Hydrogen Refueling Station Consideration and Driver Experience in California

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ABSTRACT

The recent growth in the California hydrogen fuel cell vehicle (FCV) market offers the opportunity to analyze how stations that drivers use after some experience compare to those they initially intended to use. We analyzed online surveys completed by 124 FCV adopters in California in early 2019. Respondents listed stations they initially planned to use, stations that they later used, subjective reasons for using them, and important travel destinations. We then used network GIS analysis to measure estimated travel times between both available and planned retail hydrogen stations and home, work, and frequently traveled routes, both at the time of adoption and at the time of the survey. Results show that 40% of respondents changed refueling stations over time. Those with stations objectively nearer to home, work, and frequently traveled routes were less likely to change their list. Drivers were more likely to subjectively label stations as near home and less likely to label them as on the way compared to objective measurements of these criteria, though these differences are greater for respondents who changed stations. Regardless of whether the station was available pre-adoption or opened post-adoption, stations that respondents added to their lists were farther from home than those they initially intended to use. For stations available pre-adoption, reliability positively influenced adding them after experience, while stations added by drivers that opened post-adoption tended to require short deviations to reach. These results indicate that a mixture of geographic and station-level characteristics contribute to FCV drivers changing stations over time.

Keywords: hydrogen, refueling station, GIS, California, logit model

INTRODUCTION

By the end of January 2020, over 7,900 hydrogen fuel cell vehicles (FCVs) had been sold or leased to California residents, nearly doubling the state's total since the beginning of 2018 (*1*). Over 40 retail hydrogen refueling stations and 21 additional planned stations support the growth in FCV adoption and the emergence of an FCV "business ecosystem" (*2*,*3*). Regions such as the Northeast US are following California's lead in developing plans for station networks, and lessons learned from how early adopters assessed California's network of hydrogen stations will be helpful in this process. With the first wave of FCV leases nearing their end, understanding changes in drivers' station preferences and refueling behavior over time can be beneficial to developing strategies to encourage FCV market growth. Considering both drivers' preferences at the time of purchase and after some experience is important for the initial adoption and the continued use of FCVs.

Previous work on how to locate stations to encourage adoption hypothesized that potential FCV drivers would primarily need stations conveniently located near their home or work or along their commuting route in order to adopt an FCV (*4*-*6*), which is corroborated by a recent California survey of FCV drivers (*7*). Others noted that convenience to other activities may also be important for refueling decisions once they have the vehicle (*8*). These considerations, however, may change after some initial experience with an FCV. Additionally, drivers must continually assess both the geographic convenience of stations relative to important locations (like home, work, or social and recreational destinations), and also considerations such as station reliability, amenities (such as an adjacent convenience store), and congestion both on nearby roads and at the station when evaluating potential changes in hydrogen stations they consider. With new hydrogen stations opening, FCV drivers' travel activity may have expanded, and their driving behavior may have changed, though to what extent this is a function of learning which stations better suit their needs over time or simply that there are more stations available is an unexplored topic. This period of time in the California hydrogen station network development provides an ideal opportunity to study these early changes and preferences.

In this study, we ask the general research question: to what extent do early FCV adopters change the stations they use compared to those they intended to use when they first adopted their vehicle? Additionally, we ask: how do spatial relationships of stations' proximities to home, work, and frequently used routes compare between drivers who changed refueling stations since FCV adoption and drivers who did not, and do stated reasons for listing stations change? We also determine if drivers add stations to their lists that they did not initially include and analyze how these stations differ in their revealed spatial relationships between home, work, and frequently used routes, along with differences in stated reasons that drivers list them, relative to other stations they initially listed. To address these questions, we distributed a web-based survey to a sample of FCV adopters in California in early 2019, asking drivers when they decided to adopt an FCV, which stations they intended to use at that time and why, and the stations they now use and why. To address our research questions, we conducted proximity and deviation analysis in GIS to assess the revealed relationships between home, work, and frequently used routes, and compared responses in stated subjective reasons for listing stations. Using descriptive statistics and t-tests, we explore differences between respondents who changed stations and those who did not. Then, we specify two binary logit models to compare how stations added to respondents' lists over time compare to those that were listed at the time of adoption. One model focuses on stations added to drivers' lists over time that were available pre-adoption, while the other considers those stations added that opened post-adoption.

Before adopting an FCV, drivers in urban areas were accustomed to having a nearly ubiquitous network of gasoline stations from which to choose, which meant they had multiple stations that were near home and also on their way to work, shopping, or school regardless of the direction in which they were traveling (*9*). We therefore hypothesized that the majority of respondents would list the station nearest to their home as one they intended to use when they adopted an FCV, but after some experience with the vehicle, stations on the way to or near work and other types of locations may become more important.

LITERATURE REVIEW

FCV adoption studies have identified that consumers prioritize the number and spatial distribution of hydrogen refueling stations (*10-13*); their absence inhibits FCV uptake (*14*). Studies since have attempted to characterize the convenience of both individual stations and sets of stations on road networks when recommending locations for hydrogen stations. Optimization models that locate stations on networks in order to encourage FCV adoption therefore implicitly assume certain definitions of convenience when locating facilities: nearness to homes of likely early adopters (*15*), minimal travel time deviation from road segments with high traffic flows (*16*), or some combination of factors (*17-20*). Most of these models were developed prior to the availability of empirical data on FCV refueling behavior. To overcome this limitation, prior to the construction and consumer usage of a hydrogen refueling network, studies of early adopter preferences for station locations relied on stated preference surveys, analysis of travel survey data, and observations of other AFV drivers' refueling behaviors. For example, surveys suggested that likely adopters would travel up to ten minutes (*21*) or one mile (*22*) to refuel. Prior to FCV roll-out in California, others found that transitioning to FCVs would not entail a substantial change in travel behavior for those with conventional internal combustion engine vehicles (*23*), and that the proposed hydrogen station locations in California would be sufficiently accessible for those who lived in target early adopter areas (*24*).

