How Early Hydrogen Fuel Cell Vehicle Adopters Geographically Evaluate a Network of Refueling Stations in California

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Abstract

After a few years of initial sales, there is an opportunity to analyze how early hydrogen fuel cell vehicle (FCV) adopters evaluated the spatial arrangement of a network of stations prior to adoption. Since strategies differ on how best to arrange initial stations in a region to facilitate adoption, understanding how they did so informs future station planning methods. We distributed a web-based survey to 129 FCV adopters throughout California in 2019, asking them where they lived and traveled at the time of adoption, up to five stations they planned to use, and subjective reasons for listing those stations. We estimated shortest travel times to respondents' homes and other frequent locations, and deviations from frequently traveled routes. We compared differences in subjective and objective convenience for primary, secondary, and lower-ranked stations, and tabulated the different combinations of stations that satisfied adopters' various geographic criteria. Over 80% planned to rely on a portfolio of multiple stations subjectively convenient to key activity locations, and nearly 25% who provided subjective geographic criteria for listing stations did not include "near home" as their top reason for their primary or secondary station. Estimated travel times to stations subjectively considered "near" home, work, and other location types exhibit variability, but consistently decay beyond 90 minutes. Primary stations are subjectively and objectively more convenient to home and work than lower-ranked stations, and more associated with subjective convenience to home and objective convenience to work than secondary stations. Other destination types align with lower-ranked stations.

Keywords: hydrogen, fuel cell vehicle, survey, GIS, multinomial logistic regression

1. Introduction

By the end of 2019, over 18,000 hydrogen fuel cell vehicles (FCVs) had been sold or leased worldwide (IEA 2019). California residents accounted for 8,000 of these, supported by over 40 available public refueling stations (CAFCP 2020). Other U.S. regions, such as the northeastern United States, are now exploring FCV introduction to mitigate rising emissions from the transportation sector. FCV performance, aesthetics, subsidized prices relative to other alternative fuel vehicles (AFVs), driving ranges, and refueling times similar to those of liquid petroleum-fueled vehicles have helped encourage adoption (Hardman et al. 2017; Hardman and Tal 2018; Lopez et al. 2019), but the lack of a convenient refueling infrastructure remains the primary barrier (Melaina 2007; Li et al. 2018; Kurtz et al. 2019; Kuby 2019; Linzenich et al. 2019; Xu et al. 2020).

This long-acknowledged issue has led researchers to develop various geographical methods and strategies to recommend locations for AFV refueling stations (Agnolucci and McDowall 2013; Ko et al. 2016; Lin et al. 2020). There is no general agreement, though, on which geographic criteria should be prioritized to recommend station locations that can, in turn, facilitate FCV adoption. Various models recommend placing stations near home locations of likely early adopters (Nicholas and Ogden 2006;), frequently traveled routes (Lin et al. 2008; Kuby et al. 2009; Zhao et al. 2019), travel activity spaces (Kang and Recker 2015), or some combination of these (Ogden and Nicholas 2011; Stephens-Romero et al. 2010; Brey et al. 2016; Hong and Kuby 2016; CARB 2018). The question of which prioritization scheme best supports AFV adoption remains unanswered.

Several approaches can inform the choice of station location models to facilitate FCV adoption. Some have employed stated preference surveys to evaluate hypothetical station locations and arrangements (Caulfield et al. 2010; Yetano Roche et al. 2010; Guerra et al. 2016; Brey et al. 2017), and others have used revealed preference surveys to analyze driving and refueling behavior of adopters of comparable AFVs (Kitamura and Sperling 1987; Kelley and Kuby 2013; Kuby et al. 2013; Kelley and Kuby 2017). Scenario models (Greene et al. 2013; Kang et al. 2014) and optimization models (Upchurch and Kuby 2010; Honma and Kuby 2019) help to inform station locations. Another evaluated potential financial success using the actual planned network of hydrogen stations in California (Brown et al. 2013). These approaches, however, do not capture how actual FCV adopters prioritized stations' convenience to various geographic locations prior to adopting the vehicle.

Recent surveys conducted after early adopters began using FCVs in California found that drivers consider stations near home to be important, along with stations convenient to work and that require minimal deviation to reach (CARB 2018; Ramea 2019). These findings align with long-held suggestions that stations near home, work, and commute routes would be essential to facilitate initial FCV adoption (Sperling and Kitamura 1986; Nicholas et al. 2004), but leave unanswered how drivers simultaneously evaluate and prioritize these criteria relative to a network of stations before adopting their FCV. Also unknown is how close stations realistically need to be for drivers to subjectively consider them "close enough." Proximity to locations aside from home and work—including social or recreational destinations, family and friends, schools, and shopping—likely play a role in how drivers evaluate a network of stations. Therefore, hydrogen station location models need to account for how drivers evaluate the subjective and objective convenience of a network of stations relative to these locations.

This study addresses the following general research question: how did FCV adopters assess an existing network of hydrogen refueling stations when they decided to adopt one? We further ask: where are the stations they intended to use relative to home, work, and other frequently visited locations; how do the relationships of stations to these locations vary; and how much deviation from common travel routes are drivers willing to tolerate? We compare subjective measures of convenience (whether or not drivers consider them to be "near" locations) and objective measures of convenience (estimated travel times on a road network between stations and locations) for their listed refueling stations.

Using a web-based survey, we asked drivers to recall locations specific to the time they were considering FCV ownership, including their home location, up to three regular destinations, and up to five hydrogen stations they intended to use and why they intended to use them. We compiled descriptive statistics of survey responses, evaluated the combinations of most important reasons that drivers provided for listed stations, and used network GIS analysis to evaluate the relationships between stations and locations provided by respondents. Using ANOVA and t-tests, we tested for differences among the Los Angeles, San Francisco Bay, and other regions. We specified two multinomial logistic regression models using 1) subjective geographic measures of convenience and 2) objective measures of estimated travel times between stations and important locations, assessing differences in primary, secondary, and 3^{rd}-5^{th} ranked stations. These results can assist stakeholders interested in developing station location strategies that encourage FCV diffusion.

2. Methods

2.1 Recruitment and Survey Instrument

In early 2019, 129 FCV adopters in California completed an IRB-approved web-based survey. To participate, respondents needed to reside in California, be over the age of 18, and have been in possession of an FCV at the time of the survey. We recruited respondents through social media advertisement. Facebook groups that permitted us to recruit on their pages included: Toyota Mirai Owners (1,900 members), Honda Clarity Fuel Cell Owners (650 members), Hydrogen Car Owners (4,200 members), and GM Project Driveway (600 members). Given the active nature of these online forums and the importance of information-sharing amongst early adopters in these communities (Lopez et al. 2019), these were reasonable locations from which to recruit a broad range of respondents.

