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Refuelling behaviour of California fuel cell vehicle drivers

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Summary

This research investigates FCEV drivers hydrogen station use using results from a 2017 survey of 395 fuel cell electric vehicle (FCEV) owners and a 2018 survey of 328 FCEV owners. The results show FCEV drivers use on average 2.4 hydrogen stations. The average shortest distance FCEV owners would need to travel from home, work, or their commute to a hydrogen refuelling station was 10 miles. Those whose most-used station was not the closest station available were more likely than those whose most-used station was the closest to use renewable hydrogen, suggesting that some drivers may prefer renewable hydrogen.

Keywords: hydrogen, fuel cell, fuelling, behaviour

1 Introduction

The state of California is pursuing goals of 100% zero emissions vehicle (ZEV) light-duty vehicle sales by 2035. At present, most of these sales are plug-in electric vehicles (PEVs), which include both battery electric vehicles and plug-in hybrid electric vehicles. Hydrogen fuel cell vehicles (FCEVs) are a third ZEV type currently sold in California, with around 11,000 FCEVs sold in the state, out of close to 1 million ZEVs [1]. FCEVs require an entirely new public hydrogen refueling infrastructure to operate [2,3]. PEVs can operate, though not optimally, using existing electric infrastructure (e.g., using existing 110v outlets). Hydrogen infrastructure is therefore needed for FCEVs to be purchased and used by consumers. There are currently 47 hydrogen stations in operation in California [4]. California is the only state in the United States with substantial FCEV sales and a network of hydrogen refueling stations. The network of hydrogen stations in California has been experiencing reliability issues due to hydrogen supply issues, technical problems with refueling stations, and high demand for hydrogen [1]. At the time of writing (December 10th, 2021) half all California hydrogen stations are offline, an issue that has persisted throughout 2021[1]. These reliability issues may impact consumers ability to use FCEVs or consumers decisions to purchase one.

In this study we investigate how California FCEV drivers use these hydrogen station. This includes exploring station choices, distance driven to stations, the impact of infrastructure on purchase decisions, and gaps in station coverage in the state. Results come from two questionnaire surveys of California FCEV adopters conducted in

[1]Update: Hydrogen Distribution and Supply in California https://m.cafcp.org/?_ga=2.264582863.1150402048.1639095661-473789819.1638996262

2017 and 2018. Our hope is that this information will reveal consumer preferences for hydrogen stations and provide insights to help in the future planning of hydrogen infrastructure.

2 Literature Review

Research on consumers and FCEVs & hydrogen infrastructure has focused on consumer perceptions of the technology [2–4] and consumer purchase considerations and preferences[5,6]. This research includes studies on those who have purchased an FCEV [7–9]. Researchers have also modelled hydrogen station deployment and station location planning [10,11], and hydrogen demand from FCEVs under different adoption scenarios [12].

Of most relevance to this paper are studies on consumer use of hydrogen refueling infrastructure. Kelley et al. [13] and Krafft et al. [14] surveyed 129 FCEV adopters in California in 2019. Kelley et al. [13] investigated how FCEV adopters evaluate hydrogen infrastructure availability prior to their purchase of a FCEV, including which stations they planned to use and why. They found that 80% of FCEV adopters planned to rely on multiple stations, with their ”primary” station being located near to their home or work. They report the median time to travel to the primary station is 3.4 minutes, compared to 7.1 for the secondary, and 11 for all other stations. The authors conclude that station proximity to home, work, or their commute is a priority for FCEV adopters. The study reports that drivers intended to use primary and secondary stations during the week and on weekends, while their 3rd to 5th stations were intended for weekend and recreational destinations.

3 Method

The results from this study come from two questionnaire surveys conducted by the study authors. These surveys were conducted in June-December 2017 and August-October 2018. The 2017 survey received 395 complete responses and the 2018 survey received 328 responses from FCEV owners. Respondents to the first survey had access to at least 33 hydrogen stations and those who took the 2018 survey has access to at least 36 hydrogen stations based on station open dates.