Compressed natural gas vehicle (CNGV) driver behaviors approximate FCV driver behaviors due to vehicle similarities in refueling time, driving range, station sparsity, and California context. Studies of these drivers found that both individual and fleet CNGV drivers in Southern California prioritize minimizing deviation along travel paths over refueling near residences or depots (*25-27*). These studies did not determine how CNGV drivers assessed the existing station network prior to adopting the technology, though, nor how their behaviors changed after experience with the vehicle. Studies of electric vehicle (EV) drivers demonstrated that drivers alter daily travel patterns to adapt to sparse recharging infrastructure and both use and desire more charging stations at work or near shopping destinations (*28-30*), though these findings may be of limited transferability to FCV drivers.

While the quantity and arrangement of stations has been a primary focus of attention in the literature, unreliability is the primary reason why FCV adopters in California say they avoid certain stations, particularly with the early stations (*10,31*), which is why early adopters often mention back-up stations as essential when purchasing or leasing an FCV (*11*). This signals that factors beyond proximity to home, work, or frequently traveled routes may be important when evaluating hydrogen station consideration or use by early adopters.

In sum, it is unknown how the list of refueling stations used by FCV drivers post-adoption compares to those they planned to use at the time they decided to adopt the vehicle, and how these align with hypothesized important spatial relationships of stations to homes and other activity locations of early adopters. For those who indicate they changed stations, it is unknown what the common attributes of stations are that drivers now use relative to those they intended to use at the time they adopted the vehicle. These are essential considerations for future station network planning.

METHODS AND DATA

Sampling and Recruitment

An online IRB-approved survey was created using Qualtrics and disseminated to California FCV drivers in early 2019. Survey questions asked respondents which refueling stations they considered and why, both when they decided to adopt the FCV and when they took the survey. In order to participate, respondents had to be a resident of California over the age of 18 and have taken possession of an FCV by purchase or lease.

We recruited using a convenience sampling technique through social media and email distribution. Administrators of the Toyota Mirai Owners, Honda Clarity Fuel Cell Owners, Hydrogen Car Owners, and GM Project Driveway Facebook groups permitted us to post recruitment links on their pages. These groups included between 604 and 3,200 members each. Although not all members own or

lease FCVs, it is reasonable to assume that these groups comprise a sizable proportion of all FCV owners in California. This recruitment technique effectively advertised the survey to known FCV adopters, and while recruitment via Facebook has been shown to be an effective recruiting technique for reaching a more representative audience, including a broader range of demographic groups (*32*), the degree to which FCV drivers in social media groups are representative of the general population of early FCV adopters is uncertain.

Of the 129 respondents, five were taken out of analysis because they moved to a different residence or changed their place of work. Therefore, the final number we recruited is 124 respondents, which represents approximately a 2% sample of the 6,315 cumulative FCV sales in California at the time the survey closed (*1*).

Survey Instrument

The survey consisted of two primary sections. The first prompted drivers to think back to the time they initially decided to adopt an FCV and indicate;

- the month and year they did so
- up to five refueling stations they planned to use at that time
- up to three reasons they planned to use each station listed
- their approximate home location and three most important trip destinations, using an interactive Google Maps interface embedded in the Qualtrics survey platform which prompted them to place a pin on the map
- their stated confidence in the list of stations they initially intended to use from the following options: extremely confident, very confident, moderately confident, slightly confident, and not confident at all.

Stations listed could include those currently available or those planned to be built but not yet open at the time of their adoption decision. To help respondents recall which stations they had intended to use at the time of adoption (TOA) the survey provided maps of historical hydrogen station availability (**Figure 1)** using quarterly historical AFDC station data (*2*).

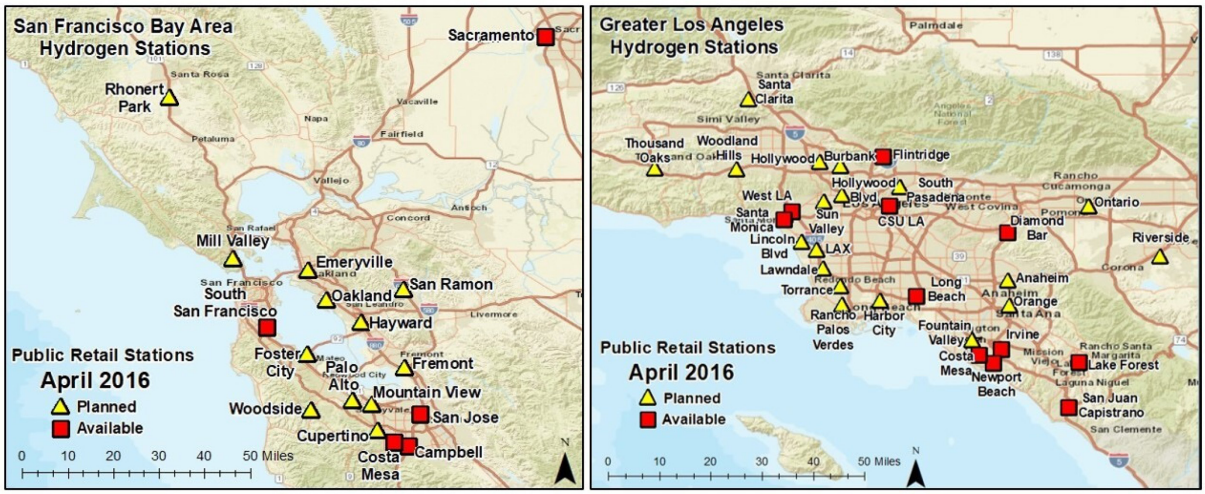

Figure 1 Modified example of a reference map, showing available and planned hydrogen refueling stations in the San Francisco Bay Area and the Greater Los Angeles area, April 2016. Similar reference maps for each quarter since 2015 were embedded in the survey instrument, including versions that showed stations statewide (not shown on these two maps).

All stations that eventually opened by the time of the survey were shown as planned from the beginning of the study period and therefore could have been chosen by respondents. Then respondents were asked to choose up to three subjective reasons for considering each of the stations from a predetermined list that included perceived proximity to a variety of locations (home, work, shopping, school, a social or recreational destination, family or friends, or long distance travel), and perceived station-level considerations (reliability, price, safety, station amenities such as a convenience store, hydrogen pressure, or a backup station). Respondents could also select "other," and expand with an open-ended response.

The second section of the survey then prompted drivers to indicate which stations they "currently" used, that is at the time of the survey (TOS), and if their list of stations *or* reasons for using them changed since they initially acquired their FCV. If so, respondents listed the stations they currently use and reasons for doing so.