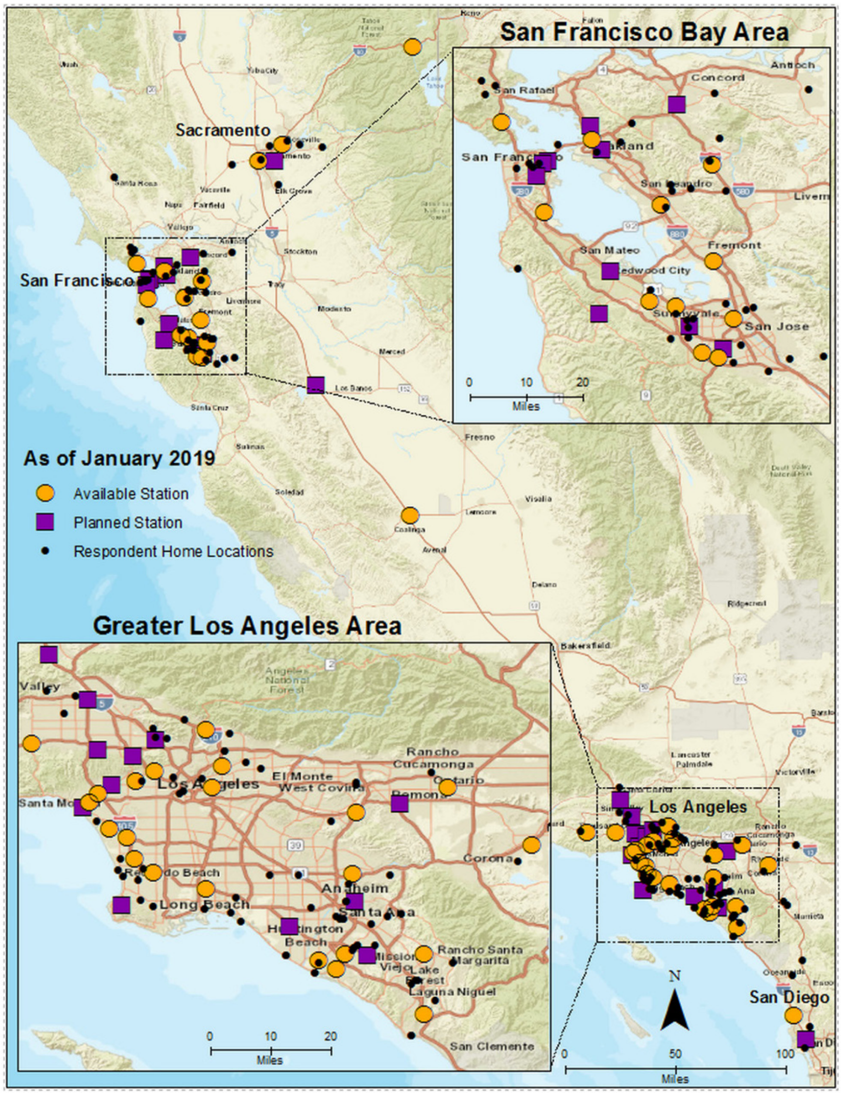

Fig 1. Map of available and planned stations as of January 2019, and approximate home locations of respondents who completed the survey in early 2019.

To help respondents recall station availability at their time of adoption, we provided maps of all available and planned hydrogen stations during that quarter-year (DOE 2019). We matched station names given by each respondent with point GIS station data, noting whether the station was available or planned at that time, such as the example shown in Figure 1 for January 2019. We also converted approximate home locations and frequented locations to point GIS data. Table 1 summarizes the survey data and how it was collected.

Table 1. Summary of data collected by survey.

<table>
<tr><th>Data of Interest</th><th colspan="2">Respondent Action</th><th>Data Returned</th></tr>
<tr><td>Location Data</td><td colspan="2"></td><td></td></tr>
<tr><td>Home</td><td colspan="2">Place pin on approximate location on Google Map embedded in survey</td><td>Latitude/longitude coordinates of home location</td></tr>
<tr><td rowspan="2">Most-frequented location of travel away from home (repeated for 2nd and 3rd most-frequented locations)</td><td colspan="2">Place pin on approximate location on Google Map embedded in survey</td><td>Latitude/longitude coordinates of up to three (3) locations</td></tr>
<tr><td colspan="2">Choose trip type from drop-down list of: work, social/recreational, shopping, school, other - specify</td><td>One trip type for each location</td></tr>
<tr><td>Station Data</td><td colspan="2"></td><td></td></tr>
<tr><td>Primary station, or first station listed (repeated for others)</td><td colspan="2">Fill in open-ended text response</td><td>Station name, matched to one in AFDC database</td></tr>
<tr><td rowspan="2">Reason for choosing station</td><td colspan="2">Choose up to three reasons below for listing station in order of importance</td><td rowspan="2">Up to three reasons, in order of importance, for planning to use each station listed</td></tr>
<tr><td>Geographic
Home
Work
School
Shopping
Social/Recr.
Friends/Family
On Way
Long Distance</td><td>Station
Reliability
Price
Safety
Amenities
Pressure
Not Crowded
Backup Station</td></tr>
<tr><td>Planned Refueling Time: Weekday or Weekend</td><td colspan="2">Choose one of following: (weekday, weekend, both)</td><td>One planned refueling time response for each station listed</td></tr>
<tr><td>Vehicle Information</td><td colspan="2"></td><td></td></tr>
</table>

Acquisition Date	Fill in open-ended text response of 1) month and 2) year that respondent adopted the FCV	Month and year of adoption. Used to calculate length of experience with FCV.
FCV Type	Choose: Toyota Mirai, Hyundai Tucson, Honda Clarity, Other	One make/model response per respondent
Respondent Information		
Confidence in recollection of stations respondent planned to rely on at time of adoption	Choose confidence in recollection of stations: extremely, very, moderately, slightly, or not confident	One confidence level per respondent

2.2 Revealed Station Convenience

We used a detailed street network GIS dataset for California to estimate travel times under free-flow travel conditions, which provides a general representation of objective convenience of stations to key locations. Using point data for home and frequented locations provided by each respondent and all available and planned station locations at the time of adoption, we estimated their shortest travel time paths along the detailed street network between home and: 1) stations listed by the respondent, 2) stations not listed by the respondent, for those either available or planned at the time. We repeated this process for the frequented locations provided by each respondent.

We automated route generation for all respondents using a Python script and ArcGIS 10.7.1's Network Analyst. These outputs produced estimated travel times between stations and home locations, and stations and frequented locations, and the rank-order position of each listed station relative to all stations either available or planned at that time.

2.3 Deviation Analysis

We estimated the deviations required to access the stations listed by each respondent and all other stations available or planned at the time. To do so, we used the California street network dataset to generate direct shortest travel time routes between each respondent's home location and their given frequented locations. For each shortest path route for each respondent, we inserted each station listed, and then all others that were either available or planned at the time of adoption but not listed, as an intermediate stop on the route between the respondents' home and frequented locations. The deviation to reach each station is the difference between the estimated shortest travel times of the home-station-location indirect route and the corresponding home-location direct route. We then determined the rank-order position of each listed station's deviation.

2.4 Spatial and Statistical Analysis

The survey prompted respondents to list up to five refueling stations that they intended to use before adopting the FCV. We classify responses as "primary," "secondary," or "3rd-5th" stations. For each station group, we compile descriptive statistics for stated (subjective) reasons for listing stations and revealed (objective) geographic relationships between stations and respondents' destinations using the estimated travel times, and deviations required to reach them. To assess how objective and subjective measures align, we evaluate and compare objective geographic relationships of those stations subjectively listed as "near" a location (e.g., near home, near work, near shopping).

Using only the highest-ranked subjective geographic reasons for listing stations, we evaluate and classify the combinations of stations that satisfied specific geographic criteria for each driver in MATLAB, and in what order. For instance, one driver might list a primary station "near home" and no other stations at all. Yet another might list a primary station that is "on the way," a secondary station both "near work" and "near home," and two other stations "near friends and family" and "long distance," respectively. When a driver listed more than one reason as the most important for choosing a station, we categorize accordingly (e.g., "near home" and "on the way").

