have a Bachelor's degree or higher. Characteristics where respondent home locations are more often in coldspots than hotspots include: population aged 18-35 (Millennial residents), households that do not own a vehicle, single-family housing units, and residents working in low-paying jobs. Except for the finding that early adopter home locations align more commonly with single-family housing coldspots than hotspots, many of the findings regarding home locations in Table 5 are consistent with past studies on early AFV adopters.

Table 5. High-High (HH) and Low-Low (LL) LISA Spatial Cluster Correspondence with Station Classifications and Home Locations.

Factor	Listed, Convenient (n=144)		Listed, Not Convenient (n=99)		Unlisted (n=124)		Home Locations (n=129)	
% in LISA Cluster Type	**HH**	**LL**	**HH**	**LL**	**HH**	**LL**	**HH**	**LL**
Age 18-35	24.1	29.0	16.1	30.4	13.0	25.2	15.8	30.0
Age 55 and over	17.0	21.3	25.0	12.0	20.3	10.6	15.8	15.8
White, non-Hispanic	34.8	10.6	43.5	7.6	28.5	15.4	33.3	12.5
Drive alone	24.1	16.3	12.0	7.6	18.7	15.4	15.0	11.7
Two or more vehicle household	17.7	13.5	25.0	13.0	17.1	12.2	26.7	13.3
Zero vehicle household	11.3	15.6	4.3	22.8	9.8	10.6	11.7	13.3
20 min commute or more	17.0	12.8	18.5	13.0	14.6	10.6	20.8	9.2
Bachelor's degree	41.1	24.1	40.2	9.8	42.3	15.4	49.2	7.5
$100k or more	48.9	5.7	46.7	4.3	45.5	8.1	43.3	6.7
Occupied housing units	34.8	14.2	27.2	12.0	24.4	10.6	24.2	20.0
Single family households	19.9	22.0	23.9	12.0	12.2	13.0	16.7	20.0
Multi-family households	19.1	19.9	22.8	17.4	10.6	10.6	20.8	17.5
High paying jobs	37.6	6.4	20.7	9.8	30.9	4.9	39.2	2.5
Low paying jobs	4.3	14.9	4.3	20.7	2.4	12.2	5.8	19.2
Jobs, age 30-54	22.7	7.1	13.0	7.6	15.4	4.9	21.7	6.7

Characteristics where stations are more commonly in hotspots than coldspots include: white non-Hispanic populations and households making $100,000/year, though these differences are smaller for unlisted stations. We note that home locations lie in hotspots more often than unlisted stations but less often than listed stations for the following characteristics: Millennial, white non-Hispanic populations, and single-family housing units. These results indicate some characteristic differences between listed stations and unlisted stations, some of which either align or diverge in notable ways from those of respondents' home areas.

4.5 Listed vs. Unlisted Station Logit Models

Given the observed differences in station and neighborhood characteristics between listed and unlisted stations, we specify two binary logistic regression models to evaluate how unlisted stations vary from listed ones, considering these factors. The dependent variable is whether a station is unlisted (1) or listed (0), using the two scenarios for which stations are considered as listed (geographically convenient and listed vs. unlisted, and geographically inconvenient and listed vs. unlisted). In each scenario, the number of unlisted stations is 124.

Table 6. Binary Logistic Regression Models: Unlisted Stations vs. Listed Stations by Scenario

Independent Variable	Listed, Convenient (n = 144)			Listed, Not Convenient (n=99)		
	β	**S.E.**	**OR**	***β***	**S.E.**	**OR**
Intercept	0.73	0.69	2.08	2.15**	0.65	8.56
Nearest other station (mi)	-0.27**	0.07	0.76	-0.21**	0.07	0.81
Distance to freeway (mi)	-0.10	0.19	0.91	-0.50**	0.18	0.60
Travel time to home (min)	0.01	0.01	1.01	0.01	0.01	1.01
Station is only on the way (0-1)[a]	2.51**	0.46	12.3	--	--	--
FCV Rebates	-0.11**	0.04	0.90	-0.11*	0.03	0.90
Station Tract: % Low Paying Jobs	0.06**	0.02	1.07	0.04*	0.02	1.04
Station Tract: % White, non-Hispanic	-0.03**	0.01	0.97	-0.02	0.01	0.98
Home Tract: Bachelors or Higher Hotspot	-0.60	0.41	0.53	0.20	0.39	1.22
Station Tract: Bachelors or Higher Coldspot	-1.10**	0.46	0.34	0.34	0.50	1.40
Station: Bachelors or Higher Coldspot * Home: Bachelors or Higher Hotspot	1.34**	0.79	3.83	0.16	0.79	1.18
Model Diagnostics						
AIC	254.9			241.4		
Nagelkerke R^2	0.53			0.36		
Log Likelihood	-116.5			-113.8		

** significant (α = 0.05), *significant (α = 0.10)
[a] This variable does not apply to geographically inconvenient stations, so is not evaluated in the model that includes them.