Proximity Analysis

Using GIS network analysis, we analyzed the proximity of the stations listed by respondents to their homes and various given travel destinations. All home locations and travel destinations were translated to point data in ArcGIS, along with the historical hydrogen station dataset from AFDC. Then, shortest travel time routes were estimated between all home locations and trip destinations (such as work locations) and all available and planned stations, both at TOA and TOS, using a detailed street network dataset and the Network Analyst extension in ArcGIS. This analysis was automated using Python 2.7 to generate all routes and repeated for all respondents. All estimated routes and travel times were generated from the network analysis under the simplistic assumption of free-flow travel speeds.

Then, based on the full list of shortest travel time routes to all available and planned stations at TOA and TOS, we evaluated if the stations listed by respondents required the shortest estimated travel times to: 1) home, 2) work, and 3) other listed travel destinations. To account for the uncertainty of network travel assumptions, such as congestion or delays, we then considered if their listed stations were one of the three closest to home, work, or a listed trip destination.

Deviation Analysis

To assess the convenience of stations to respondents' driving routes, we computed the deviation that would be required to travel from home to a listed destination via all potential hydrogen stations, both at TOA and TOS, for all respondents. We first generated the direct shortest travel time paths between their home and their three given destinations. Then, each station in California that was either available or planned at TOA was inserted as a stop on a shortest travel time path between home and each given destination for all respondents. This analysis was repeated for all stations available at TOS. To calculate the deviation, we computed the difference in travel time in minutes between the estimated shortest travel time without the station stop and for the route that included the station. Similar to the proximity analysis, we then determined if the driver listed a station that was either the most convenient or among the most three convenient in terms of minimal deviation to reach one of their listed travel destinations at both time periods.

We also consider deviation from commuting routes, which are classified as those between a respondent's home and any work location (some respondents listed multiple work locations). This analysis was conducted both for the primary station listed by the respondent and their secondary stations (2^{nd}-5^{th}).

Respondent Station Changes

Classification

Of particular interest is the degree to which respondents changed the list of hydrogen refueling stations between TOA and TOS. We use the terms "Changed" and "No Change" to describe these two groups of respondents. No Change respondents have an identical list of stations at TOA and TOS (**Figure**

2). All other respondents are considered to have "Changed" their stations in some way. To focus on the effect of driving and refueling experience, we removed four respondents who moved to a different residence or changed their place of work. For changed respondents, we classified each change by a respondent according to the nature of the station change over time: 1) Added, 2) No Longer Uses, 3) Changed Importance, and 4) Never Opened, Never Used. As shown in Figure 2, the 46 respondents who changed their list of stations from TOA to TOS listed a total of 141 different changes. Examples of these categories can be seen in Figure 2's Changed Respondent Example. Added stations were not listed by respondents at TOA, but were at TOS. The term "Added" conveys that the station was added by the respondent to their list at TOS rather than added to the network. Our respondents added stations that fit one of two categories: those that were either available both at TOA and TOS ("Available Pre-Adoption"), or those were built after they took possession of the FCV ("Opened Post-Adoption"). "No Longer Uses" refers to any station that is not used at TOS but was listed at TOA. "Changed Importance" stations refer to those that moved higher or lower in the respondent's list between TOA and TOS. Finally, some respondents listed planned stations that they intended to start using when they opened, but they were "Never Opened, Never Used" by these drivers. These ten stations are omitted from further analysis. There were other classifications of station changes possible that we did not encounter in our survey data and are therefore not discussed further in this study. These include: a planned station at TOA remaining planned at TOS, an available station at TOA that closed by TOS, and a station planned at TOS that had not yet reached that status at TOA.

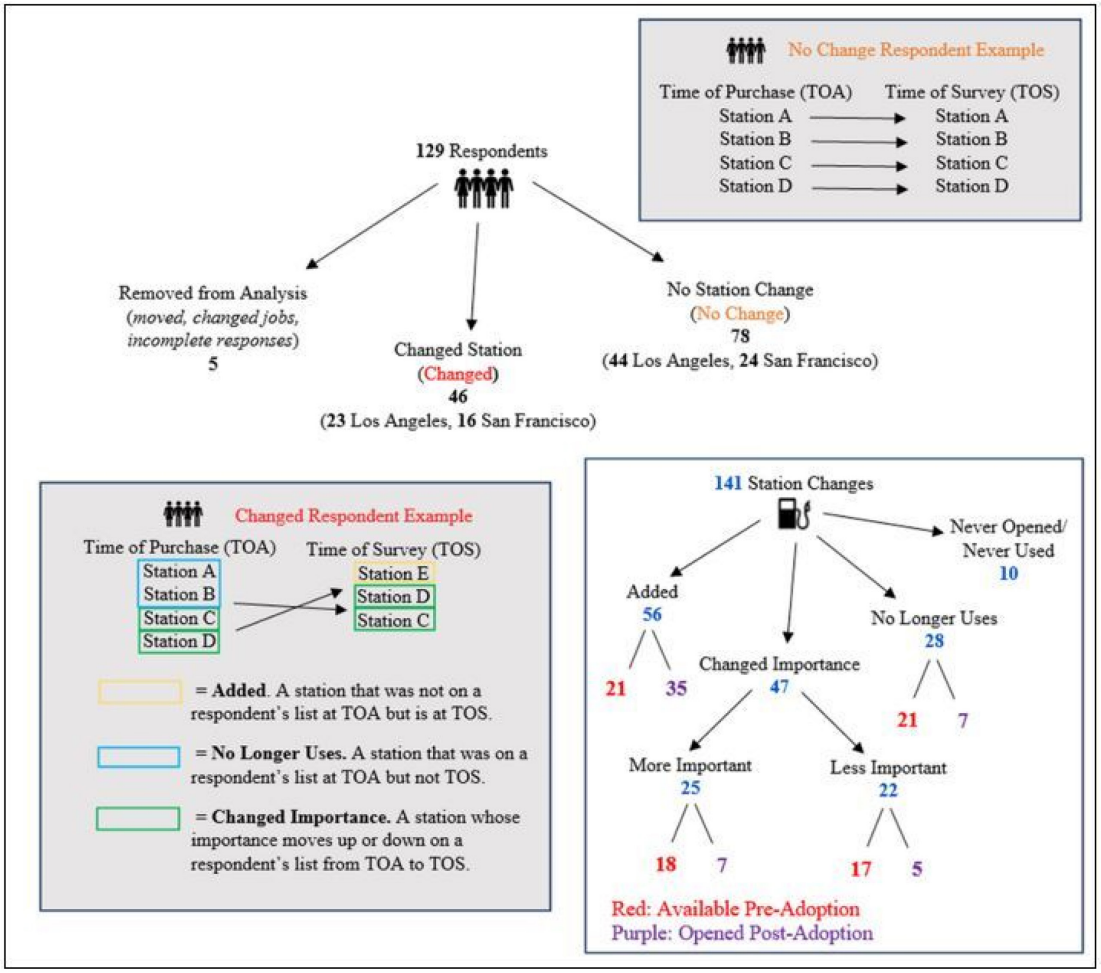

Figure 2 FCV respondent breakdown and station change classifications, with illustrative examples