Statistically, we test for differences of percentages between the Los Angeles, San Francisco Bay, and other regions using t-tests and ANOVA. Finally, we specify two multinomial logistic regression models to evaluate differences among primary, secondary, and 3rd-5th stations. We specify separate models using 1) stated subjective reasons and 2) corresponding revealed objective geographic relationships as independent variables to determine significant predictors of how respondents categorize their intended stations.

3. Results

Of the 129 survey respondents, 106 (82%) planned to rely on more than one station when they decided to adopt their FCV (Figure 2), while 77 (60%) planned on using at least three. Nearly one-third of the respondents for whom a single station was sufficient lived in San Diego and Sacramento, reflecting the dearth of stations in those areas. The majority of respondents who listed five stations lived in greater Los Angeles, where stations are most abundant.

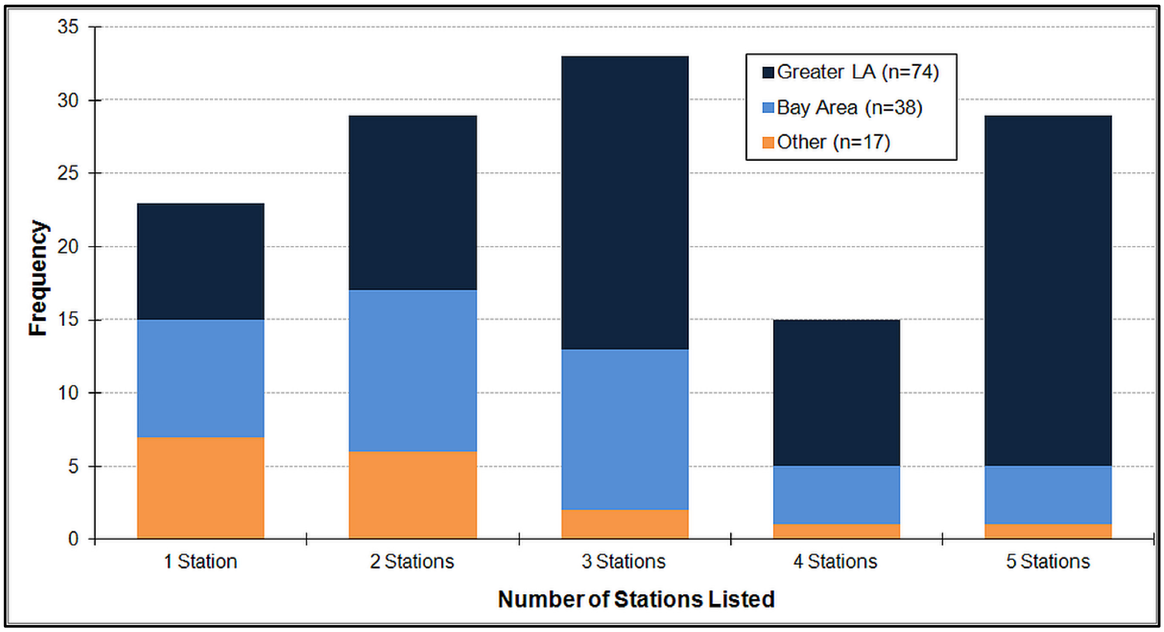

Fig. 2. Number of stations FCV adopters listed, by geographic region.

In this Results section, we first evaluate subjective and then objective convenience of stations for all respondents statewide. Then we compare these responses across regions (greater Los Angeles, San Francisco Bay area, other). We then compare subjective and objective convenience, evaluate how respondents use combinations of stations to satisfy varying subjective geographic criteria, and model differences in listed primary, secondary, and 3rd-5th stations.

3.1 Subjective Convenience of Stations

Table 2 demonstrates several key differences in subjective reasons for listing primary, secondary, and 3rd-5th stations for all respondents statewide. We first focus on the frequency that drivers listed any of the three reasons provided. Most respondents (70%) subjectively gave "near home" as a reason for listing their primary stations.

Table 2. Percentages of subjective reasons for listing primary, secondary, and 3rd-5th stations, by a) most important reason, and b) any reason.

Factor	Primary Station (n=118)		Secondary Station (n=96)		3rd-5th Stations (n=115)	
Subjective Reason for Listing Station	*Most Important Reason*[a]	*Any Reason*[b]	*Most Important Reason*	*Any Reason*	*Most Important Reason*	*Any Reason*
Near Home	43.2	69.5	18.8	45.8	10.4	27.8
Near Work	14.5	38.1	14.6	37.5	5.2	19.1
Near School	0	10.2	0	6.3	0	1.8
Near Shopping	0	16.1	2.1	15.6	1.7	13.0
Near Friends and Family	0	14.4	4.2	15.6	8.7	19.1
Near Social or Recreational Location	2.5	15.3	2.1	17.7	4.3	20.0
On Way	7.6	32.2	10.4	31.3	9.6	29.6
Backup	0	11.9	11.5	46.9	13.9	37.4
Long Distance	0	9.3	0	9.4	6.1	20.9
Not Crowded	0	16.1	0	14.6	1.0	12.2
Pressure	0	7.6	1.0	9.4	1.0	5.2
Amenities	0	7.6	0	7.3	0	5.2
Reliability	0	22.9	2.1	21.9	1.7	14.8
Price	1.7	9.3	1.0	10.4	1.7	7.0
Safety	0	7.6	0	8.3	0	4.3
Other Factors						
Available at time of adoption	86.4		79.2		77.4	
Plan to use - Weekday	16.9		22.3		18.3	
Plan to use - Weekend	1.7		14.6		26.1	
Plan to use - Both	80.5		58.3		48.7	

a Numerator is number of times reason is the highest ranked: responses with multiple reasons tied for highest are not included here. Denominator is number of stations by classification, so column percentages may be lower than 100.
b Numerator is number of times a reason is given, denominator is number of stations by classification. Column percentages may therefore exceed 100.

Respondents also commonly associated secondary stations with "near home" (46%), along with 3^{rd}-5^{th} stations (28%). Primary stations are also considered to be "near work" (38%) and "on the way" (32%). Secondary stations were commonly listed as "backup" stations (47%) and "near work" (38%), while 3^{rd}-5^{th} stations are listed most frequently as "backup" stations (37%) and "on the way" (30%). The prominence of the "backup" reason for stations besides the primary signals reluctance to rely on only one station, perhaps due to noted reliability issues with the developing California hydrogen refueling infrastructure; the frequency of "reliability" as a reason for station choice supports this conjecture.

We next consider the columns in Table 2 that show the most important reason drivers gave for listing stations. For primary stations, "near home" is again most common, and again, the relative prevalence of being "near home" declines with station importance. The primary reason for listing secondary stations is "near home," followed by "near work," "backup station," and "on the way." "Backup" stations surpasses "near home" as the top primary reason for stations 3^{rd}-5^{th}.

Available stations comprise most stations listed for each group, though planned stations are most common in the 3^{rd}-5^{th} group. Respondents intended to use primary stations more often on weekdays and weekends; they distinguished secondary and other stations as more appropriate for either weekday or weekend-only use. This aligns with stations being considered near home, since most drivers are home at some time every day of the week.

3.2 Objective Convenience of Stations

When estimating the objective convenience of stations to key trip locations, the relationship to home remains important: 55% of primary stations listed require the lowest estimated travel time to respondents' homes, while over 80% are one of the three shortest travel times (Table 3). Primary stations are frequently one of the three most convenient to shopping (77%) or school (77%) locations, while fewer than half of primary stations listed are of the three lowest travel times to work (49%) or social/recreational (46%) locations. Secondary and 3^{rd}-5^{th} stations require greater travel times to all location types than primary stations. The 3^{rd}-5^{th} listed stations are more convenient to social/recreational, shopping, and school locations than they are to respondents' homes and workplaces.