We use secondary data from the California Fuel Cell Partnership the California Air Resources Board to gather information on hydrogen station attributes including:

- Station location
- Station refueling capacity and on-site hydrogen storage capacity
- Station operator
- Whether hydrogen is renewable
- Hydrogen delivery (pipeline, truck, on site production)
- Station open date

3.1 Hydrogen Station Distances

We quantify access to hydrogen stations for households with FCEVs in terms of travel distance to a fueling station from home, from work, and “from the commute,” meaning the minimum detour distance added to a commute if the traveler goes to the station while driving to or from work. We also quantify access to hydrogen stations for the general population in terms of the travel distance between a station and the block group centroid. Travel distances were computed in R using the {cppRouting} package [15,16] which was weighted by travel time at maximum speed on each link. The road network for this analysis consists of all roads classified as motorway, link, trunk, primary, secondary, or tertiary in California. Residential streets and access roads were excluded to save processing time and because they make up a very small portion of travel distance. Fueling stations, home locations, work locations, and block group centroids were attached to the nearest point on a road in the network that was not classified as a motorway or motorway link.

For households with FCEVs, the travel distance was computed from home and work to each fueling station in California. To identify station distances drivers might use on their commute, we computed a detour distance by subtracting the travel distance from home to work from the combined distance from home to the fueling station and from the fueling station to work. In this way, if a driver has a typical one-way commute of 10 miles and has a fueling station located 6 miles from home and 5 miles from work, their detour distance for that station is 1 mile, since adding it as a stop on their commute would only increase their total travel distance by that much. The overall minimum travel distance from each household to each station is the minimum of 1) the round-trip distance from home to the fueling station, 2) the round-trip distance from work to the fueling station, and 3) the detour distance from their commute.

For the general population, block group interior points were used as a proxy for the home location and only a single distance was calculated, since work locations are not known.

3.2 Hydrogen Station Choices

Most of our data analysis is descriptive with some statistical comparison using t-tests or chi-squared test. We investigate the decision to use as a primary station one that is further away vs. the closest one to an FCEV owners home, work, or commute. To do this we use a binary logistic regression mode where 1 is the decision to travel further, and 0 is the decision to travel to the closest station.

The model includes household variables including whether FCEV drivers commute, their access, number of vehicles in the household, and gender; variables on the hydrogen station including whether it is located on a major road, whether it is within walking distance to single family homes and stores, whether it supplies renewable hydrogen, and how many hours per day it is open; and variables on drivers use of hydrogen stations including the number of stations they use and how often they use their primary station. We intended to include as station variables how fuel was delivered to the hydrogen station (truck, pipeline) and station capacity, but these variables strongly correlated with whether the station supplies renewable hydrogen. Therefore, we could not use them due to the issue of multicollinearity.

4 Results

First, we explore fuel cell vehicle use on the commute and longest trip in the 12 months prior to the questionnaire survey, then we explore hydrogen station use including station choices, then we investigate the impact of hydrogen stations on FCEV purchase, and finally we explore hydrogen station coverage in the state using assumptions taken from FCEV driver fueling behavior.

4.1 Fuel Cell Vehicle Use

For 73% of households the FCEV is the most frequently used vehicle by the survey taker. Seventy percent (70%) of survey takers reported commuting in their FCEV, the remainder commute in other household vehicles. The average commute distance for FCEV drivers is shown in Table 1. More than half of drivers who commute in an FCEV report a commute of under 20 miles, and the mean commute distance is 18.7 miles. The mean reported commute distance in an ICEV is in our survey is 20.8 miles. The differences among FCEV, BEV, HEV, PHEV, and ICEV commute distances were not significantly different, according to paired student t-tests. This indicates that in our sample FCEVs commute a similar number of miles as other vehicle types, though we note the sample size for BEVs, HEVs, and PHEVs is small, which gives a large margin of error.

Table 1. Mean one-way commute distance for vehicles used by survey respondents to commute in.