In both models, distance to the nearest other available station and the number of FCV rebates in the tract are negatively and significantly associated with a station being unlisted (Table 6). The station tract's percentage of low-paying jobs is a positive and significant predictor in both models. Distance to the nearest freeway entrance is a negative and significant predictor of an unlisted station in the model that compares inconvenient listed stations to unlisted ones, and the station tract's white, non-Hispanic population percentage is a negative and significant predictor in the model that compares similarly convenient stations. In the model that includes only geographically convenient listed stations, unlisted stations are significantly associated with the station lying in a coldspot of the population holding a Bachelor's degree or higher with the respondent living in a hotspot of those holding a Bachelor's degree or higher. We include this same interactive variable for comparison in the inconvenient stations model, but in this case, neither it nor the individual variables are significant predictors. Of note, in the model that includes geographically convenient stations, if a station is geographically convenient because it is only on the way, and not near home, it is more likely to be unlisted than listed. Station reliability, distance to the freeway, travel time from home, and respondent confidence in recollection of stations were not significant predictors in any model.

5. DISCUSSION

Nearly half of all available stations at the time of adoption that were either near home or conveniently on the way between home and a location they frequented went unlisted by respondents. Just over half of the drivers adopted an FCV without a single station within a 10-minute drive of home. Together, these carry important implications for station planning approaches that aim to encourage FCV adoption by catering to the two most frequently considered geographic criteria in this station planning literature, though there are important caveats and limitations.

First, some drivers may have extensively researched which stations they intended to use independently or through online communities while others may have done less advance research, and to what extent this influenced intention to use geographically convenient stations is unclear. Second, while the survey instrument allowed respondents to choose from a list of pre-generated reasons why they intended to use certain stations at the time of adoption, they did not have the chance to do so for unlisted stations, nor did respondents have the chance to indicate if exclusion of certain stations was intentional or not. Third, it suggests that the threshold of how close stations need to be relative to home locations to encourage FCV adoption may be larger than the approximate 10-minute threshold identified in prior stated preference survey work.

The uncertainty regarding intent must be considered when evaluating these results. It is unclear if an unlisted station in this analysis results from someone simply not realizing how convenient that station was at the time of adoption, prioritizing other stations elsewhere for other reasons, intentional avoidance, or some alternative explanation. Therefore, purposeful intent on the part of early FCV adopters to avoid or prefer certain stations or locations cannot be inferred from these results. Care must also be taken to avoid the ecological fallacy and not attribute neighborhood-level characteristics or findings to individual FCV adopters in this study. The survey instrument did not collect information on income, race/ethnicity, or education level of respondents, so these findings only reflect characteristics of the station or home neighborhood, not the individual. We also do not know how drivers' perceptions of neighborhoods in general influenced their decisions, which is a promising area for future work.

Of particular importance to station planning is that drivers did not intend to use nearly half of the available stations convenient to home or frequently traveled routes at the time of adoption. Even if a station was geographically convenient for a driver, a station's proximity to other stations significantly deterred listing it, suggesting that having stations too close to one another may be considered repetitive to some drivers. Of note, though, are the significant differences in the sociodemographic and employment characteristics of neighborhoods surrounding listed and unlisted stations, many of which are consistent with past research on characteristics of early AFV adopters.

These results are also reflective of when respondents first decided to adopt an FCV, when they likely had limited experience with the stations they intended to use. Additionally, while most respondents noted that they felt "extremely confident" in their recollection about which stations they intended to use at the time they decided to get an FCV, it is unclear if that meant that they were also extremely confident about which stations they had not intended to use.