The percentage of primary stations that require the least deviation to reach from any of the three home-location travel routes (60%) is slightly higher than the percentage of primary stations that require the shortest travel time to home (55%). The corresponding percentages of stations that are one of the three shortest travel times to home or require one of the three lowest deviations to reach are nearly identical (~80%). The percentage of secondary stations that require one of the three lowest deviations to reach is likewise nearly identical to the percentage of secondary stations that are one of the three shortest travel times to home.

Table 3. Percentage of stations meeting objective criteria, by primary, secondary, and 3rd-5th stations.

Revealed Relationship to Location Type	Primary Station (n=118)		Secondary Station (n=96)		3rd-5th Stations (n=115)	
	Shortest Travel Time	*One of Three Shortest*	*Shortest Travel Time*	*One of Three Shortest*	*Shortest Travel Time*	*One of Three Shortest*
Home	55.1	80.5	17.7	68.1	17.4	28.2
Work	35.5	49.0	19.0	46.3	7.4	17.5
School	53.9	76.9	20.0	50.0	12.5	37.5
Shopping	46.7	76.7	33.3	68.2	13.6	36.4
Social or Recreational	23.7	45.6	10.8	37.9	16.5	32.2
Least Deviation	60.2	79.6	25.2	67.8	14.0	41.1

While the occurrence of stations being measurably near home in Table 3 largely mirrors the frequency of respondents subjectively considering stations "near home" in Table 2, we note that respondents infrequently listed primary, secondary, and 3rd-5th stations as being "on the way," despite their objectively low deviations from travel routes. In addition, Figure 3 demonstrates that the median lowest deviation to reach primary stations is 3.4 minutes, compared to 7.1 for secondary stations, and 11.0 for other stations, indicating that primary stations are aligned with short deviations. Three-quarters of all primary stations' lowest estimated deviations are less than 10 minutes.

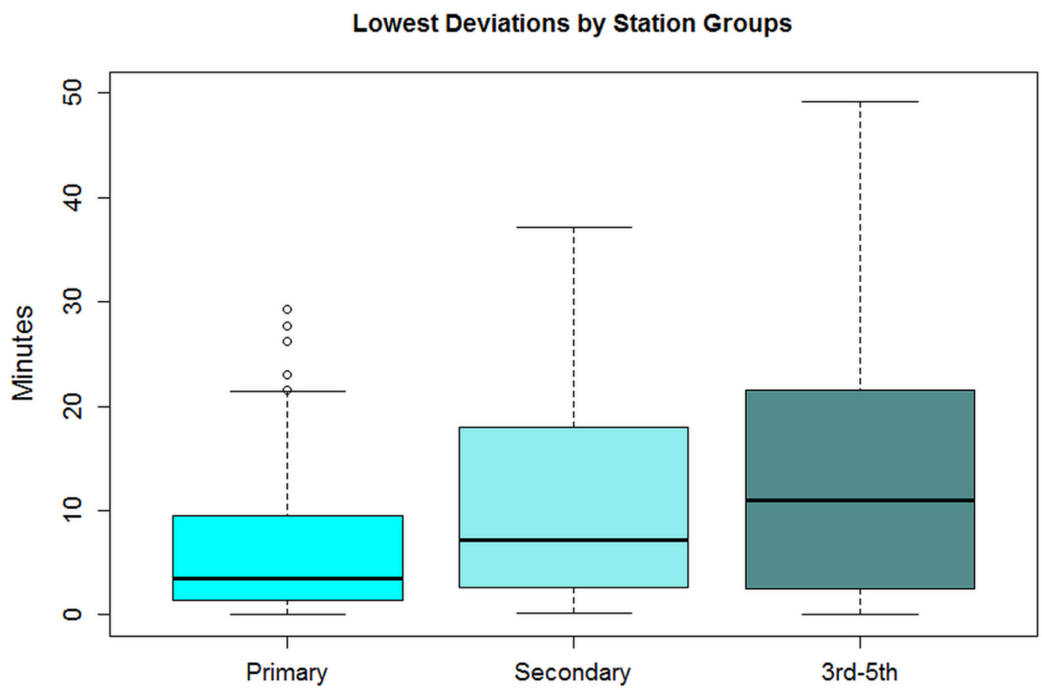

Fig 3. Lowest deviations to reach listed stations from any estimated home-location shortest travel time path.

3.3 Regional Comparisons

Next, Table 4 compares subjective and objective convenience measures from different geographic regions: greater Los Angeles, the San Francisco Bay area, and those who live elsewhere (primarily San Diego or Sacramento). Due to small sample sizes of listed stations for those that live outside the two major metropolitan areas—*n*=11 secondary stations provided by ten unique respondents and *n*=7 for 3rd-5th stations provided by four unique respondents—comparisons are limited in nature. To test differences in regional responses, then, we run a series of one-way ANOVA tests for all subjective and objective factors evaluated in Section 3.1 and 3.2 across the three regions for primary stations, then a series of t-tests across these same subjective and objective factors for respondents in greater Los Angeles and the San Francisco Bay Area.

While there are few significant differences, Table 4 does show that those in the San Francisco Bay area list primary stations as “near home” and as “backup” stations more frequently than their counterparts elsewhere, and also select “amenities” as a reason for choosing a station more often. Those who live outside the two major metropolitan areas do not consider their primary stations to be “near home” as frequently, even though the majority of them are revealed to be one of the three closest to home. In these cases, stations indeed may not be particularly “close” to the respondents’ homes, but due to the sparse infrastructure outside of the Los Angeles and San Francisco Bay areas, these listed stations are almost always one of the nearest. Other revealed measures show there are differences in percentages of primary stations being one of the three closest to work and to a social or recreational destination, with higher percentages outside of Los Angeles. This, too, is likely a function of increasing sparsity of stations and fewer opportunities for other stations to be nearer to destinations than those listed.

Few factors differ significantly between the two major metropolitan areas. Secondary stations in Los Angeles are less frequently one of the three closest to a social or recreational destination, and 3rd-5th stations in the San Francisco Bay area are more often subjectively associated with being “on the way,” a “backup station,” or convenient to a long-distance travel destination. Given the Bay Area’s more fragmented geography, fewer number of stations, and easier access to commonly listed recreational destinations such as the Lake Tahoe area, Yosemite, and locations in Napa County and others throughout wine country, these differences are not unsurprising.

Table 4. Percentages of primary, secondary, and 3rd-5th stations listed subjectively by respondents (top half) or ranking in the top three objectively (bottom half), by criteria and by region of California.