Level	n	Mean	Std Error	Lower 95%	Upper 95%
BEV	15	22.056	4.6936	12.839	31.273
FCEV	456	18.781	0.8513	17.110	20.453
HEV	31	17.587	3.2649	11.176	23.999
ICEV	130	20.815	1.5943	17.685	23.946
PHEV	13	19.961	5.0417	10.061	29.862

Figure 1 shows the household vehicle used by survey takers for the longest trip their households took in the 12 months prior to the questionnaire survey. Less than 1/3 of households reported using their FCEV for this trip while more than half reported using an ICEV. Table 2 shows the mean distances of these trips by vehicle type. Trips in HEVs and ICEVs are significantly longer than trips in FCEVs, according to paired student t-tests. The trip distances for FCEVs compared to BEVs, PHEVs, and rental cars are not significantly different.

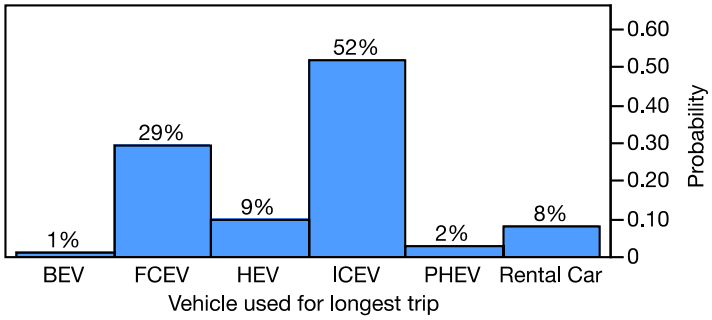

Figure 1. Vehicle used for the longest trip the households completed in the 12 months prior to taking the survey.

Table 2. Mean long distance trip distance for vehicles used on that trip.

Level	n	Mean	Std Error	Lower 95%	Upper 95%
BEV	4	1040.98	301.88	447.92	1634.0
FCEV	152	480.44	48.97	384.23	576.6
HEV	48	704.44	87.15	533.24	875.6
ICEV	268	722.37	36.88	649.91	794.8
PHEV	13	697.98	167.45	369.01	1027.0
Rental Car	40	650.49	95.46	462.95	838.0

4.2 Hydrogen Station Usage

Survey takers were asked to report up to 5 hydrogen stations they used in order of use frequency. More than 33% rely on only 1 hydrogen station, with close to 60% using 2 or fewer stations. Only 11% of the sample report using

5 or more hydrogen stations. The mean number of stations reportedly used is 2.4. Station A (the most frequently used station) is used more than once per week, Station B is used just more than once every two weeks, Station C is used just more than once per month. Station D and E are used every 1-2 months.

Figure 2 to Figure 5 show station driving distances from home (Figure 2), work (Figure 3), the shortest detour from the home-work commute (Figure 4), and the shortest distance of these three (Figure 5). On average station A (the most frequently used station) is the closest station to drivers home, work, or commute. The most frequently used stations are an average of 18 miles from FCEV drivers' home location and 26 miles from their work location, and 16 miles "from their commute"—i.e., the distance added to a trip between work and home when the driver makes a detour to a hydrogen station. The average shortest distance to a hydrogen station from either home, work, or commute is 10 miles.

For 51.9% of respondents, the most frequently used station (Station A) is the closest station to home, for 33.4% it is closest to work, and for 44.9% it is the closest station to their commute. Overall, for 69.6% of drivers, Station A is the closest possible station to them from any of these locations. This shows that 1/3 of drivers choose as their primary hydrogen station one that is further away than the station closest to work, home, or commute. However, 98.9% of FCEV driver report using the station closest as one of their top 5 stations.