The topic of station reliability must be considered, as station unreliability has the potential to supersede any geographic convenience. Other work on FCV adoption and station usage has highlighted station unreliability as a constant source of driver frustration [3,13] and given that we recruited our respondents from online communities that included information sharing, it is possible that some of the unlisted stations reflect well-established reputations or experiences reported in these environments, even if a station was not explicitly noted as such by a survey respondent. Even though station unreliability was not a significant predictor in our models, that does not mean it is an unimportant consideration to drivers. We were only able to identify station reliability issues using other drivers' survey responses. Better ways to collect and represent station unreliability would help inform future similar analysis.

There are two other key limitations of the study. First, a larger sample of FCV drivers in California would help better understand differences between listed and unlisted stations. We were only able to recruit 129 respondents, and the sample size does limit generalizability to some extent. We do note, though, that our sample accounted for about 2% of the total population of FCV owners at the time of the study [1]. Still, our findings should be contextualized as reflective of very early adopters of FCVs in California. Given the growth in the number of FCVs sold or leased since the study, and the number of stations planned to be built in the state, it will likely become easier to recruit a greater number of respondents in the near-term future, which will help inform more robust analysis. Second, the initial survey distributed to FCV adopters was designed to understand the nature of the stations they did intend to use at the time of adoption instead of ones they did not. Future surveying or interview work should be designed to ask respondents more explicitly about stations they did not intend to use and why not, given these initial findings in this study, particularly at a moment in station network planning where consideration of disadvantaged areas is becoming more of an emphasis.

6. CONCLUSION

The initial diffusion of FCVs to early adopters in California provided an opportunity to evaluate to what extent respondents had stations near home or on the way to frequently visited locations at the time they decided to adopt an FCV, and if so, to what extent they intended to use them. We find that over half had an available HRS within 10 minutes' drive of home at the time of adoption, while nearly all had at least one station conveniently on the way between a frequented location and home. If stations were convenient according to both criteria, drivers more frequently listed them compared to stations convenient according to only one. This adds to the growing body of evidence that locating stations convenient to multiple geographic criteria is a promising pathway to encouraging initial FCV diffusion, though this study did not consider geographic criteria beyond these two. It also suggests that while proximity to home is important for drivers who have stations near them, station planners should note that nearly half of survey respondents made the decision to adopt an FCV without a single station within a 10-minute drive of home, while very few did without a station on the way. In total, nearly half of all available stations conveniently near home or on the way to a location they visited often went unlisted by drivers.

Geographically convenient stations that drivers could have listed but did not are in neighborhoods with higher levels of low-paying jobs, lower percentages of resident white, non-Hispanic populations, and lower amounts of other early adopters who used the FCV rebates compared to listed stations that are also geographically convenient. They also tended to be only on the way, but not near home. These early adopters also tended to live in areas where many residents had a Bachelor's degree or higher, while convenient stations they did not list tended to be in areas where fewer residents had a Bachelor's degree or higher. When comparing inconvenient listed stations to unlisted ones, we again find that higher levels of low-paying jobs and lower resident FCV rebate use are associated with unlisted stations, but that the neighborhood-level differences found between similarly convenient stations are not observed. Stakeholders interested in seeing a widespread transition to AFVs are continuing to develop strategies to ensure their broader roll-out among the population. Avoidance of stations in areas that share some of these characteristics could limit the local diffusion of FCVs and the host of benefits that come along with that process to these areas, so policymakers should take note of this potential when crafting station location strategies.

As stations networks grow and availability increases, it is unclear how consistent these findings will remain, or to what extent they are reflective of California-specific factors. In future networks, station planners should not only continue to prioritize station locations that can satisfy multiple geographic criteria for respondents, but also continue to consider strategies that ensure broader access across neighborhood types. As vehicles become more widespread among the population, these considerations may change and results such as those found in this study may differ, but station planners must continue to pay attention to how respondents evaluate these factors in station choices in the coming years. This study also suggests that while research efforts should continue to evaluate which stations drivers intend to use and why, additional knowledge can be gained from learning about stations they did not.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: S. Kelley, S. Gulati, J. Hiatt, M. Kuby; data collection: S. Kelley, M. Kuby; analysis and interpretation of results: S. Kelley, S. Gulati, J. Hiatt, M. Kuby; Author; draft manuscript preparation: S. Kelley, S. Gulati, M. Kuby All authors reviewed the results and approved the final version of the manuscript.

DATA STATEMENT

Survey respondents were assured raw data would remain confidential and would not be shared. However, anonymized data that contains no personally identifying information may be made available by contacting the research team directly.

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