Factor	Primary Station (%)			Secondary Station (%)		3rd-5th Station (%)	
	LA (64)	SF (37)	Other (17)	LA (58)	SF (27)	LA (86)	SF (22)
Subjective Criteria - reason (of any importance) given by respondent for listing station							
Near Home*	64.1	91.2	41.1	50.0	48.1	27.9	31.8
Near Work	39.1	37.8	35.3	36.2	44.4	17.4	31.8
Near School	7.8	18.9	0.0	3.4	14.8	0.0	9.0

Near Shopping	15.6	24.3	0.0	16.6	16.7	10.5	27.2
Near Friends/Family	12.5	18.9	11.8	15.5	22.2	19.8	18.2
Near Social or Rec.	14.1	21.6	5.9	13.8	29.6	19.8	22.7
On Way+	29.7	37.8	29.4	27.6	44.4	23.3	45.5
Backup*+	6.3	24.3	5.9	39.7	55.6	31.4	68.2
Long Distance+	7.8	16.2	0.0	6.9	14.8	14.0	40.9
Not Crowded	18.8	18.9	0.0	13.8	22.2	12.8	13.6
Pressure	6.3	13.5	0.0	10.3	11.1	4.7	9.1
Amenities*	4.7	16.2	0.0	5.2	14.8	3.5	13.6
Reliability	25.0	27.0	5.9	17.2	33.3	11.6	27.2
Price	9.4	13.5	0.0	10.3	14.8	5.8	13.6
Safety	6.3	13.5	0.0	6.9	14.8	2.3	13.6
Objective Criteria - station is one of the three most convenient in terms of travel time							
Home	76.5	83.7	91.7	75.9	55.6	29.1	27.2
Work*	41.4	50.0	83.3	44.0	47.6	16.9	26.7
School	87.5	50.0	100.0	62.5	0.0	0.0	0.0
Shopping	64.2	81.2	29.4	63.6	75.0	66.7	33.3
Social or Recreational*+	31.1	61.5	75.0	27.5	57.1	40.0	47.1
Least Deviation	70.3	78.3	100.0	65.5	66.7	43.0	27.2

* significant ($\alpha = 0.05$) one-way ANOVA test among all three regions for larger sample of primary stations.

+ significant ($\alpha = 0.05$) t-test between LA and SF regions for smaller samples of secondary or 3rd-5th stations.

Unless otherwise noted, the remaining results present findings from respondents statewide, given the relatively few observed significant differences and the primary focus on how respondents evaluate a network of stations across the state at the time of adoption.

3.4 Comparison of Subjective and Objective Convenience of Stations

Five logarithmic distributions of estimated travel times between stations subjectively characterized as being "near" the five location types in the survey (home, work, social or recreational, shopping, school) and those corresponding locations are shown in Figure 4. Each distribution (except the *n*=5 school curve) has a similar characteristic shape, with a few very close stations, a lower rate of decay in the middle, and a handful of extreme outliers. There is also a somewhat consistent "ceiling" on the main group of travel times to stations considered "near" home, work, and social destinations between 70 and 90 minutes.

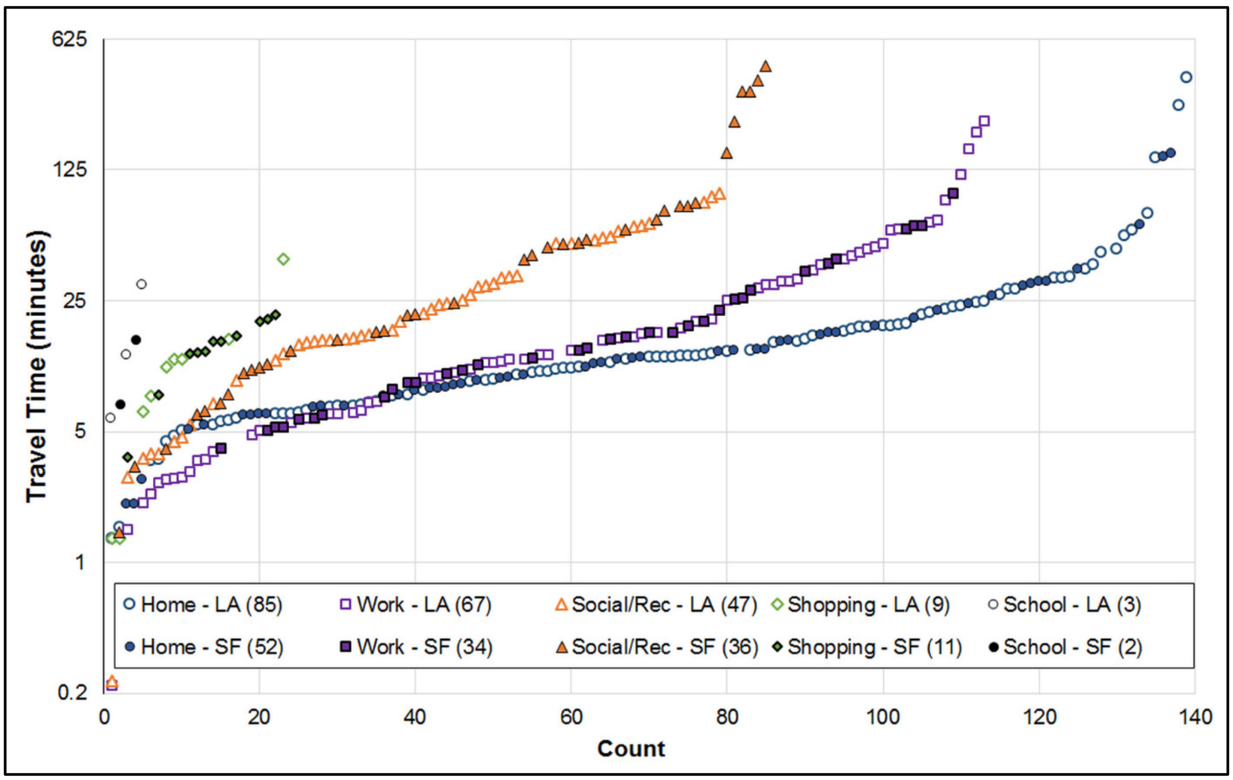

Fig. 4. Rank-ordered estimated travel times between stations, home and frequent locations by respondents in either the greater Los Angeles region or San Francisco Bay Area region, if respondent subjectively considered the station to be geographically "near" that location for any reason.

For the 139 stations subjectively considered near home, 40% were within 10 minutes of home and 75% within 25 minutes, although some over an hour away are also considered to be near home. The 30 closest stations to work require objectively shorter travel times to reach respondents' work locations than the 30 shortest to their homes. Beyond eight minutes away, this relationship reverses. Stations tend to require further travel times to respondents' social/recreational destinations than their work or home locations, with nearly a third over an hour away. Only 23 stations were considered "near" shopping destinations, though most are within 20 minutes of those destinations.

Table 5 summarizes how estimated travel times between stations and key locations vary by whether a station was listed for a given subjective geographic reason or not, and how this differs by primary, secondary, or 3rd-5th stations. Of the 118 primary stations, the 82 stations (69%) that were subjectively considered to be near home were an average of 14 minutes away from home; primary stations not considered near home were nearly 7 minutes farther away. Differences were more pronounced relative to work locations, with 45 primary stations (38%) subjectively considered to be near work and, on average, 13 minutes away from work, while primary stations not considered to be near work were 35 minutes away.

Table 5. Comparison of objective convenience between stations and destination types, by subjective convenience to each destination type.

	Primary Station (n=118)				Secondary Station (n=96)				3rd-5th Station (n=115)			
Subjective Convenience to Trip Type	Subjectively Near		Not Subjectively Near		Subjectively Near		Not Subjectively Near		Subjectively Near		Not Subjectively Near	
	n	Mean Minutes	n	Mean Minutes	n	Mean Minutes	n	Mean Minutes	n	Mean Minutes	n	Mean Minutes
Near Home	82	13.9	36	21.1	44	17.7	52	34.8	32	34.5	83	76.2
Near Work	45	12.9	73	34.8	36	14.9	60	40.9	22	34.5	93	57.4
Near Shopping	19	9.2	99	33.2	15	11.1	81	19.1	15	20.6	100	38.9
Near Social or Recreational	18	31.9	100	54.6	17	28.2	79	58.9	23	19.6	92	84.4

Across most geographic criteria, primary stations that are subjectively characterized as "near" a destination type are consistently more convenient to that destination type, followed in order by secondary stations and 3rd-5th stations. This relationship reverses for social or recreational destinations—respondents who list three or more stations may prioritize them only after convenience to home and work has been satisfied. Secondary stations listed as near home or work respectively average only 3.8 and 2.0 minutes farther from those locations than primary stations, while 3rd-5th stations are even farther still. "Near shopping" is infrequently noted as a reason for choosing a primary or secondary station; when it is listed, the station is objectively nearby.