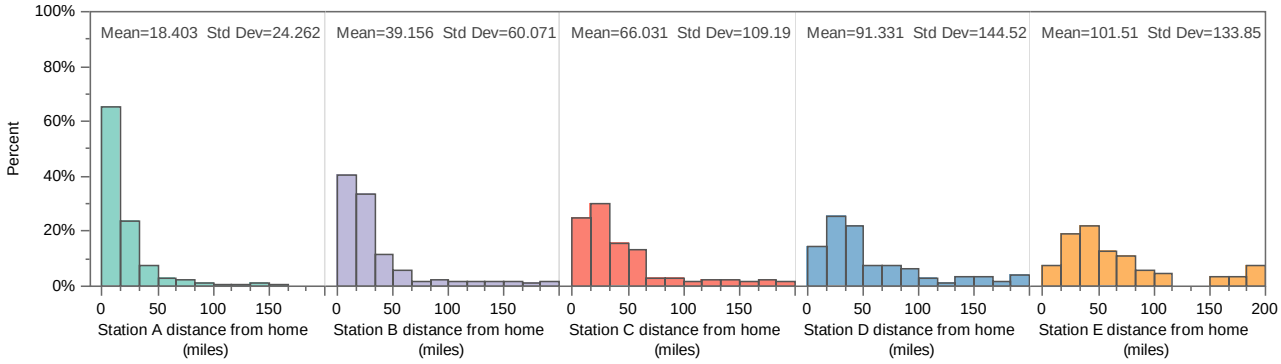

Figure 2. Histograms for station distances from home for the 5 most frequently used stations.

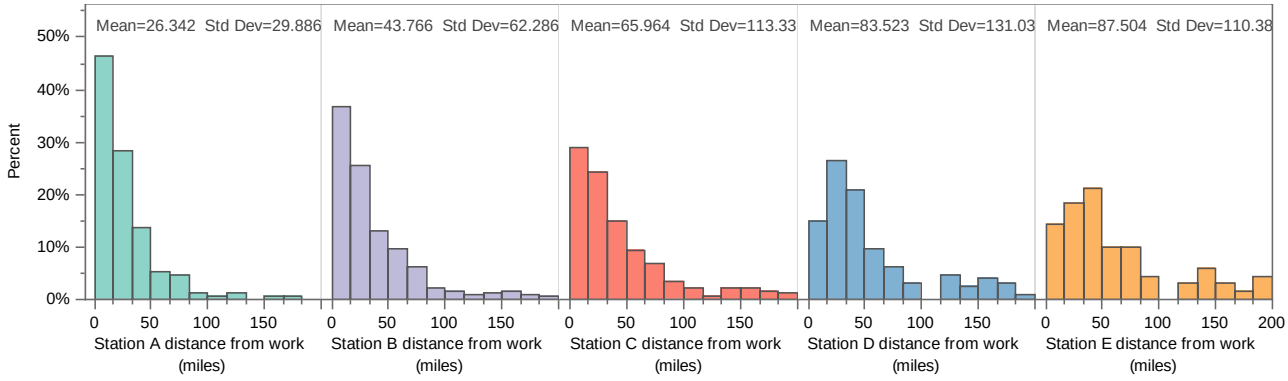

Figure 3. Histograms for station distances from work for the 5 most frequently used stations.

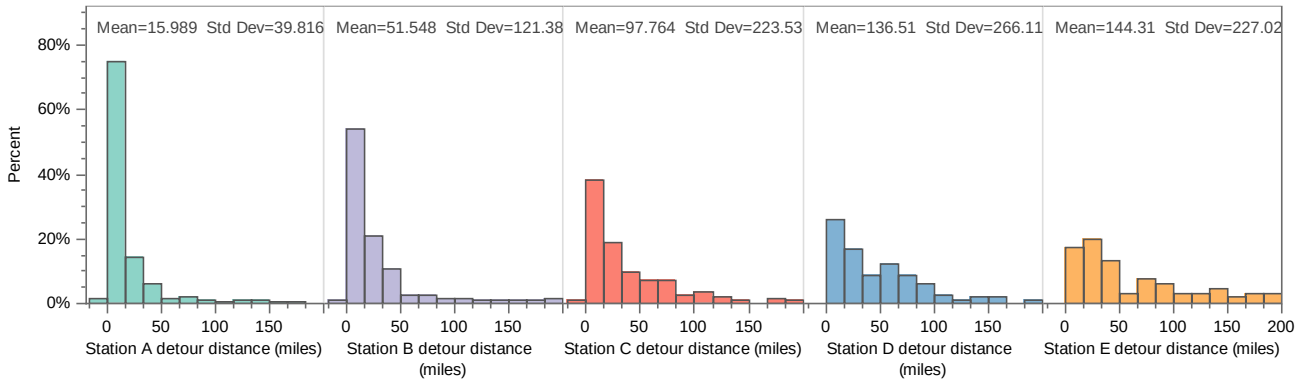

Figure 4. Histograms for station distances from the home to work commute for the 5 most frequently used stations.