Individual stations can belong to more than one of these four groups of changes across respondents. For example, a station added by one respondent could be one that another respondent no longer uses or has changed in order of importance.

We computed summary statistics for the stated reasons why respondents listed their stations at TOA and TOS, along with the travel times and deviations required to reach them in the proximity and deviation analysis. Then, we compared differences in stated reasons for listing all stations between the Changed and No Change groups, along with differences in estimated travel times generated in the proximity and deviation analysis. Based on the month and year of FCV acquisition provided by each respondent, we then compared length of experience with the vehicle, i.e., the amount of time from when the respondents' adopted their vehicle to when the survey was distributed, between the Changed and No Change respondent groups.

Statistical Analysis

Several inferential statistics tested for significant differences between Changed and No Change groups. First, a series of two-sample t-tests identified significant differences in occurrences of stated reasons and in estimated travel times produced by the proximity and deviation analysis between these groups of respondents (Figure 2), both for the primary station listed and the other stations listed.

Second, we compare Added stations to all other station changes in terms of differences in stated reasons for listing stations, and estimated travel times and deviations required to reach them. The reason we focus on Added stations is that they are the strongest indication of what drivers learn after some experience with the FCV. However, adding stations is not entirely due to learned experience with the refueling infrastructure but instead may be a function of stations being built and opened. Therefore, in order to focus on learning after experience, we further distinguish whether the Added station was available both at TOA and TOS, hereafter termed "Available Pre-Adoption", or if the station was planned at TOA and then became available at TOS, hereafter termed "Opened Post-Adoption". If the Added station was Available Pre-Adoption, this best indicates the effect of learned behavior based on driving experience.

Third, we specify two binary logistic regression models that compare Added stations to all other station changes for each of the two primary classifications of stations (Added Pre-Adoption and Opened Post-Adoption). In the station-level logit analysis, the sample size is the number of station changes listed by respondents. Given the emphasis on exploring the nature of differences of station changes, this part of the analysis focuses on listed changed stations as the unit of analysis.

RESULTS

In total, 124 respondents completed usable surveys between January 1st and March 31st, 2019. Geographically, 67 respondents lived in the greater Los Angeles area, 40 in the San Francisco Bay Area, and the remainder in or near Sacramento and San Diego. The vast majority (80%) of respondents were either "extremely confident" or "very confident" in their recollection of the stations they had been planning to use when they decided to get their FCV. After filtering out respondents who indicated a change in home or work location and incomplete responses, there is a final sample of 46 Changed respondents (37%), while the remaining 78 (63%) indicated No Change in stations (**Figure 2**). The ratio of Changed to No Change respondents is slightly higher for the San Francisco Bay Area, but favors No Change respondents throughout California. Changed respondents listed 141 station changes. Collectively, these respondents Added 56 stations, No Longer Use 28 stations, and had 47 stations that Changed Importance. Ten stations were Never Used because they Never Opened and were taken out of analysis.

Length of Experience

Respondents had their FCVs for 3-37 months, and Changed respondents generally had their vehicles longer (**Figure 3**). Of the No Change respondents, nearly 70% have had their vehicle for 19 months or less, while about 70% of Changed respondents have had their vehicle for 20 months or longer.