We next evaluate the spatial arrangement of stations relative to all estimated home-work shortest travel time paths. Figure 5 standardizes the relative position of each station listed by these respondents as "near home," "near work," or "on the way." We represent stations on the y-axis based on their relative position between the home-work shortest path (e.g., a station halfway along a commute is represented at 50% on the y-axis). Values greater than 100% represent stations that are past the work location relative to the home-work route and values less than 0% represent those that are in the opposite direction of the home-work route. A station's position on the x-axis represents the deviation required to reach it.

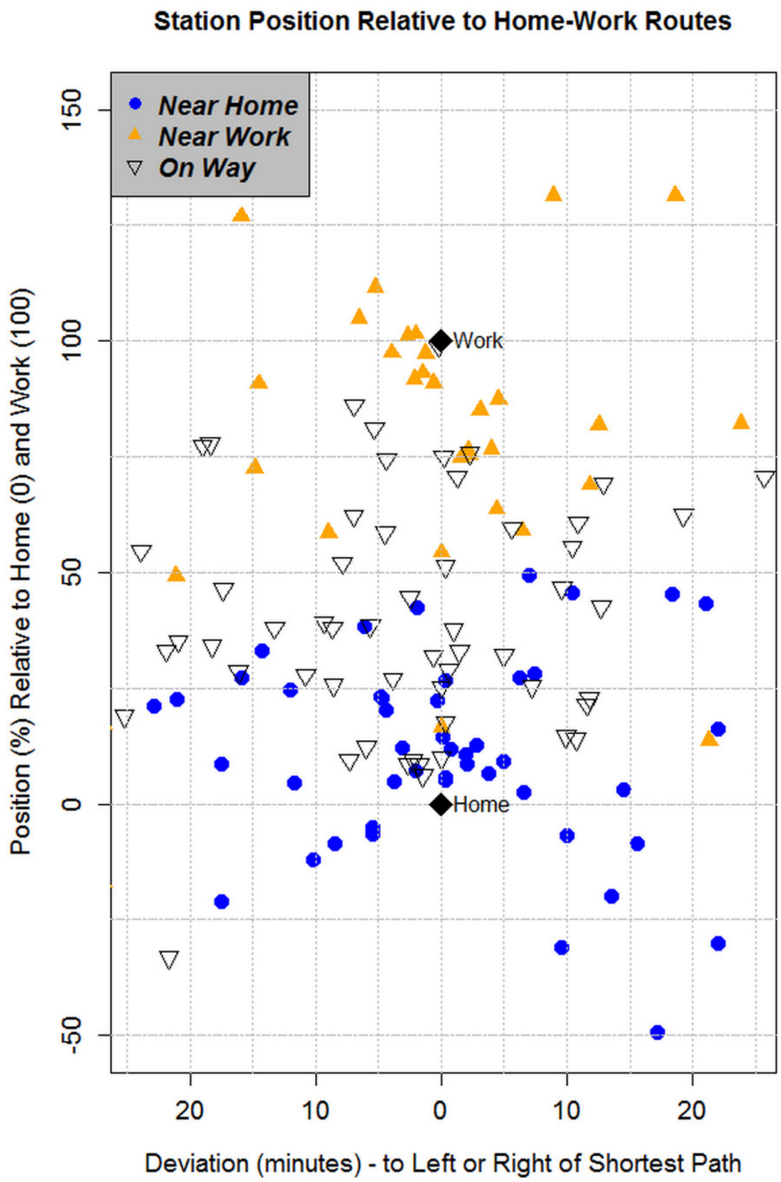

Fig. 5 Standardized locations of listed stations relative to home-work shortest travel time paths for respondents with work locations that subjectively listed stations as either "near home," "near work," or "on the way."

There is a distinct transition halfway between home and work where respondents subjectively consider stations to be "near home" and "near work." Most stations lie somewhere between the home and work locations; eleven are "behind" home and seven are "beyond" work. In contrast, all stations subjectively considered to be "on the way" are between home and work, with the exception of a single outlier. The "on the way" stations appear to be distributed more horizontally across the middle of the diagram rather than vertically around the axis that represents zero deviation. This suggests that many drivers may interpret the phrase "on the way" more as "midway" between home and work than as stations that require minimal time deviation to reach. Two additional generalizations are that more of the "on the way" stations are closer to home than to work, with the majority within 15 minutes deviation.

3.5 Evaluation of Combinations of Stations

This section analyzes the ordered lists of stations that respondents intended to use as a "portfolio" of stations that they considered sufficient for supporting their travel with an FCV. Figure 6 displays the combinations of most important subjective geographic reasons for which respondents planned to use stations, in the order of which the station was listed.