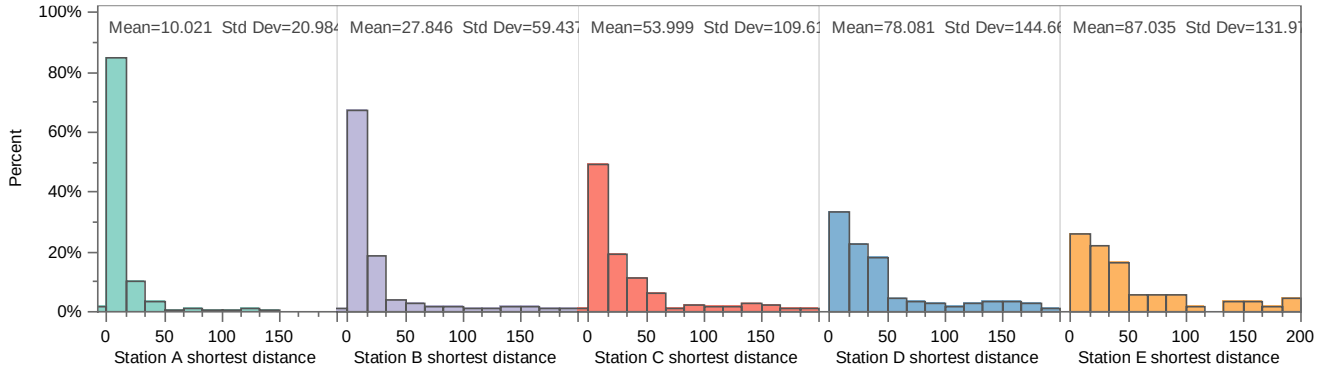

Figure 5. Histograms for station distances from the shortest possible distance from home, work, or the detour from commute for the 5 most frequently used stations.

4.3 Understanding Why Some Drivers Travel Further Than Needed to Refuel

We investigate why some FCEV drivers choose as their primary station one that is further away than necessary (i.e., further than the station that is closest to home, work, or commute). This may reveal something about FCEV drivers' preferences for hydrogen refueling. The minimum driving distance drivers travel when the station is not the closest one to them is 15.7 miles compared to 5.5 miles for those travelling to the closest station. For those travelling to a further away station 19% use a station with renewable hydrogen compared to only 6% for those travelling to the closest station.

Table 3 shows results of a binary logistic regression model of choosing as a primary hydrogen station one that is further away vs. one that is among those closest to home, work, or the commute. Since the majority of drivers choose to travel to the closest station to home, work, or their commute, we hope that this model can reveal something about hydrogen station preferences beyond simply stating drivers travel to the closest station, which is something prior research shows is a primary consideration. The results show that the odds of travelling to a station further away increase by 2.1 if the station has renewable hydrogen, holding all else constant. The odds of fueling at a further away station also increase by 0.2 for each additional hydrogen station drivers use. Finally, the odds of travelling to a further away station are lower for drivers who commute. This may indicate drivers who have more stations to choose from, more free time available (since they do not commute), travel to further away stations due to a desire to use renewable hydrogen.

Table 3. Binary logistic regression model of the decision to use as a primary hydrogen station one that is further away vs. one that is among the closest to home, work, or the commute.

Term	Estimate	Std Error	ChiSquare	Prob>ChiSq	Odds Ratio
Intercept	-1.374	1.3510	1.03	0.3091	
Stations used	0.2082	0.0808	6.64	0.01**	1.2315
Frequency of use for primary station (uses per year)	-0.0010	0.0027	0.04	0.8395	0.9994
On major roadway (1=Yes)	-0.1619	0.3399	0.23	0.6337	0.8504
Single family in walking distance dummy (1=yes)	0.3625	0.3073	1.39	0.2381	1.4370
Stores in walking distance dummy (1=yes)	-0.0223	0.4580	0.00	0.9611	0.9779
Renewable dummy (1= renewable)	2.0993	0.4101	26.21	<0.001***	8.1611
Station number of hours open per day	-0.0068	0.0411	0.03	0.8667	0.9931
Number of vehicles in HH	0.0777	0.1210	0.41	0.5206	1.0800
Gender dummy (1=male)	-0.2864	0.2671	1.15	0.2837	0.7509
Commute dummy (1 commute)	-0.5659	0.3181	3.16	0.0753*	0.5678
FCEV driver age	0.0035	0.0098	0.13	0.7183	1.0030