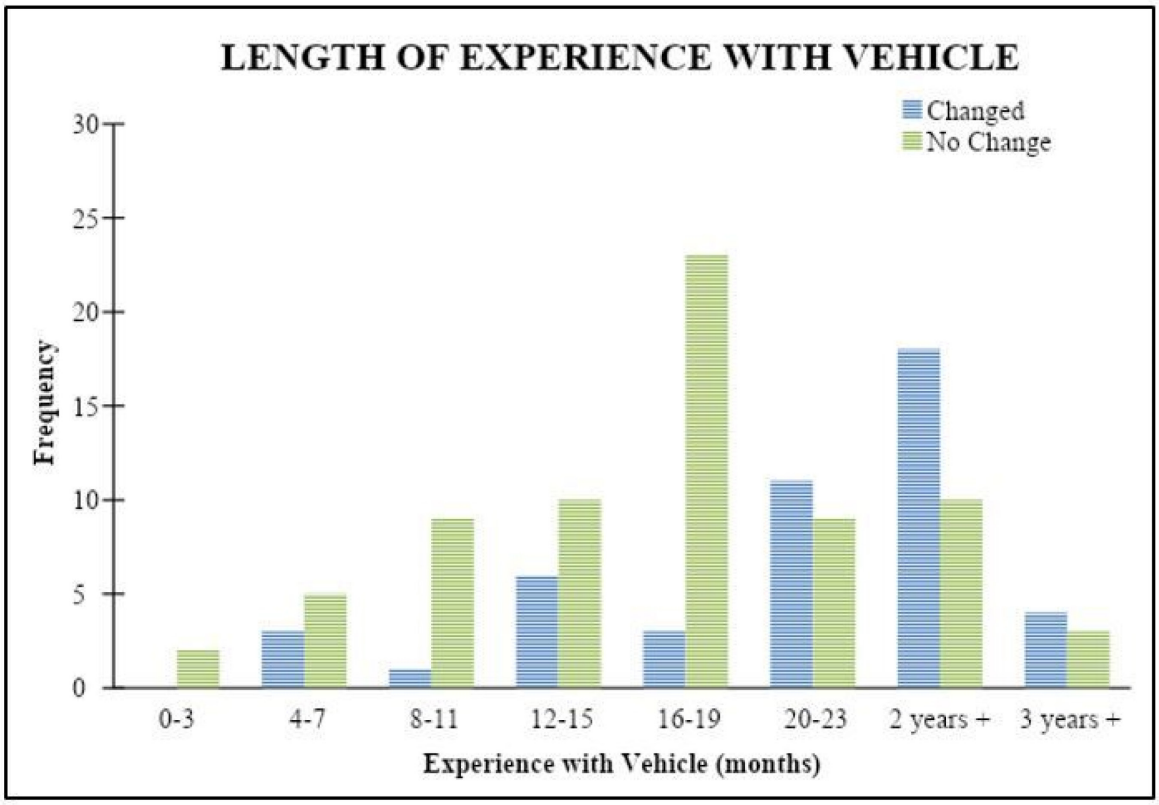

Figure 3 Length of FCV experience for Changed and No Change respondents

Comparison of Changed and No Change Respondents

Table 1 summarizes respondents' 1) stated reasons for listing stations, and 2) the results of proximity and deviation analysis. We present these results both at TOA and TOS for Changed respondents, but only for TOA for the No Change respondents because there is no difference in their listed stations across time periods. For all respondents, the factors are analyzed both for primary stations and for stations ranked 2nd through 5th. For the secondary stations, a reason only needs to be listed for one of the driver's secondary stations, not all. Respondents could give the same reason for multiple stations, or list multiple reasons for the same station, which is why neither rows nor columns add up to 100%. For the proximity and deviation analysis, percentages are the percent of respondents who listed a station that meets the criterion in each row (e.g., the station is in fact the closest to home, closest to work, etc.).

TABLE 1 Respondent and Station Classifications, by Stated Reasons and Estimated Travel Times Produced by Proximity and Deviation Analysis, Including Comparison of Factors at Time of Purchase (TOA) and at Time of Survey (TOS) for Changed Respondents

	Changed (**n=46**)				No Change (**n=78**)	
	Primary Station		2nd - 5th Stations		Primary Station	2nd – 5th Stations
Factor	**TOA**	**TOS**	**TOA**	**TOS**	**TOA**	**TOA**
Stated Reasons for Listing Stations (% of respondents who listed the reason)						
Near Home	58	70	51	57	68	37
Near Work	35	37	33	44	35	32
Near School	11	11	4	7	9	5
On the Way	28	33	44	46	31	28^{+}
Near Shopping	17	15	17	22	14	21
Near Social/Recreation	7	11	24	30	18^{++}	15
Near Friends/Family	11	13	20	30	14	21
Long Distance Trip	7	4	17	26	10	17
Reliability	13	28*	20	17	24^{+}	19
Price	7	4	11	9	9	8
Backup Station	11	11	41	44	12	46
Not Crowded	13	20	15	20	17	14
Pressure	7	11	9	9	8	6
Safety	7	4	7	7	8	6
Amenities	4	28**	9	17	9	6
Station Status						
Station Available at TOS	77	--	70	--	93^{++}	84^{++}
Station Planned at TOS	23	--	30	--	7^{++}	16^{++}
Proximity and Deviation Analysis (% of respondents who listed a station meeting the criteria)						
Closest Station to Home	31	28	29	31	58^{++}	21
Closest Station to Work [a]	12	19	12	12	40^{++}	38^{++}
One of Closest 3 Stations to Home	35	31	29	31	69^{++}	78^{++}
One of Closest 3 Stations to Work [a]	21	21	26	23	67^{++}	40
Most on Way - Commute [a]	17	19	44	29	37^{++}	35
One of 3 Stations Most on Way - Commute [a]	37	27	67	50	69^{++}	60
Most on Way - Primary Destination	21	18	11	21	39^{+}	18
One of 3 Stations Most on Way - Primary Destination	42	34	34	50	71^{++}	45
Proximity and Deviation Analysis (mean minutes)						
Home to Closest Listed Station (minutes)	26	30	29	26	23	22
Lowest Home to Destination Deviation (minutes)	10	8	6	5	10	14

* significant (α=0.10), TOA vs. TOS, ** significant (α=0.05), TOA vs. TOS

$^{+}$ significant (α=0.10), Changed vs. No Change, $^{++}$ significant (α=0.05), Changed vs. No Change

[a] percentages reflect only those respondents who listed a work location

Stated Reasons

"Near Home" was the most important reason for listing primary stations for all groups of respondents and classifications. Looking at the first row of Table 1, 68% of No Change respondents considered their primary station to be "Near Home." For Changed respondents, 58% considered their primary station to be "Near Home" at TOA, but this rose to 70% at TOS: nearly identical to the No Change group. Over 50% of stations ranked 2nd-5th were also subjectively "Near Home" for Changed respondents, while only 37% of secondary stations were for No Change respondents. For those who listed a work location, nearly one-third considered their primary station to be "Near Work" for both Changed and No Change groups. At TOA, 28% of Changed respondents considered their primary station to be on the way, and this increased to 33% at TOS. They also associated secondary stations with being on the way more frequently than No Change respondents did at TOA (44% vs. 28%). For the primary station, both reliability and station amenities became significantly more important to Changed respondents after experience with the FCV. Notably, the percentage of respondents who considered reliability at TOA for their primary station was 11% lower for the Changed respondents than the No Change respondents, which implies that by considering reliability at TOA, there was less need to change stations later. At TOS, this relationship reversed and reliability was noted more frequently by Changed respondents than No Change respondents. Fewer than half of Changed and No Change respondents listed any of their 2nd-5th stations as backup stations.

Revealed Reasons

There are more statistically significant differences between the Changed and the No Change groups for the objective measurements of station convenience produced by the proximity and deviation analysis, in contrast to the subjective stated reasons. The percentage of drivers whose primary station was objectively one of the three closest stations to home is significantly lower for Changed respondents, both at TOA (35%) and TOS (31%), than No Change respondents (69%). This is also the case for work locations: 40% of No Change respondents list the closest station to work, while only 12% of Changed respondents did, both at TOA and TOS. We also find that Changed respondents do not list a station measurably nearer to home at TOS: primary stations are on average seven minutes farther away from their home than No Change respondents and four minutes further away than the closest one at TOA. This suggests that stations closer to their home become less important over time for this group. These findings also imply that stations measurably nearer to home or work provided more lasting utility to No Change drivers.