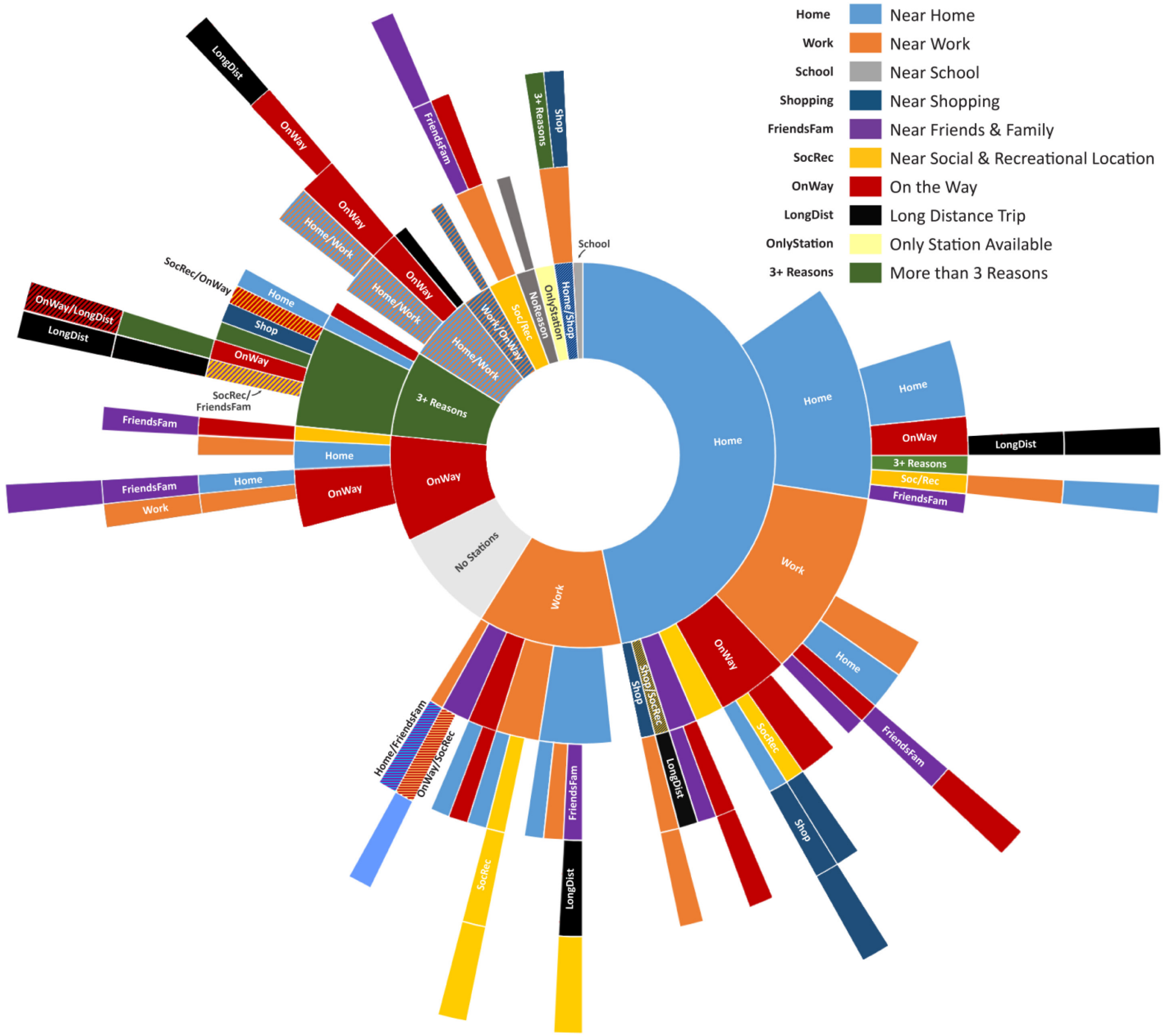

Fig. 6. Combinations of Stations Analysis. Each ring corresponds to a station group, starting with respondents' primary stations on the inner ring through the number of stations listed (up to 5) on the outer ring. Each radial wedge represents one respondent. Wider wedges represent multiple respondents who identified the same order of station and reason. For interpretation, at the "3 o'clock" position, a Home1-Home2-OnWay3-LongDist4-LongDist5 respondent is visible.

Station-level reasons such as price, reliability, or being a backup station are excluded, as only geographic criteria are considered. For interpretation in the text, respondents' combinations are referenced by reason and rank-order position of station. For example, if a respondent's most important subjective reason for their primary station is "near home," it is referred to as "Home1."

A secondary station "on the way" would be "OnWay2", and a driver listing this combination of stations for these reasons would be "Home1-OnWay2."

"Near home" is the most important geographic reason for listing a primary station, as evidenced by its prevalence in the inner ring. Home1-Home2 accounted for 14% of respondents who listed geographic criteria, with an additional 12% as Home1-Work2. A particularly strong finding is that for 18% of all respondents, a single primary station near home (Home1-None2) was sufficient to adopt an FCV. For respondents who listed three stations, Home1-Home2-Home3 was the most frequently observed combination, but by the time a third station is listed, a diversity of combinations is evident.

Nearly half (46%), though, did not include "near home" as the top geographic reason for their primary station, while 14% indicated that their primary station was "near work." Of these, Work1-Home2 was the leading combination at 5% followed by Work1-Work2 at 3%. The next largest group was the 10% of drivers who listed "on the way" as the top geographic reason for listing a station. For some respondents, these stations can form a robust platform on which to adopt a vehicle: some respondents relied solely on these stations, either as their top two stations (4%) or as their only one (4%).

The remaining 22% of respondents listed other combinations of geographic reasons for their top two stations. Some respondents listed three or more equally important top reasons for their primary and/or secondary station, including 6% who did not describe either of their top two stations as being "near home." Altogether, 25% of respondents felt comfortable adopting an FCV without the top reason for either their primary or secondary station being "near home."

For the stations listed 3rd, "on the way" is more frequently the top geographic reason than "near home." For the 22 stations ranked 4th, "backup" stations and "near friends and family" are listed most often, with stations serving long-distance trips close behind. Finally, for the 5th ranked station, long-distance becomes most frequent.

3.6 Multinomial Logistic Regression Model

We specify two multinomial logistic regression models using a 3-category dependent variable representing primary (n=118), secondary (n=96), and 3rd-5th stations (n=115). Each model contains the following covariates: dummy variables for whether or not the station was available at the time of adoption, whether or not the respondent provided "reliability" as any of the three reasons for listing the station, and if they planned to use the station on both weekdays and weekends. In addition to these, the first model contains four subjective geographic dummy variables, while the second model uses four corresponding objective ones.

The four dummy variables in the subjective model represent whether or not the station was listed as "near home," "near work," "near a social or recreational destination," or "on the way" as any of the three reasons for listing the station. For the objective model, to account for uncertain or unknown factors that could influence station choice (such as congestion, perceived safety, reputation for reliability, other stops a driver could make nearby or on the way, or other personal preferences) we generate dummy variables that indicate whether or not the station is one of the three shortest travel times to home, work, a social or recreational destination, or requires one of the three lowest deviations on the way to a given frequent destination. In both models, the primary station is the reference case.

Results show that secondary and 3^{rd}-5^{th} stations were significantly less likely to be considered for both weekend and weekday use (Table 6). Stations listed 3^{rd}-5^{th} are significantly less likely to be both subjectively and objectively near home or work. There are some notable inconsistencies between the models, though. Secondary stations are less likely to be objectively near work, though there is no significant corresponding subjective measure. This is also the case for 3^{rd}-5^{th} stations and estimated deviations. Secondary stations are less likely to be subjectively "near" home, and 3rd-5th stations are less likely to be subjectively "near" a social or recreational destination. In each case, though, no parallel objective measure significantly differs.

Table 6. Multinomial Logistic Regression Model Results

Subjective Reasons Model					Objective Estimated Travel Times Model				
Factor	2nd (n=96)		3rd-5th (n=115)		Factor	2nd (n=96)		3rd-5th (n=115)	
	RRR[§]	*p*	RRR	*p*		RRR	*p*	RRR	*p*
Near Home	0.41	<0.01*	0.19	<0.01*	Closest (3) To Home	0.60	0.32	0.19	<0.01*
Near Work	0.78	0.42	0.29	<0.01*	Closest (3) To Work	0.67	<0.01*	0. 09	<0.01*
Near Social	2.03	0.11	3.94	0. 01*	Closest (3) To Social	1.07	0.88	1.44	0.49
On the Way	0.98	0.95	0.91	0.89	Lowest (3) Deviation	0.71	0.49	0.28	0.01*
Reliability	0.97	0.94	0.65	0.28	Reliability	1.09	0.87	0.44	0.17
Station is Available	0.59	0.17	0.53	0.11	Station is Available	0.76	0.64	1.05	0.94
Weekday and Weekend Use	0.40	<0.01*	0.28	<0.01*	Weekday and Weekend Use	0.34	0.03*	0.23	<0.01*
Constant	4.05	<0.01*	10.6	<0.01*	Constant	4.43	<0.01*	29.5	<0.01*

* significant (α = 0.05). Gray shading indicates independent variables that are statistically significant at the α = 0.05 level in both models.

[§]RRR = relative risk ratio.

4. Discussion

We observe heterogeneity in both the number of stations that drivers intended to rely on when they decided to adopt the vehicle and their reasons for relying on them. For some, a single station near their home was enough to make them feel comfortable adopting an FCV. Many more drivers, though, made their commitment based on a group of 2-5 stations, including a number of cases where the primary station was not associated with subjective or objective convenience to home. For these drivers, stations near work and on the way were a priority, and enabled them to adopt an FCV. Others adopted their vehicles intending to rely on a portfolio of stations that together covered their geographic criteria of need. In short, it does not appear that the prescriptive approaches recommended by many past studies that prioritize one form of geographic convenience (near home, on the way, etc.) appeal to all FCV adopters.