4.4 Impact of Infrastructure on Purchase Decisions

Error! Reference source not found. shows survey takers responses to the question that asked what purchase decision they would have made if the hydrogen station they use most frequently were not available. Only 30% of the sample indicated they would still choose their fuel cell vehicle. Thirty-one percent (31%) would still have chosen a zero-emission vehicle, while 18% would have chosen a conventionally fueled vehicle (either an ICEV or HEV). Those that indicated they would have purchased their FCEV if their most used station were not available use on average 2.6 hydrogen stations; those who would not have purchased an FCEV use on average 2.3 hydrogen stations. This may indicate higher reliance on a smaller number of stations for those that would not purchase an FCEV if their most used station were not available. There is no difference in distance station from home, work, commute, or the closest minimum distance for those who would or would have purchased an FCEV if the primary station were not available. This highlights the relative fragility of the system and that if a small number of stations were to become unavailable, this could impact FCEV adoption.

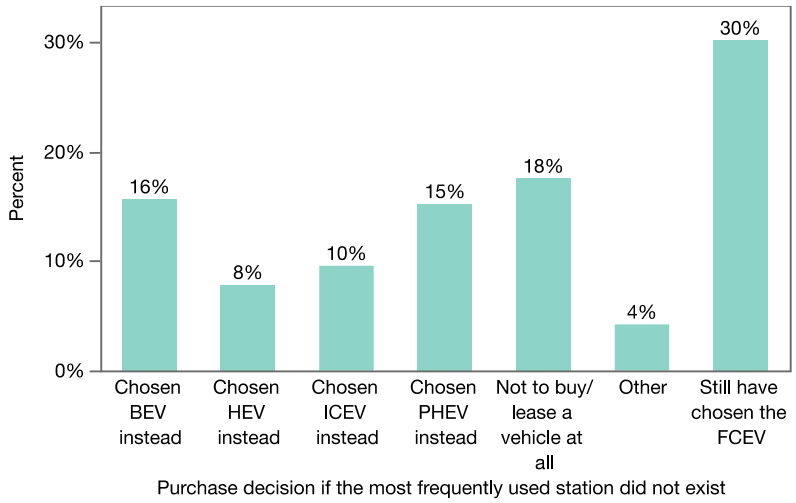

Figure 6. Responses to "If the fueling station that you use most frequently did not exist when you got your fuel cell vehicle, what would you have done?"

4.5 Station Coverage

Using information on station use we analyze statewide access to hydrogen stations. We show distances in increments of 5 miles, 5-10 miles, 10-20 miles, and 20–55-mile. Since FCEV drivers use more than two stations on average, we also map the distance to the second closest hydrogen station to FCEV drivers.

The median distance drivers travel to their preferred station is 5 miles, and the 75% quartile distance is 10 miles. The median distance to the second most used station is 10 miles, and the 75% quartile is 20 miles. In the following maps, we show station access by California census block groups to one, two, and three stations within 5, 5-10, 10-20, and 20-55 miles. Figure 7 shows California census block groups that are within the indicated distances, respectively of at least one, two, and three hydrogen refueling station. We focus only on the San Francisco Bay, Sacramento, and Los Angeles areas since coverage is limited to these areas. The census block groups with at least one station within 55 miles are concentrated in the major metropolitan areas of Sacramento, San Francisco, Los Angeles, and San Diego, as well as Harris Ranch (not shown) in Central California where one station exists in isolation.

Based on the finding that drivers used two stations on average, drivers preferred a station being within 10 miles, and there are current network reliability issues, we consider three stations within 10 miles to be *reasonable access* to hydrogen refueling. Using that criterion, 22% of California households have access to sufficient hydrogen refueling (Table 4). If we were to use a more lenient criterion of access to 2 stations within 10 miles, 34% of California households have access to hydrogen stations. A criterion of 3 stations within 20 miles would mean that 51% of the population have access to hydrogen refueling.