When considering commuting routes between home and work locations for each respondent, a significantly higher percentage of No Change respondents listed a primary station that required the shortest possible deviation to reach. Of the No Change respondents, 69% relied on a primary station with one of the three smallest deviations from their home-work commute route, while only 37% of Changed respondents did at TOA and 27% did at TOS. Therefore, we do not find strong evidence that Changed respondents switched to stations with shorter deviations, nor we do we find that they switch to stations nearer to home, but we do find that short deviations are associated with a stable set of stations. The average lowest deviation to reach a primary station on any route between home and the three given destinations is 10 minutes both for Changed and No Change respondents. Changed respondents, though, reduce this average by 2 minutes at TOS. Secondary stations are nearly 8 minutes more convenient to these routes for Changed respondents at TOA compared to their No Change counterparts, and 9 minutes more convenient at TOS. These findings indicate that stations more convenient to Changed respondents' travel routes become more important over time.

In summary, there are a number of inconsistencies between respondents' stated reasons for listing stations and the revealed relationships between stations and respondents' important geographic locations, and we note two general takeaways. First, the inconsistencies are more exaggerated for the Changed respondents compared to the No Change respondents. Changed respondents subjectively consider 58% of primary stations near home, but only 35% of these stations actually are one of the three shortest travel times to home under free flow conditions. At TOS, these differences become even more pronounced, as 70% are subjectively considered near home by Changed respondents, while only 31% are actually one of

the closest three and are four minutes farther from home than they were at TOA. In contrast, for the No Change respondents, 68% subjectively consider their primary station closest to home, which is almost identical to the 69% for whom these stations are in fact one of the three closest. Note that this alignment of the subjective and objective criteria only happens with the "near home" label, but does not apply to "near work" or "on the way."

Second, Changed respondents consistently label stations "near home" and "near work" that are not the closest three to either of those locations, and consistently fail to label stations as being "on the way" that actually are among the three most on the way to one of their primary destinations. For "near home" and "near work", Changed respondents listed stations as near these locations far more frequently than they were observed to actually be one of the three closest. In contrast, Changed respondents labeled primary stations as "on the way" 14% less frequently than they were observed to actually be one of the three most on the way. We also find, somewhat surprisingly, that Changed respondents did not change at TOS to stations that are objectively nearer to home or work, or more on the way.

Analysis of Added Stations

We now analyze how stations added by Changed respondents over time compare to all other station changes they made (Table 2), including stations dropped after TOA and stations that changed importance after TOA, but not stations that were listed at TOA and never opened. These station changes are then broken down into the two distinct groupings of interest. The first group, "Station Available Pre-Adoption", consists of listed changed stations that were available for use at both TOA and TOS. Of the 77 station changes in this first group, 21 were added to the respondents' lists after TOA. The second group, "Station Opened Post-Adoption", consists of listed changed stations that were planned but not yet available at TOA, then opened for operation between TOA and TOS. Of the 54 station changes in the second group, 35 were added to respondents' lists at TOS.

The primary hypothesis of the paper was that early adopters start out with more focus on locations near home, but over time they begin to use stations farther from home but on their way to or near work or other important travel destinations. Table 2 shows that for all station changes, the Added stations tend to be farther from home than all other stations changed after TOA. Both for stations that were initially available and those that opened post-adoption, median travel time from home is 17 minutes longer for Added stations compared to other changed stations that Changed respondents initially listed. Both groupings of Added stations also include a higher percentage of stations an hour or more away from home. It is important to note that the times generated by the Proximity and Deviation analysis reported below are dependent on the use of average free-flow travel times.

The deviations required to reach stations between respondents' homes and one of their three listed travel destinations present a more complicated picture. For the group of stations that were available pre-adoption, the median deviation of Added stations is higher (14 vs. 8 minutes), contrary to our hypothesis, but the percentage of Added stations opened post-adoption with extremely short (< 3 minutes) deviations is also higher (33% vs 25%), consistent with our hypothesis. Of the 21 Added stations, 10 have deviations less than 7 minutes. The other 11 Added stations have calculated deviations to one of the drivers' destinations ranging from 14 minutes to 39 minutes, plus one outlier with 74 minutes. The willingness of at least some drivers to add stations with very long deviations requires further research. It is unknown how many of the very long calculated deviations would involve a much shorter deviation to an unlisted travel destination, which is possible given that respondents were asked to list up to five stations but only three frequent destinations.

TABLE 2 Comparison of Added stations vs. all other Changed stations by two categories of interest: stations "Available Pre-Adoption" and those "Opened Post-Adoption."

Factor	Available Pre-Adoption (n=77)		Opened Post-Adoption (n=54)	
	Listed at TOA: Changed Station (n=56)	Added Station (n=21)	Listed at TOA: Changed Station (n=19)	Added Station (n=35)
Proximity and Deviation Analysis (median minutes)				
Lowest Home to Destination Deviation	8	14	4	4
Home to Station Travel Time	26	43	21	38
Proximity and Deviation Analysis (% of listed stations meeting the criteria)				
Shortest Home-Destination Deviation is < 3 Minutes	25[a]	33[a]	31[b]	49[b]
Station is > 1 Hour from Home	16[a]	33[a]	16[b]	43[b]
Stated Reasons for Listing Stations (% of listed reasons)				
Near Home	15	13	7	18
Near Work	11	15	14	11
Near School	4	0	0	4
Near Shopping	6	0	0	5
Near Friends and Family	6	5	10	7
Near Social or Recreational	6	10	10	11
On the Way	7	13	10	11
Backup Station	13	5	7	8
Long Distance Trip	6	5	7	7
Not Crowded	6	8	10	7
Pressure	5	5	0	3
Station Amenities (e.g., convenience store)	4	0	0	1
Reliability	6[a]	18[a]	14[b]	5[b]
Price	4	3	7	3
Safety	4	0	3	1

[a]Descriptive statistics for independent variables in Table 3, Available Pre-Adoption Model. [b]Descriptive statistics for independent variables in Table 3, Opened Post-Adoption Model.