The role of social and recreational destinations is an important one to consider for future FCV station location strategies, particularly for lower-ranked stations. Many types of locations fit this description, as a review of the maps provided by respondents shows that restaurants, sports facilities, movie theaters, hiking trails, and beaches are classified accordingly. This variety makes a single location strategy for providing convenience to social and recreational locations more difficult to develop. While clearly of interest to FCV adopters, respondents seem to view stations that support this kind of travel as a lower priority than convenience to home, work, or frequent trips.

We also note that respondents appear to understate the convenience of stations that they can visit en route to frequent locations, as the percentage of listed stations that measurably required the least deviation (or one of the three least deviations) to reach is far higher than the frequency with which drivers indicated stations were "on the way." These differences are less pronounced for objective relationships to home and work and subjectively characterizing stations as "near" those two locations.

When evaluating these findings, it should be kept in mind that the locations of initial hydrogen stations in California generally followed a strategy that prioritized placement of multiple local stations near likely early adopters' neighborhoods to provide redundancy, and connector stations between these areas and to other long-distance destinations (Ogden and Nicholas 2011; CARB 2018). Station redundancy does appear to be important, as this study adds to the growing body of evidence that station reliability is a concern of early FCV adopters in California. Certain stations that may be subjectively and objectively near home, work, or other important locations may suffer from operational issues that require frequent maintenance, rendering their geographic convenience irrelevant. Reliability is very likely the reason why secondary and 3rd-5th stations are so frequently considered "back up" stations. If and when station reliability issues improve, this reason for listing a station should decline in importance.

There are some key limitations to this study. First, for the sake of streamlining the survey, we only prompted respondents to list their three most frequented locations when they decided to adopt the FCV, and up to five stations they planned to use. Some of the longer estimated travel times observed between locations and stations ranked 3rd-5th may in some cases result from not having the opportunity to list less frequently visited locations; such a relationship would suggest that these lower-ranked stations are associated with less-frequented travel destinations.

Second, the survey asked respondents to identify stations they chose because they were "on the way," but did not ask them to identify which destinations they were on the way to. This required us to test each listed station for each listed destination and then assume that the destination generating the lowest deviation was likely the one they had in mind when saying a station was "on the way." How respondents think about stations being "on the way" and how researchers measure them objectively also may not be aligned. In Figure 4, the stations characterized subjectively as "on the way" appear to be more consistently somewhere midway on the trip between home and work rather than those requiring small deviations from the shortest path. Stations with minimal deviations that are also close to work are more often characterized by drivers as "near work" than as "on the way."

Third, we did not prompt respondents to indicate the number of vehicles available in the household beyond the FCV at the time of adoption. Therefore, some of the prioritization of covering home, work, and frequent trips may be a function of using the car for more limited travel, such as a commuting, while respondents may have had access to another vehicle to support longer-distance trips.

Finally, these respondents are early FCV adopters, and as such, may be more willing to travel and refuel in sparse infrastructures that require greater travel times and deviations than future adopters may be. Given the nature of our recruiting efforts that sought FCV adopters via social media, our results are reflective of those who participate in these online communities. The degree to which these respondents are reflective of all early FCV adopters is uncertain.

5. Conclusion

After decades of speculation about what early adopters would consider to be a convenient enough refueling infrastructure to make them feel comfortable adopting an FCV, results from this study largely support the long-held notion that early adopters would prioritize station convenience to home at the time of FCV adoption, with convenience to work or on the way also playing key roles. A key contribution of this study is that many unique combinations of stations are able to satisfy these demands for early adopters. Some drivers acquired an FCV without a primary station objectively near home, and some did so without *any* stations that they subjectively considered to be near home. A station near home, therefore, while clearly most desired by early adopters, is neither necessary nor sufficient for drivers to adopt an FCV.

Another key finding is that many drivers subjectively characterize stations as near home, work, or other locations, or on the way, even when they objectively require sometimes long travel times to reach under free-flow travel conditions, although beyond 90 minutes we find a sharp decay in respondents considering a station to be "near" a given location. This finding reinforces the importance of analyzing revealed measurements in addition to asking for drivers' stated preferences regarding station locations.

Modeling results show that respondents intended to use primary stations both during the week and on the weekend, in contrast to other stations. Secondary stations, while also commonly associated with both measures of convenience to home, work, or on the way, are objectively less convenient to work and subjectively less likely to be considered near home relative to primary stations. Stations listed 3rd-5th are subjectively associated more with social or recreational destinations and objectively less with lower deviations from frequent routes.

Over 80% of respondents planned to rely on more than one station to satisfy their refueling needs at the time of adoption. When evaluating the unique ways that drivers list stations and top subjective geographic reasons for doing so, we find a surprising variety of combinations of stations and reasons. This suggests that any "one size fits all" station location method that only prioritizes convenience to one geographic criterion is unlikely to encourage widespread FCV diffusion—at least not until stations are ubiquitous enough for there to be one in most neighborhoods.

To better address the infrastructure barrier, station developers need to think in terms of a network of stations from which drivers can assemble a portfolio of leading and supporting stations that provide sufficient convenience to home, work, and frequently traveled routes. Station location planners should also feel comfortable placing stations away from residential and employment clusters, as early adopters aligned lower-ranked stations with activities such as social and recreational destinations. Stations at these locations offer another advantage: they are often visible, high-profile locations that can provide exposure to hydrogen refueling stations and FCVs to people across the region. Given the long travel times that drivers still consider to be "near home," stations do not have to be located within a specific residential neighborhood in order to provide viable options to its residents; they can be more flexibly located where they can also serve as non-primary stations for people from other neighborhoods refueling near or on the way to work and other activities.

Adjusting station planning methods to more prominently consider a combination of geographic criteria represents a challenge to infrastructure modelers. Rather than relying on single-objective models focusing solely on demographics or traffic counts or origin-destination flows alone, these results suggest a greater emphasis on multi-objective analysis. Furthermore, the findings from analyses such as this could help inform the parameters and/or weights for each objective. For instance, one might propose a tri-objective modeling approach. First, given (a) the popularity of stations considered to be near home (Table 2), (b) the long travel times observed for many of these stations (Figure 4), and (c) the absence of primary or secondary stations near home from 25% of drivers' portfolios (Figure 6), one could suggest a *p*-median objective for minimizing total population-weighted travel time from residential nodes to nearest stations with a covering-type upper limit on travel time of 25-30 minutes. Second, the tighter clustering of stations "near work" in Figures 4 and 5 might argue for a simple maximum-covering-of-jobs objective with a shorter travel time threshold of 10-15 minutes. Third, the relatively short deviations observed in Section 3.2 to any of the drivers' listed destination could argue for including a flow-capturing type of objective using multiple trip purposes and a fairly stringent maximum deviation. We emphasize that our results need to be reproduced elsewhere before optimization models are parameterized around them, but these are potential examples of how to proceed.

Station planners and developers should continue to address station reliability, given how prominent this concern is among early FCV adopters, but redundancy can also be provided by stations outside of a driver's neighborhood. Future studies should also focus on how station reliability influences the way respondents evaluate a geographic distribution stations, both at the time of adoption and after experience.

It should also be noted that these results may not be directly transferable to other regions in the U.S. even after their refueling infrastructures become more developed, due to differences in land use, population density, traffic patterns, and driver demographics, preferences, and attitudes. However, similar studies could be conducted in South Korea, Japan, Germany, or the Netherlands, which also have developed initial hydrogen station networks to evaluate the consistency of these results.

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