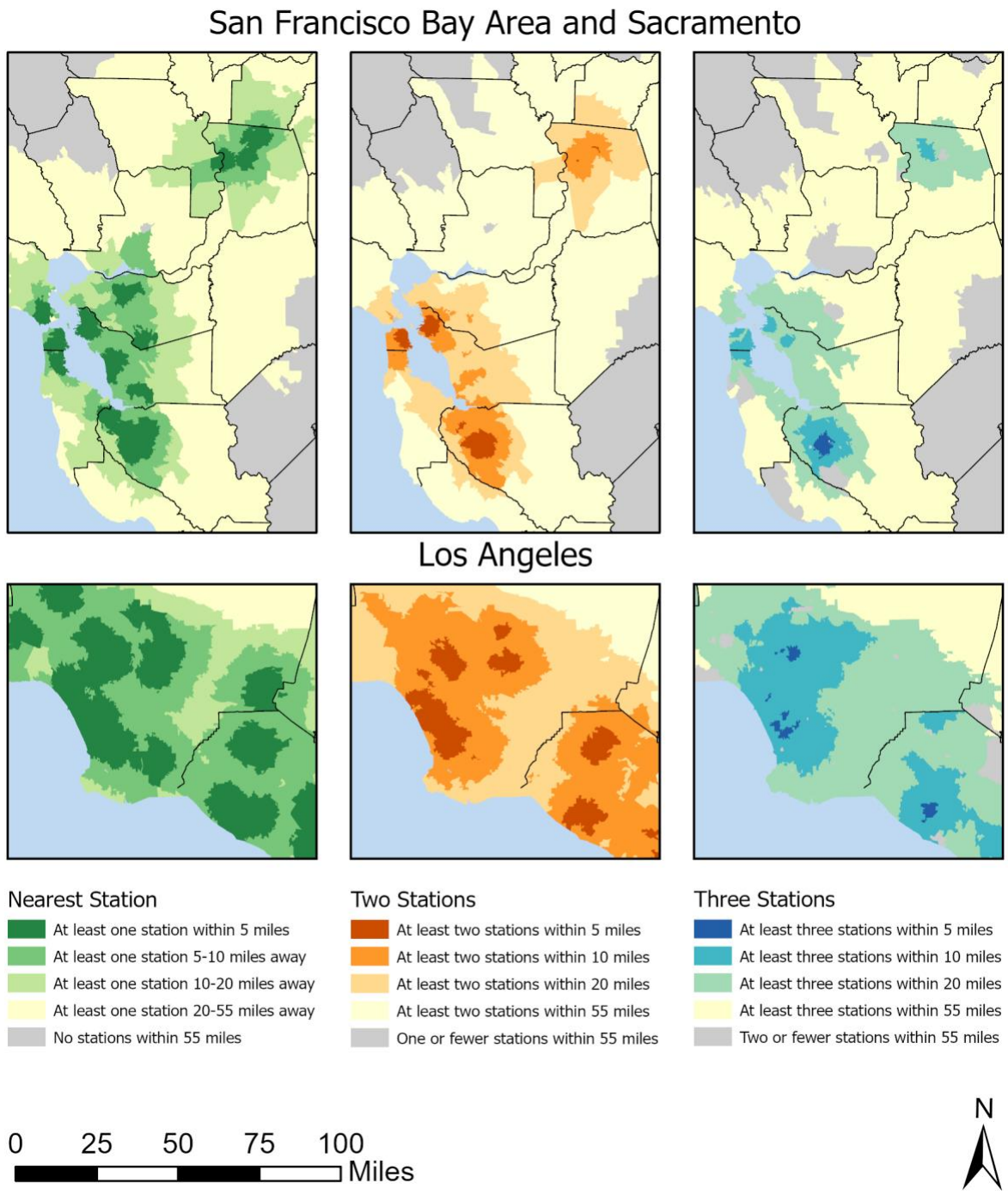

Figure 7. Road network distances to the nearest, second nearest, and third nearest hydrogen station on the census block group level in California in Los Angeles and the San Francisco Bay Area and Sacramento Area.