Table 2 reveals some insights into how drivers view stations that opened post-adoption when they are considering purchasing an FCV. The stations closer to home (median 21 minutes) and with short deviations to some destination (median 4 minutes, 31% under 3 minutes) tended to be on the driver's radar at TOA and they listed them as stations they were intending to use, despite not being open yet. Added stations that opened post-adoption are farther from home (median 38 minutes) than those listed at TOA. Despite their shorter deviations to reach (a median of 4 minutes, with 49% under 3 minutes), they were not initially on the driver's radar but were added after they opened.

For both availability classifications, stated reasons for listing stations are relatively similar for Added stations and those initially listed, with the exception of reliability. For the more telling category of

stations available pre-adoption, reliability was stated more often for Added stations (18%) than for other changed stations (6%).

Given these differences between the two classifications of Added stations, we specified two binary logit models (**Table 3**) to assess differences between these stations and other changed stations initially considered by respondents. Separate models were specified for stations available pre-adoption and those opened post-adoption. The unit of analysis in each model are changed stations, where $y_i = 1$ for added stations and $y_i = 0$ for stations initially listed that respondents no longer use or have changed in importance. Table 2 contains the comprehensive list of variables considered for the models in Table 3. A series of two-sample t-tests helped identify differences in key metrics between the two groups in each model. We also computed correlation matrices to avoid selecting multiple interdependent variables. Variables were then added or removed iteratively to improve model fit - assessed by comparing AIC values - to the point where no further improvement could be observed.

TABLE 3 Logit Model Results: Characteristics of Added Stations Relative to Changed Stations Initially Listed by Changed Respondents, by Station Availability Classification

Available Pre-Adoption				***Opened Post-Adoption***			
Station Available TOA and TOS *DV:* y_i =1 for added stations and y_i = 0 for other initially listed changed stations				***Station Planned at TOA, Available TOS*** *DV:* y_i =1 for added stations and y_i = 0 for other initially listed changed stations			
Coefficients[a]	**Est.**	**OR**	***p***	**Coefficients[a]**	**Est.**	**OR**	***p***
Station is > 1 Hour from Home[b]	1.26	3.54	0.04*	Station is > 1 Hour from Home	1.60	4.93	0.03*
Shortest Deviation < 3 min.	0.42	1.52	0.48	Shortest Deviation < 3 min.	1.16	3.20	0.08^{+}
Reliability	1.29	3.64	0.05*	Reliability	-0.51	0.60	0.55
Constant	-1.72	0.18	<0.01*	Constant	-0.22	0.80	0.64
Model Diagnostics				**Model Diagnostics**			
Log Likelihood	-41.6			Log Likelihood	-31.1		
Likelihood Ratio Test (*p*)	<0.01*			Likelihood Ratio Test (*p*)	<0.01 *		
AIC	91.1			AIC	70.3		
Hosmer-Lemeshow Test (*p*)	0.45			Hosmer-Lemeshow Test (*p*)	0.51		

*significant α = 0.05, $^{+}$significant α = 0.10. [a] All variables entered in the two models are dummy variables

In each model, stations being an hour or more from home was a positive and significant predictor of an Added station relative to one initially listed by a respondent. In the Available Pre-Adoption model, in contrast to the Opened Post-Adoption model, Added stations are positively influenced by listing reliability as a reason for using the station (OR = 3.64) while the station requiring a short deviation to reach is not a significant predictor. In the Opened Post-Adoption Model, Added stations are positively influenced by requiring a short deviation to reach (OR = 3.20) while listing a station for reliability reasons is not a significant predictor of adding these stations since TOA.

DISCUSSION

Much AFV refueling station planning literature has focused on the need to place stations conveniently near home locations, work locations, or along commuting routes in order to encourage AFV

adoption. These considerations do indeed appear to be prominent in this study at the critical moment when respondents decided to adopt their FCVs, and seem to have some influence on whether or not respondents change stations and the nature of those changes. Notably, the percentage of No Change respondents who listed their primary station as the one closest station to their home at TOA is nearly identical to that of a larger sample in the recent AB8 Report on FCV drivers in California (*7*).

Analysis of responses from those that did not change their list of stations after some time with the vehicle provides some evidence that, for them, the strategy that recommended aligning early stations with neighborhoods of potential early adopters allowed them to feel comfortable adopting the FCV without yet needing or desiring to change their initially intended stations. The No Change group was fortunate enough to have stations that were both measurably near home and perceived to be near home. For Changed respondents, the discrepancies between stated perceptions of proximity to home and results of the proximity analysis between listed stations and home locations are distinct, and warrant future attention, as we note that they did not change to stations that were measurably nearer to home even though the percentage who said the station was subjectively "near home" increased. Regarding the apparent understating of stations being considered on the way, we speculate that this may be a function of the inherently more complex nature of assessing a station's relative position between two points as opposed to its proximity to one. It is also possible that stations that are both near home and on the way are primarily conceptualized by drivers as being near home, though precisely how drivers simultaneously balance these criteria is unclear.

A surprising finding was the willingness of some drivers to add some stations to their lists at TOS that are an hour or more away from home and, in some cases, requiring very long deviations to reach. It is possible they assumed the nearest stations would be the most convenient at the TOA before taking their activity space and driving behavior into account after experience. We speculate that the long driving range of FCVs (over 300 miles) enables some drivers to refuel on other kinds of semi-regular routes that they may not drive daily, and the addition of these stations to their list signals an expansion of FCV travel activity from home and may reflect greater confidence and a greater degree of experience with the vehicle and refueling infrastructure. An analysis that also considers travel direction as a component of deviation required to reach a station relative to two given locations (e.g., between home and work), in combination with proximity, could provide future insight. While proximity is currently accounted for in the deviation analysis by measuring the time required to travel from an origin, to a station, then to a destination, it is possible that these kinds of deviations would be tolerated to a far lesser degree by drivers as the infrastructure matures and more stations become available.

More broadly, these findings may also be a signal that once early adopters have a set of stations that they consider convenient enough to home locations, work locations, and commuting routes, other trip types become the next priority. There are some unique considerations that should be noted. Recent studies have shown that retirees have been among the early adopters of FCVs (*11*), and these respondents would understandably prioritize non-work locations. However, the percentage of respondents in this study who did not list a work location was nearly identical (about 20%) for both Changed and No Change groups, so these results do not seem to be a function of behavior changes from retirees specifically. Some respondents listed multiple work locations, while still others may take advantage of recent policies in California that encourage employees to telecommute more often and are conducting different types of travel. We also did not ask how long respondents spent researching the station network, which may influence the degree to which respondents changed stations or not.