Table 4. Number and percentage of California households with 1, 2, or 3 hydrogen stations at distances of 5, 10, 20, 55, or more than 55 miles.

	Number of hydrogen stations		
Distance from home	**1**	**2**	**3**
5 miles	3,808,430 (29%)	1,265,491 (10%)	171,286 (1%)
10 miles	2,795,592 (21%)	3,193,822 (24%)	2,697,410 (21%)
20 miles	1,659,567 (13%)	2,451,354 (19%)	3,721,237 (29%)
55 miles	2,717,323 (21%)	2,681,040 (21%)	2,771,873 (21%)
More than 55 miles	2,063,354 (16%)	3,452,559 (26%)	3,682,460 (28%)

4.6 Station Distances and Disadvantaged Communities

Here we consider access to hydrogen refueling for Disadvantaged Communities in California. This stage of analysis was done using census tracts because this is the scale at which DACs are defined, but analysis methods are identical to those used in the rest of the study at the census block group level. Results show 55% of DAC and 51% of non-DAC census tracts have access to one hydrogen station within 10 miles, 43% of DAC and 33% of non-DAC census tracts have two stations within 10 miles, and 29% of DAC and 20% of non-DAC census tracts have three hydrogen stations within 10 miles.

T test results show mean distance to the closest station is significantly shorter for DAC census tracts, while there is no difference in the distance to the second or third closest station. The mean number of stations within 5, 10, and 20 miles of DAC and non-DAC census tracts. T-test results show significantly fewer hydrogen stations within 5 miles, but significant more within 10 and 20 miles.

5 Conclusion and Discussion

Our results on FCEV use show commute distances in FCEVs are the same as those completed in other vehicle types. The longest trip distances completed in FCEVs are shorter than those completed in ICEVs or HEVs and are the same as those completed in BEVs. This suggests that while FCEVs can driver further than BEVs, at present drivers do not take FCEVs on long trips, perhaps due to the limited availability of hydrogen refueling stations.

Our results show that California FCEV drivers use 2.4 hydrogen stations on average. Drivers' primary and secondary stations are used on a weekly to 2-weekly based. While other stations are used monthly or less often. Primary stations are on average closest to the home, work, or commute, and for 70% of drivers, their primary station is located at the shortest possible drive of any stations that existed at the time of the survey. We use a logistic regression model to investigate the decision to use a station other than the closest one as the primary refueling station and find that drivers who do no commute and who have access to more stations travel further away. Also, the odds of travelling further away increases if hydrogen stations use renewable hydrogen, which may indicate some drivers prefer renewably generated fuel. Seventy percent (70%) of FCEV adopters indicated they would not have purchased an FCEV if their primary station were unavailable, indicating that greater adoption will require additional stations.

Currently the percentage of California census block groups with one, two, and three hydrogen stations within 10 miles of households are 60.9%, 35.6%, and 22.5%. These census block groups are concentrated primarily in large metropolitan areas.

Using assumptions from the survey data on station use and distances driven to currently existing stations, we consider criteria for defining *reasonable access* to hydrogen refueling across California. Given that drivers use 2.4 stations, their primary stations are on average 10 miles away, and there are current issues with hydrogen station reliability, we consider 3 hydrogen stations within 10 miles to be a reasonable criterion for access to hydrogen stations. Using these assumptions 22% of California households have reasonable access to hydrogen stations. This means only around 1/5 of the state could feasibly consider an FCEV based on existing infrastructure alone (not considering hydrogen supply, station capacities, consumer preferences & knowledge, vehicle supply, etc.).

Limitations and Future Research

The network of hydrogen stations in California has been experiencing reliability issues due to hydrogen supply issues, technical problems with refueling stations, and high demand for hydrogen [1]. How station reliability impacts FCEV owners' hydrogen station choices is an important area of research, this may impact the decision to adopt a FCEV and the decision to continue owning one. Since we were unable to obtain station reliability or station downtime data, we do not know how this may impact drivers' hydrogen station choices. The survey data is also from 2017 and 2018, a more recent analysis of FCEV drivers use of hydrogen stations may reveal different findings especially given that survey takers had access to 33-36 stations while 47 are currently operable

Acknowledgments

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