We do note that Changed respondents are not disproportionately located in either the San Francisco Bay Area or greater Los Angeles, and neither are Added stations. When considering the two availability classifications, the percentage of Available Pre-Adoption Added stations in the San Francisco Bay Area is 15%, with 70% in the Los Angeles area, and the remainder adding the station at Harris Ranch (Coalinga) that facilitates travel between the two areas. For stations Added that Opened Post-Adoption, these percentages are 30% for Bay Area stations 42% for those in Los Angeles, with the remainder scattered between Sacramento, Coalinga (Harris Ranch), and Truckee. Planned stations that have been added to a respondent's list over time, then, appear to not be disproportionally added to one metropolitan

area or the other, but instead, to stations that support longer-distance travel elsewhere in the state. This is reflected in the finding that Added stations tend to be farther from home than those initially considered.

Reliability remains a key consideration with the fledgling hydrogen refueling infrastructure, and the results of this study reflect that consideration. Due to supply constraints and equipment failures, early FCV adopters have had to deal with station closures and reliability issues more frequently than they ever did for gasoline stations. Reliability, which was subjectively defined by respondents, becomes more important after experience for drivers who changed stations, and is a significant predictor of adding a station over time that was available both at TOA and TOS. It is also possible that No Change drivers were more aware of this issue than Changed drivers when they acquired their vehicles, and did not end up changing stations for reliability-related reasons as a result of upfront planning. Other studies have found some were aware that station reliability was an issue prior to FCV adoption and others were not (*11*). Prior knowledge of the reliability issue at TOA was not directly considered in this study.

Our survey instrument did not explore interactions between respondents and other drivers prior to their purchase, which might account for the disparity in reliability import between Changed and No Change respondents. Information-sharing between current and prospective FCV drivers via online forums and in-person communication proves highly important to consumers' understanding FCV technology and planning for its adoption (*11*). It is possible that Changed respondents added stations over time that had gained a reputation in these communities as being reliable. Backup stations, on the other hand, declined in importance over time, which may indicate that drivers who switched to more reliable stations had less need for a backup station after experience. Uncertainty remains, though, about how respondents interpreted the "backup" terminology.

Of relevance to the network analysis, we also did not ask respondents to indicate how factors such as the time of day of respondents' trips or congestion may have altered their travel routes to their primary travel destinations and stations, and we assumed travel under free-flow travel conditions, which are priorities for future work. Expanding consideration to the three closest stations to home, work, or a frequently traveled route helped address this to a degree, though future specificity on these factors may help indicate which stations are considered more or less convenient as a function of nearby travel or traffic congestion. Additionally, we relied on respondents to provide their approximate home and trip destination locations using an interactive web map in the survey. Asking drivers for up to five stations but only up to three destinations may have introduced some uncertainty into the proximity and deviation analysis relative to the station locations. For example, there could be at least two or more stations listed by respondents that are near or on the way to some other destination that respondents could not indicate in the survey. However, given the sparse nature of the refueling infrastructure, it is unlikely such geographic uncertainty would dramatically influence the rank-order position of the listed stations relative to the others available both at TOA and TOS. It is also possible that respondents may change their three most frequent travel destinations over time after this study, so station changes resultant from changes in travel destinations should be monitored accordingly.

Finally, a larger sample in a future study would be helpful to verify these findings, alongside analysis with a more robust refueling network that is planned to be available for such a study in a few years.

CONCLUSIONS

Researchers have long anticipated the introduction of hydrogen FCVs into regional transportation systems and have developed a suite of station planning strategies that would encourage adoption when the vehicles came to market. This study addresses an understudied topic in the literature, which is how drivers re-prioritize station locations after adopting the vehicle. Analysis of survey data collected from 124 FCV drivers in California demonstrates that if drivers have stations objectively near home, work, and frequently traveled routes when they made the decision to adopt an FCV, they were less likely to change their list of stations over time. This finding provides some evidence to support the notion of locating stations near the home and work locations of likely early adopters, and further, that drivers will continue to use these stations over time.

We also find that drivers who changed stations overstated stations' subjective convenience to home and work, and understated that of stations on the way, and did so to a greater extent than those who did not change their list of stations. However, these respondents did not change to stations that required lower estimated travel times to any of these criteria. For those who did add stations after experience, reliability is a significant factor, particularly for stations that were available at the time they adopted the vehicle. It is a clear signal to station developers that reliability is a concern of early FCV adopters that is strong enough to change the list of stations they initially intended to use, even if it means adding stations far less convenient to home.

Regardless of whether the station was available pre-purchase or opened post-purchase, stations added by respondents were more likely to be farther from home, and in the case of those that opened post-purchase, require minimal deviation to reach. This is an important first glimpse at how stations built to serve potential customers in one target area also allow drivers from other areas to expand their travel activity with the FCV after an initial period of acclimating to the vehicle and refueling infrastructure, though to what extent these changes are a function of desire or need is a topic for future inquiry. New station locations that are convenient to a number of different trip destination types that facilitate travel farther away from home, including corridors and recreation areas, may be appealing to drivers after they gain experience with the vehicle, so long as the station maintains a reputation for being reliable. New station locations can also increase local awareness of FCV technology, thus encouraging adoption.

Some future additional research directions have been identified by this study. First, there is an opportunity to learn more about the relationship between experiences with the refueling infrastructure and respondents' willingness to continue using their FCVs over time, especially as many begin to approach the end of their three-year lease period. Second, an analysis of precisely how FCV adopters initially evaluate a network of stations that they consider to be both subjectively and objectively convenient to both home and multiple trip destinations is an important future research direction that can help other regions carefully plan the future locations of hydrogen stations is an essential next step.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: A. Krafft, S. Kelley, M. Kuby, O. Lopez, R. Stotts; data collection: A. Krafft; analysis and interpretation of results: A. Krafft, S. Kelley, M. Kuby, O. Lopez, R. Stotts; Author; draft manuscript preparation: A. Krafft, S. Kelley, M. Kuby, O. Lopez, R. Stotts. All authors reviewed the results and approved the final version of the manuscript. The authors do not have any conflicts of interest to declare.

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The datasets used for analysis in this study are available from the corresponding author on reasonable request.

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